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2021 Year in review

247 kilometers on one charge

and dozens of other breakthroughs

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In October, an Orion spacecraft was lifted atop NASA's Space Launch System rocket at NASA's Kennedy Space Center in Florida. The work at the Vehicle Assembly Building is in preparation for the Artemis I launch scheduled for February 2022.

NASA

The Year in Review

The most important developments as described by AIAA's technical, integration and outreach committees

ON THE COVER: Joby Aviation's S4 prototype flying over the company's Electric Flight Base near Big Sur, California, this year.

YEAR IN REVIEW

Adaptive Structures....8
Aeroacoustics....18
Aerodynamic Decelerator Systems....31
Aerodynamic Measurement Technology....19
Aerospace Power Systems....47
Aerospace Traffic Management....74
Air Transportation Systems....32
Aircraft Design....33
Aircraft Operations....34
Applied Aerodynamics....20
Astrodynamics....21
Atmospheric and Space Environments....22
Atmospheric Flight Mechanics....23
Balloon Systems....35
CFD Vision 2030....75
Communications Systems....40
Computer Systems....41
Design Engineering....9
Digital Avionics....42
Electric Propulsion....48
Energetic Components and Systems....50
Flight Testing....36
Fluid Dynamics....24
Gas Turbine Engines....51
Ground Testing....25
Guidance, Navigation and Control....26
High-Speed Air-Breathing Propulsion....52
History....79
Human-Machine Teaming....43
Hybrid Rockets....53
HyTASP....37
Inlets, Nozzles and Propulsion Systems....54
Intelligent Systems....44
Life Sciences and Systems....61
Lighter-Than-Air Systems....38
Liquid Propulsion....55
MVCE....27
Microgravity and Space Processes....62
Missile Systems....63
Modeling and Simulation....28
Multidisciplinary Design Optimization....11
Non-Deterministic Approaches....12
Nuclear and Future Flight Propulsion....56
Plasmadynamics and Lasers....29
Pressure Gain Combustion....57
Propellants and Combustion....58
Reusable Launch Vehicles....64
Small Satellite....65
Society and Aerospace Technology....80
Software Systems....46
Solid Rockets....59
Space Architecture....66
Space Automation and Robotics....67
Space Exploration....76
Space Logistics....68
Space Resources....70
Space Systems....71
Space Tethers....72
Spacecraft Structures....13
Structural Dynamics....14
Structures....15
Supersonics....77
Survivability....16
Systems Engineering....17
Terrestrial Energy Systems....60
Thermophysics....30
Transformational Flight....78
V/STOL Aircraft Systems....39
Weapon System Effectiveness....73

DEPARTMENTS

4 Editor's Notebook

5 Corrections

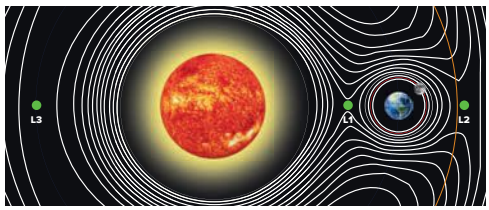
7 Flight Path

81 AIAA Bulletin

92 Career Opportunities

94 Looking Back

96 Jahniverse



6 AeroPuzzler

The point of Lagrange points

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- Forum 360: Sustainability Through Innovation Diversification
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Joby Aviation's all-electric, vertical-takeoff-and-landing S4 aircraft.

A hard decision in a year of multiple aerospace breakthroughs

The decision about how to illustrate the cover of this annual issue comes easily to us in some years. SpaceX's 2018 photo of "Starman" was irresistible as he headed off into deep space in a Tesla launched by a Falcon Heavy as a demonstration. Almost as irresistible was 2019's head-on image of the first Stratolaunch flight. Last year's overhead shot of airliners in storage captured the potential energy of the air transportation market during the pandemic.

This year felt different.

NASA's flight of the Ingenuity helicopter on Mars in April was a technical achievement, and one that suggests that other new modes of exploring planets and moons could be on the way. A few months later, the first flights to the fringes of space by the billionaires and their friends jolted the system: Suddenly regulators, analysts and journalists, including us, are taking our hardest looks yet at what it will take to get humans into space in significant numbers and the impacts that could have on the environment.

You will find these and numerous other developments referenced in this issue, but we felt the biggest emphasis on the cover should go to Joby Aviation's 247-kilometer flight of its all-electric, vertical takeoff and landing S4 prototype. That flight on a single charge without a pilot aboard was emblematic of the progress this year in advanced air mobility. In fact, this year might someday be looked back on as the turning point toward the goal of whisking cargo and passengers around locally and regionally aboard electric aircraft that do not require runways. Our choice for the cover should be no slight to the other breakthroughs in that field this year, including Beta Technologies' 330 km flight of its Alia aircraft with its vertical flight propellers removed and a pilot aboard. Joby's vertical takeoff and landing flight without a pilot aboard better reflects the characteristics that most experts think these aircraft will require for air mobility services to become profitable.

Aside from the coolness of the air mobility feats, this field stood out to us because this mode of transportation could become "part of daily life," as the consulting firm Deloitte of Washington, D.C., and the Aerospace Industries Association of Virginia put it in a report this year. Many of us could ride in AAM aircraft within our lifetimes, it seems, but scoring a ride to space will, for the foreseeable future, require winning a lottery or befriending a billionaire. The suborbital flights were significant not for their economic potential but for the awakenings they brought, such as William Shatner's post-flight speech about humanity's place in the cosmos.

And if you're the dollars-and-cents type, projections of market values bear out our decision. Deloitte and the Aerospace Industries Association of Virginia predicted earlier this year that the AAM market in the United States alone will soar to $115 billion by 2035. That's about five times NASA's annual budget. In August, Allied Market Research based in Oregon issued a more conservative projection that the global value will reach $17 billion by 2025 and $110 billion by 2035. Whichever is right, the point is that the numbers are huge. ★

Ben Iannotta, editor-in-chief, beni@aiaa.org

Incorrect metric conversion

In the Looking Back section of the November issue, we misstated the speed in kilometers per hour of the Curtiss CR biplane that a set a record on Nov. 3, 1921. The plane flew at 283 kph.

Millions not billions

The sidebar, "The price of Webb," in our November feature misstated the anticipated operating costs of the James Webb Space Telescope. The correct figure is $900 million.

AERO PUZZLER

Do you have a puzzler to suggest? Email us at aeropuzzler@aiaa.org.

The point of Lagrange points

Q: A spacecraft is headed to the L2 Lagrange point, and once it arrives, sadly, no other spacecraft will be able to take advantage of L2, because obviously two spacecraft can't simultaneously occupy the same point in space. Is this statement true or false and why?

Your challenge is to answer the above in a maximum of 250 words that someone in any field could understand. Email your response by noon Eastern Dec. 15 to aeropuzzler@aiaa.org for a chance to have it published in the next issue.

FROM THE NOVEMBER ISSUE

ESCAPING THE BERMUDA TRIANGLE: We asked you to explain why digging a trough in a runway would help get stretch version of a passenger jet off an island in the Bermuda Triangle:

TWO WINNERS THIS MONTH:

To take off on a short runway, the pilot will need to lift the nose higher than usual to generate the required lift. This will make the tail go down more than usual. With a longer-than-usual airplane, the tail will drag on the ground unless a trench is dug. (This is also why the bottom of the aft end of the C-130 is inclined.)

John Fay, AIAA associate fellow, Freeport, Florida

A stretch version of a passenger jet would need a higher-than-normal Angle of Attack for an early lift off due to the "short" runway. That would have caused a "tail strike" before lifting off safely. For this reason, he instructs the other flyers to help him dig a trough in the center of the runway toward the far end to prevent the tail strike.

Savas Uskent, AIAA member, Istanbul

For a head start ... find the AeroPuzzler online on the first of each month at https://aerospaceamerica.aiaa.org/ and on Twitter @AeroAmMag.

Creating a National R&D Plan for Aerospace Autonomy

The United States needs a national research and development (R&D) plan for autonomous capability for aerospace, according to a recommendation from the AIAA Autonomous Vehicles and Systems Task Force. Autonomy is certainly going to be part of America's transportation and off-world future.

The benefits of autonomy will enhance safety for all Americans in the 21st century and enable capabilities we are only just imagining. Autonomy will drive new missions and capabilities otherwise unimagined, as well as improve performance and lower cost and/or risk for aerospace systems and their missions. In the "2021 AIAA State of the Industry Report" we released in September, more than 60% of industry professionals ranked autonomous aircraft as an emerging technology with more opportunities than challenges.

It is imperative that AIAA helps clear the way for American industry to flourish in the evolving aviation and space markets. The AIAA Autonomous Vehicles and Systems Task Force believes that AIAA should play a leading role in forming the national R&D plan. A first step in creating that national plan was made during a recent gathering of leaders from government, industry, and academia in Washington, DC, at the AIAA Aerospace Autonomy Summit. More than 80 thought leaders and industry influencers invested a day exchanging ideas and making plans together for autonomy in aerospace. The event was intentionally limited to autonomy in the aviation sector in order to ensure sufficient focus there. A future event will address autonomy in the space sector.

Congressman Garret Graves (R-LA), Ranking Member of the House Subcommittee on Aviation, delivered a spirited keynote address during the event. We also heard from Congressman Rick Larsen (D-WA), the subcommittee's chairman. The remarks from these influential lawmakers resonated with the attendees, and we learned that the House Subcommittee on Aviation will soon organize roundtable discussions on autonomy. AIAA hopes to be an active participant in those important conversations. Throughout the day senior officials from the Department of Defense, the FAA, and NASA also shared their critical voices in setting our national autonomy strategy and policy.

With the numerous experts gathered, the conversations were lively and productive. Several themes emerged—and re-emerged:

- **Balance is needed between innovation and safety.** Innovation in autonomy is vital—and safety must not be diminished as a core value in our community.
- **We are developing a common understanding of trust.** Trust, transparency, and clear explanations of autonomous systems and their behavior will be key to acceptance.
- **Partnerships are key.** Industry associations, manufacturers, and government stakeholders will need to partner and cooperate to advance aerospace autonomy and realize its promise. Adjacent industries such as automotive and IT provide valuable starting points.
- **"Accommodation" will be followed by "integration" of autonomy.** Incremental, intentional steps that add value—like safety, reliability, and economy—are vital for gaining acceptance of aerospace autonomy by industry, by government, and critically, by the public.
- **We face a "people" challenge.** Industry, academic, and government aerospace autonomy experts agree that changes are needed to prepare the aerospace workforce for increasing autonomy.

Our members are now planning their approach on engaging the aerospace autonomy challenge. The AIAA Intelligent Systems Technical Committee and the AIAA Guidance, Navigation, and Control Technical Committee were already committed to working with industry, government laboratories, and academia to develop a certification plan for unmanned aerial systems (UAS). They will present their plan at a special session during the 2023 AIAA SciTech Forum.

On behalf of our 30,000 professional and student members, and nearly 100 corporate members, AIAA will continue this proactive approach to autonomy. As we establish our new Domain approach at AIAA, autonomy is a vital part of the Aerospace R&D Domain. We are committed to convening our community on this topic and we will keep pushing for outcomes to maintain the momentum.

Working together in partnership with government policymakers, regulators, industry innovators, and academia we acknowledge that advancing aerospace autonomy will not be an easy task, yet it will be worthwhile, as we venture into what is arguably a new golden age of aerospace innovation and democratization. ★

Dan Dumbacher
AIAA Executive Director

Morphing structures reach new heights, from tests on Earth to Mars

BY JEFFREY L. KAUFFMAN

The work of the **Adaptive Structures Technical Committee** enables aircraft and spacecraft to adapt to changing environmental conditions and mission objectives.

▲ This morphing wing can change shape during flight by selecting one of its two configurations. At top, the wing is instrumented and prepared for wind tunnel testing. At bottom left, the red and blue bistable device determines how stiff the wing is; additional actuators are on the upper airfoil surface. At bottom right, simulations predict the available morphed configurations.

Purdue University

Purdue University's Programmable Structures Lab tested a **selective stiffness morphing wing section** in a wind tunnel in May. The lightweight wing combines high stiffness for bearing aerodynamic loads and high compliance for aerodynamic adaptability. Geometrically bistable elements grant rigidity or compliance on demand via internal topology conversion. The wind tunnel campaign revealed that switching stiffness at low airspeeds triggers no aeroelastic instabilities, clearing an important hurdle for selective stiffness in aircraft structures.

Also in May, researchers at **DLR, the German Aerospace Center**, demonstrated a **variable chord rotor** in a Bristol wind tunnel and a DLR Braunschweig whirl tower. The demonstrator, developed by the European Union's Shape Adaptive Blades for Rotorcraft Efficiency project, includes a structural concept for chord morphing in the blade root region. The tests confirmed that increasing chord length improves the demonstrator's performance characteristics for hover. These results point to future rotor blades that morph across flight regimes, using a longer chord for hover flight and a shorter chord for fast forward flight.

A team at the Research Laboratory in Active Controls, Avionics and Aeroservoelasticity, or LARCASE at the **University of Quebec's School of Higher Technology, or ETS**, in Montreal validated another morphing wing design. Tested in the Price-Païdoussis subsonic wind tunnel, the **modified UAS-S4 wing airfoil** has a morphing camber system that alters both leading and trailing edges. The tests confirmed the morphing camber system improves aerodynamic performance, including reducing the stall angle and drag. The morphing camber system uses the same servomotor as in the UAS-S4 to ensure the morphing actuation does not increase the overall weight.

The **Harbin Institute of Technology** in China conducted the **first on-Mars application of shape memory polymer composites**. A self-deployable mechanism released the national flag of China during the Tianwen-1 mission. Images sent back to Earth in June showed the rolled flag was flattened when two epoxy-based SMPC release devices recovered their original flat configurations. The validation of the self-deployable flag mechanism extends the application of SMPCs from geosynchronous orbit to deep space explorations.

Texas A&M University researchers eyed morphing in space for thermal control, finalizing a composite design for the **Shape Memory Alloys for Regulating Thermal Control Systems in Space, or SMARTS**, a NASA Tipping Point project. Researchers initiated fatigue testing of the intricate composite laminate in August. Test results show promise for the integration of the SMA-driven radiator into **future lunar habitat thermal control systems**.

Also at Texas A&M, researchers **actuated additively manufactured SMA tensile bars via interior liquid metal circuitry for the first time** in April, using current densities as high as 25 amps per square millimeter. These high current densities are difficult to achieve due to spontaneous liquid metal rupturing, but the circuits could increase the actuation power densities of SMAs to new regimes with multifunctional induction heating and fluid convection cooling.

In March, a team at **Arizona State University** demonstrated an **automatic damage diagnosis technique** through in-situ composite fatigue testing with funding from the **U.S. Army Research Laboratory**. The semi-supervised technique uses ultrasonic Lamb waves and machine learning to detect and classify fatigue damage in composite structures. In the tests, the team captured damage by identifying statistically significant patterns in waves and then classified it by analyzing patterns in the extracted damage features using a clustering algorithm. The same group extended its diagnosis and prognosis expertise to in-air flight safety, including data-driven aircraft health monitoring using an autoencoder with funding from the NASA University Leadership Initiative Program. The performance of the techniques was validated through integration into an air traffic management framework module in late July.

Researchers at California-based **AlphaSTAR** also focused on structural health monitoring with a **customizable digital twin sensing and computing architecture**. The approach includes both event detection and damage identification using onboard sensors, real-time analysis and feedback to estimate the remaining useful life. ★

Space tourism flights show off distinctly different designs approaches

BY LISA SAAM AND MICHELLE COURTNEY

The **Design Engineering Technical Committee** promotes the development and dissemination of technologies that assist design engineers in defining practical aerospace products.

Two distinct commercial and crewed spacecraft vehicles flew in July, demonstrating how radically divergent engineering design solutions have led to the start of the commercial human spaceflight era. The variances in launch configuration, engine design, reentry, descent and landing profile for these spacecraft generated significantly different design engineering approaches for materials, structures, propulsion, flight controls and systems integration.

Virgin Galactic's SpaceShipTwo spacecraft VSS Unity has a hybrid propulsion rocket motor and a variable-shape aircraft-like structure that becomes a glider for its return to Earth, requiring pilots to guide it to the ground. Taking off from New Mexico in July, a double-fuselage aircraft, VMS Eve, carried VSS Unity to 50,000 feet before releasing it so VSS Unity's hybrid rocket motor could propel it, four passengers and a crew of two pilots to an altitude of 86 kilometers. **Blue Origin's New Shepard** launch vehicle design, in stark contrast, uses a vertical launch powered by liquid-hydrogen rocket propulsion and an Apollo-era capsule design concept. New Shepard's capsule with four passengers reached an altitude of 107 kilometers and autonomously returned to Earth for the parachute landing in West Texas.

Boeing began production in February of the **U.S. Air Force's ET-7A Red Hawk advanced jet trainer**. The jet is the Air Force's first with an eSeries designation, indicating that it was designed and produced using a digital foundation. The **Boeing ET-7A** development embraced model-based engineering and design tools that resulted in 80% lower assembly hours and 50% less software development time. A memorandum in May from the Air Force's acting acquisition chief Darlene Costello outlined the "Digital Trinity" requirements for an e-Program designation: digital engineering, agile software and open systems architecture. ESeries acquisition programs will be connected in a digital environment to produce a digital twin and enable faster digital design iterations and higher performing, higher quality products.

Beginning with its landing in February, the Mars 2020 spacecraft demonstrated several novel technologies. During descent and landing, cameras and a microphone captured the images and sounds of a Mars landing. In addition, NASA's **Terrain Relative Navigation** technology system allowed the spacecraft to determine autonomously a safe landing area that was within reach prior to the backshell separation and powered descent events. In April, **NASA's Ingenuity Mars Helicopter** detached from the Perseverance rover and completed three technology demonstration flights, proving for the first time that powered and controlled flight in the thin atmosphere of Mars are possible. By early November, Ingenuity had completed 15 flights, logging about 25 minutes of flight time. Ingenuity's operational demonstration flights explored the advantages of aerial surveillance to rover operations. Perseverance also collected the first Mars rock samples with its sample handling system. A pair of robotic arms coordinated the drilling and sample tube placement for collection, sealing and storage. ★

▼ In July during its 10th flight on Mars, NASA's Ingenuity Mars Helicopter took the image at left with its color camera and the image at right with its black-and-white navigation camera.
NASA

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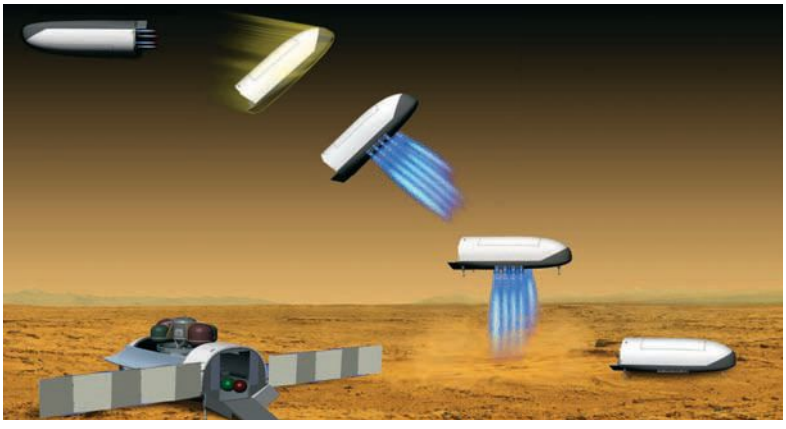
Researchers pursue design optimization in vehicle development technologies

BY MIKE HENSON, GIUSEPPE CATALDO AND JOHN HWANG

The **Multidisciplinary Design Optimization Technical Committee** provides a forum for those active in development, application and teaching of a formal design methodology based on the integration of disciplinary analyses and sensitivity analyses, optimization and artificial intelligence.

Researchers at the Massachusetts Institute of Technology, University of Texas at Austin and Jessara Group released in May experimental data and a code suite that demonstrates the calibration and deployment of a structural **digital twin** for an uncrewed aerial vehicle. In August, Rolls-Royce UK and its university research centers at Southampton and Sheffield presented novel **turbomachinery topology MDO** applications, carried out as part of the European Union-funded Multidisciplinary Adjoint-based Enablers for Large-scale Industrial Design in Aeronautics, or Madeleine, project. One of these studies achieved a reduction of up to 10 decibels in a fan while still improving its aerodynamic efficiency and structural integrity.

Several important software releases were delivered to the user community for **OpenMDAO**, NASA's open-source high-performance modeling and optimization platform. In August, the Co-Optimization Bluntbody and Revolutionary Aircraft, or **COBRA**, team ported its model of a medium lift-to-drag rigid Mars entry vehicle design concept, named CobraMRV, to a programmatic OpenMDAO interface. The upgrades enabled model solution in multiple computing environments and will greatly reduce the time required for large design space and optimization studies. In June, the University of California San Diego published **ATOmiCS**, a multiphysics topology optimization toolbox in OpenMDAO with fully automated adjoint-based derivative computation. In August, the University of Michigan developed new coupling methodologies within OpenMDAO to study the design and integration of advanced propulsion systems. The capability enabled large parameter studies and solution of **fully coupled multipoint aeropropulsive design optimization problems**.



▼ A Mars entry vehicle design concept called CobraMRV, a potential technology for delivering human-scale vehicles to the surface of Mars, was made available to the OpenMDAO community.

NASA

In May, Sandia researchers leveraged novel developments in **uncertainty quantification** to better enable statistical goal orientation within optimization under uncertainty. The researchers expanded the **Dakota** software using a multilevel Monte Carlo methodology to provide formulations for robust/reliable design at a reduced computational cost.

In July, IRT Saint Exupery released a new version of Generic Engine for Multi-disciplinary Scenarios, Exploration and Optimization, or **GEMSEO**, providing a disruptive approach to couple industrially mature, highly detailed models using a unique bilevel formulation. Airbus has used GEMSEO as part of its companywide **digital transformation** program.

In July, researchers at Stanford University developed new MDO capabilities for the design of electric vertical takeoff and landing and short takeoff and landing configurations in its **SUAVE** conceptual design framework. This included modeling of battery degradation, aeropropulsive coupling between propellers and lifting surfaces, and acoustic prediction methods for vehicle-level noise.

In August, researchers at the University of California San Diego published the open-source library **PENGoLINS**, which extends the computational fluid dynamics concepts of immersed boundaries and overset meshes to the structural analysis domain.

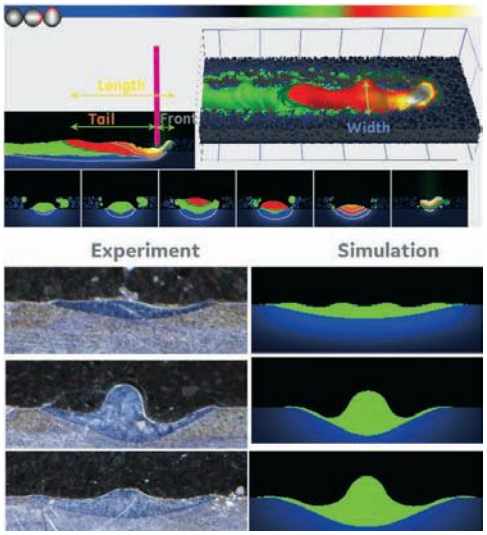
The **Engineering Sketch Pad** software package version 1.19 was released in June, funded by the U.S. Air Force Research Laboratory's Multidisciplinary Science and Technology Center through the Enhanced Computational Aircraft Prototype Syntheses program. Executed by MIT, Syracuse University and Mississippi State University, the release contained enhancements to the software interfaces, a speed boost of geometric sensitivity calculations and improved mesh generation capabilities. Additionally, the NATO technical team on goal-driven, multifidelity approaches for military vehicle system-level design, or AVT-331, co-led by the Air Force Research Laboratory and the National Research Council of Italy, developed analytical and vehicle-scale (air, sea, space) **benchmark problems to evaluate different multifidelity methods**.

In May, the Air Force Institute of Technology in collaboration with the University of Michigan, Ohio State University and Virginia Tech received a three-year contract for **MDO-based hypersonic vehicle development**, funded by the University Consortium for Applied Hypersonics. In July, a team led by the University of California San Diego received a three-year contract through NASA's University Leadership Initiative to use MDO to investigate the design of **urban air mobility vehicle concepts**. ★

From probabilistic machine learning to "look ahead" decision-making in the design of complex engineered systems

BY ASHWIN RENGANATHAN

The **Non-Deterministic Approaches Technical Committee** advances the art, science and cross-cutting technologies required to advance aerospace systems with non-deterministic approaches.



▲ Probabilistic machine-learning models adjust the powder-bed fusion process in additive manufacturing.

GE Research

The **Probabilistic Design and Optimization Laboratory at GE Research** of New York leads research on design, development and application of non-deterministic approaches on industrial problems for GE businesses. In January, the group, in collaboration with the University of Notre Dame and with funding from the **Advanced Research Projects Agency-Energy's DIFFERENTIATE program**, developed novel probabilistic methods toward the explicit inverse design of industrial gas turbine blades and additive manufacturing via powder-bed fusion. The methodological innovation includes a two-orders-of-magnitude input-space dimensionality reduction for high-dimensional engineered systems. **NASA's Jet Propulsion Laboratory** in California and **Sandia National Laboratories** in New Mexico continued their multiyear joint seminar series, "Quantification of Uncertainty Across Disciplines," aimed at communicating state-of-the art practices in model verification, validation and uncertainty quantification, or V&V/UQ, between the two institutions; organizing training sessions and seminars to broaden a community of practice in V&V/UQ across technical disciplines; and initiating research and development that improves the state-of-the-art in V&V/UQ.

In January, the Aerospace Systems Directorate within the **U.S. Air Force Research Laboratory** secured U.S. Patent No. 10902089 for its development of a "method for predicting stochastic output performance or scaling stochastic inputs." In August, the directorate awarded a contract for the **EQUATE*** research programto **Northrop Grumman**. EQUATE focuses on the role and impact of UQ in multidisciplinary aircraft design through a physics-based approach that enables trades of risk and performance.

Early in the year, the **Southwest Research Institute** based in Texas wrapped up its part of a Small Business Innovation Research award to reduce variability in carbon-carbon composites manufacturing for hypersonic applications. Funded by the FAA and NASA, the SwRI investigated applicability of its Design Assessment of Reliability With Inspection, or **DARWIN**, software for probabilistic damage tolerance analysis, to aerospace components of higher criticality made by additive manufacturing. The SwRI is also leading a team to develop simulation tools to predict the fatigue life of composite bonded and bolted joints, under an Air Force Research Laboratory contract.

Sandia researchers continued investment in multifidelity UQ approaches, with a focus on methods that retain efficiency in the presence of the general nonhierarchical modeling relationships that are often encountered in production-scale applications. Multifidelity activities have included neural network training in collaboration with the **University of Notre Dame**, functional tensor train surrogates with the University of Michigan, dimension reduction with the **University of Southern California**, stochastic simulations, hyper-parameter model tuning and nonhierarchical model management. In May, new algorithmic advancements were released in Sandia's Dakota software, including improved dimension reduction by basis adaptation and support for embedded cross validation within greedy refinement for multifidelity surrogates.

Also in May, the optimization group at the Mathematics and Computer Science Division at **Argonne National Laboratory** completed a project funded by the U.S. Department of Energy's **Advanced Scientific Computing Research office** to develop a suite of derivative-free stochastic optimization methods for decision-making in the presence of uncertainty, with limited and expensive information. This novel approach, inspired by the game of chess, uses a Bayesian framework to "look ahead" several steps to make optimal decisions that hedge against risks with future decisions, thereby resulting in using limited information. Software that implements the suite of methods is slated to be published as "open source" for broader use by the scientific community.

In August, the **University of Alabama** developed a new regularization technique to solve an underdetermined and ill-conditioned system of equations, especially obtained in the application of polynomial chaos. Researchers carried out uncertainty quantification of delamination of composites using the new regularization technique with polynomial chaos. ★

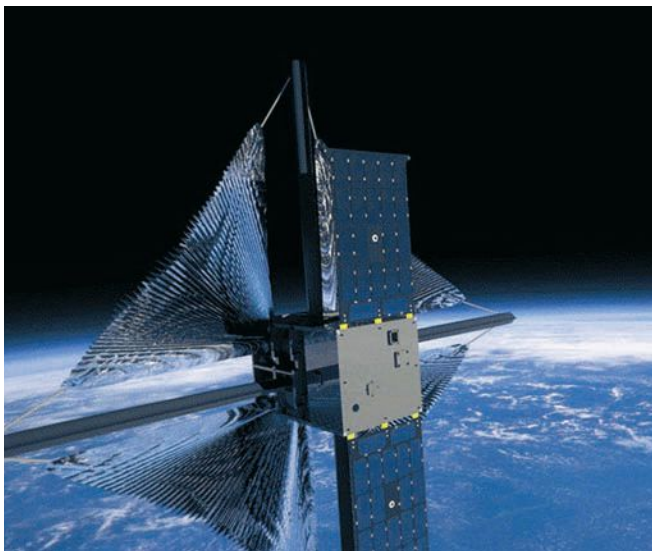
Contributors: *Barron Bichon, Michael Eldred, Edwin Forster, Gianluca Geraci, Sayan Ghosh, Sameer Mulani and Vicente Romero*

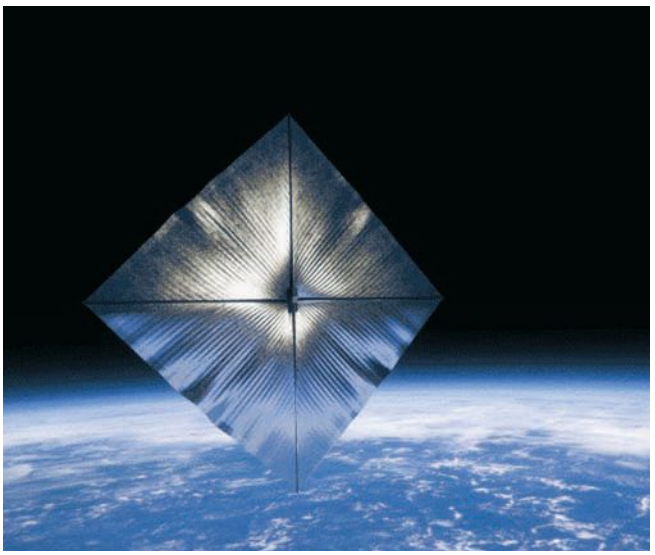
* Enabling Quantification of Uncertainty in Aerospace Technology Evaluation

Focusing on large spacecraft to carry out exploration plans

BY ERIK PRANCKH

The **Spacecraft Structures Technical Committee** focuses on the unique challenges associated with the design, analysis, fabrication and testing of spacecraft structures.





▲ Renderings of NASA's prototype 80-meter-squared Advanced Composite Solar Sail System show it as it would look in the process of unfurling (left) and then complete.

NASA

With NASA's planned return to the lunar surface and progress toward deep space exploration, the development of large spacecraft structures to meet those exploration objectives continued.

In October, NASA selected **Rocket Lab** to launch **NASA's Advanced Composite Solar Sail System**, or ACS3. NASA's Langley Research Center in Virginia completed prototype testing of the ACS3 at the end of 2020. Once in space, four booms will unroll 7 meters from the 12-unit cubesat to unfurl the 80-meter-squared reflective membrane to harness the pressure of the sun in space and demonstrate solar sail propulsion. This method of propellent-less propulsion could be key to reducing the cost of deep space missions. William Keats Wilkie, principal investigator of the ACS3 at Langley, said, "The flight ACS3 solar sail will be deployed in low-Earth orbit from a 12U cubesat in late 2022. The DCB project, in cooperation with the **German Aerospace Center** (DLR), also recently completed zero-G parabolic flight testing of a 16-meter boom design that could be implemented on larger-scale versions of ACS3 to provide a practical low thrust propulsion system for future deep space small spacecraft."

Student-led teams also contributed to developing deployable high-strain composite boom structures for novel spacecraft structures. In May, **Virginia Tech** announced the launch of **ThickSat**, one of 30 student-built satellites launched in a ride-share. It will test the deployment of a high-strain composite boom for Langley's ACS3 sail.

Pushing the limits of large deployable spacecraft structures even further, in January, **Roccor of Colorado** was selected to develop an even larger solar sail architecture slated to follow a few years after the ACS3 mission. NASA chose Roccor, a subsidiary of Redwire, to develop a 1,600 m^2 solar sail called **Solar Cruiser**, which will have a deployed area 20 times the size of the ACS3. Principal investigator Les Johnson of NASA's Marshall Spaceflight Center in Alabama is leading the program. Roccor took a similar approach to Langley and will use its own high-strain composite boom technology for a cost-effective small spacecraft to host the payload.

In March, NASA selected five companies to receive up to $700,000 each to develop technology concepts for **high-power, relocatable solar arrays on the moon**. Astrobotic Technology of Pennsylvania, ATK Space Systems of California, Honeybee Robotics of New York, Lockheed Martin and Space Systems Loral of California began the technical work in August as part of NASA's **Vertical Solar Array Technology project**. NASA plans to select two of the companies in 2022 to receive up to $7.5 million each to develop high-fidelity prototypes that would be demonstrated on the lunar surface as early as 2028. The VSAT project, within the Game Changing Development program at NASA's Space Technology Mission Directorate, is planned as the initial and primary source of electric power for operations on the lunar surface for the Artemis program. ★

Structural dynamicists turn out important lab work despite another year of covid

BY RAFAEL PALACIOS

The **Structural Dynamics Technical Committee** focuses on the interactions among a host of forces on aircraft, rocket and spacecraft structures.

In January, researchers at the Politecnico di Milano, or **POLIMI**, in Italy concluded an extended experiment to validate technologies for gust and maneuver load alleviation under European Union Clean Sky 2 funding. This was carried out on a large aeroelastic half model named WTT3, free to move in plunge and pitch, in POLIMI's 4-by-3.85-meter wind tunnel. The model, originally equipped with primary control surfaces, such as aileron and elevator, demonstrated at vehicle scale an innovative wing tip actuator fully dedicated to gust load alleviation.

With the **NASA's Ingenuity Mars Helicopter** making history in April by flying the first powered flight on another planet, larger and more capable rotorcraft are being envisioned for Mars. The unique Martian conditions will likely lead to unusual designs and open a new world for aeroelasticity. **NASA's Jet Propulsion Laboratory** and **Ames Research Center** in California and the **University of Maryland** are leading that effort, and in a new project, scientists at Ames will design, fabricate and test several concepts, while the University of Maryland will carry out structural design and analysis.

Also in April, researchers at the Faculty of Aerospace Engineering, **Technion-Israel Institute of Technology**, tested a very flexible wing, known as the **Pazy wing**, in their wind tunnel. The objective was to explore nonlinear aeroelastic phenomena and provide validation data for the computational community. The Pazy wing is a 100 millimeter chord, 550 mm span rectangular wing made of a core aluminum plate and a 3D-printed nylon chassis. In static wind tunnel tests, the wing deformed to over 50% of its span. In the dynamic tests, researchers documented regions of flutter and limit cycle oscillations instability. Data collection includes displacements and strains collected with a motion tracking system and fiber optic sensors. The results are publicly available and benchmarked by the aeroelasticity community in the third **Aeroelastic Prediction Workshop**, or AePW, which aims to assess and enhance the state-of-the-art in computational aeroelastic predictions and has drawn international participation across industry, academia and government laboratories. Beyond the large deflection working group, built around the Pazy wing model, the AePW includes the flight test working group to explore the body freedom flutter mechanisms of the X-56A vehicle and the high-angle working group to focus on transonic flutter and shock buffet of the benchmark supercritical wing.

In June, researchers at the **University of Washington** and **POLIMI** completed a demonstration of active flutter suppression funded by the FAA. The plan is for the information to be shared with the aeroservoelasticity community to test and analyze novel flutter suppression control methods. The analysis work followed tests, at the POLIMI large wind tunnel, of a swept-wing/T-tail configuration equipped with wing-tip flutter stopper devices for safety. At the University of Washington, researchers carried out additional gust alleviation tests on a wing/fuselage/tail model in the 3-foot-by-3-foot (91-by-91-centimeter) low-speed wind tunnel and an elastic wing with six trailing edge control surfaces in the 12-foot-by-8-foot **Kirsten Wind Tunnel**. In the low-speed wind tunnel tests, researchers investigated the effects of gust sensing preview on control law design and closed-loop performance, simulating what in full-scale flight will be provided by LIDAR technology. In the Kirsten Wind Tunnel, the team demonstrated active distributed gust alleviation by simultaneous closed-loop actuation of multiple trailing edge flaps. ★

Contributors: *Pawel Chwalowski, Anubhav Datta, Eli Livne, Daniella Raveh, Sergio Ricci and Walt Silva*

The Pazy wing is shown in its highly deformed state in the Technion wind tunnel at a 7-degree angle of attack and a 55-meters-per-second free stream.

Technion

Achievements include better composite laminate curing using nanotubes and a new integrity sensor

BY EMILY J. ARNOLD AND CRAIG G. MERRETT

The **Structures Technical Committee** works on the development and application of theory, experiment and operation in the analysis and design of aerospace structures.

The **U.S. Air Force Institute of Technology** conducted research this year on a variety of projects funded by the **Air Force Office of Scientific Research**, or AFOSR. Researchers introduced a new design for a lighter-than-air vehicle with internal vacuum. Related to this project and in collaboration with the University of Colorado, computational fluid dynamics was used to assess the effect of a vehicle during reentry into the atmosphere. A second project used heat transfer methods and structural mechanics to mimic the wear present in the Holloman test track at lower speeds. The final project determined the ideal heat treatment to optimize the residual stress field after a nickel-based alloy specimen has undergone a shot peening process.

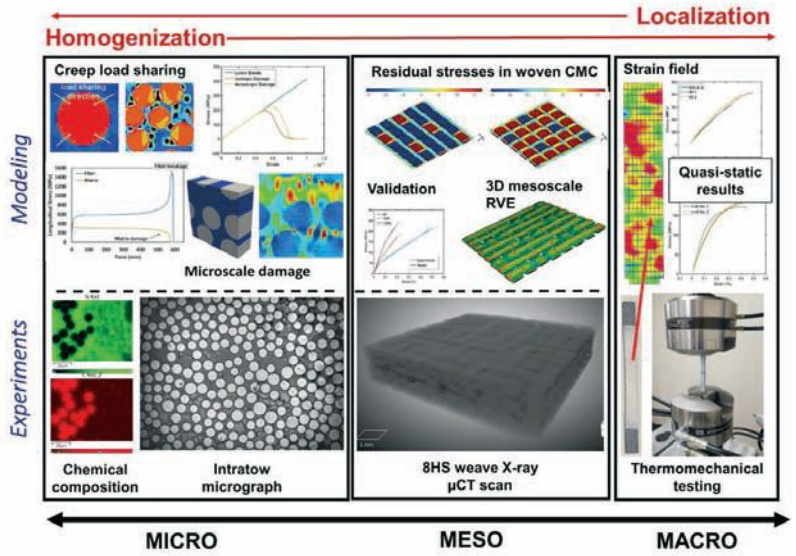
Beginning in October, researchers from **Mississippi State University**'s Aerospace Engineering Department, working with **M4 Engineering** of California under a NASA Small Business Innovation Research grant, conducted gas permeation studies of stitched composites under thermal and mechanical loads. These projects identified barrier concepts to reduce gas permeability and prevent through-thickness cracking in cryogenic propellant tanks. MSU also performed experimental and computational studies under a separate Air Force Research Lab-funded project to determine optimum stitch parameters to limit facesheet core debonding in 3D-stitched sandwich composites.

MIT and **Metis Design Corp.** of Boston developed lower-cost, energy-efficient manufacturing techniques for aerospace grade composites. Joule heating is provided conductively to laminates out-of-oven, or OoO, by carbon nanotube networks integrated into thermally insulating tools. Nano-porous-network subplys are stacked between each prepreg layer to aid full resin consolidation. Using faster, more accurate uniform OoO heaters, a model-derived cure cycle was implemented, accelerating cure processes by 35% to 50%. Researchers deployed this OoO process to fabricate and test aerospace-grade carbon fiber laminates in dimensions of up to 0.6 by 0.6 meter, demonstrating equivalent or improved mechanical properties versus autoclave cured panels. The method consumes 100 to 1,000 times less energy than conventional methods and is performed with cheaper tooling without high-pressure cycles, leading to significant cost savings.

MIT, **Analog Devices** of Wilmington, Massachusetts, and Metis Design developed a tool for aerospace structural condition-based maintenance. This **Wireless Integrity Sensor Platform**, or WISP tool, captures maximum data with minimum infrastructure such as cables or connectors. WISP hardware with fatigue crack gauges was evaluated for airworthiness this year. These gauges are undergoing probability of detection analyses where they exhibit better than 1 millimeter at 90% probability of detection.

Widespread use of primary structure adhesive joints is hampered by the current inability to predict and measure the adhesive bond strength. As a result, industry and the U.S. Department of the Navy demands for lower structural weights and reduced part counts on their assets must compete with the high safety standards demanded by the certification authorities. In January, **Clarkson University** received an $800,000 grant from the **Office of Naval Research** Advanced Naval Platforms Division to develop physics-based, analytical and computational models for predicting the strength of bonded joints. This research is in collaboration with the Carderock Division, U.S. Naval Surface Warfare Center in Maryland.

With **U.S. Department of Energy** and AFOSR funding, **Arizona State University** developed multiphysics-based experimentally validated multiscale analyses for ultra-high-temperature ceramic matrix composites. High-fidelity stochastic volume elements, obtained from material characterization image processing algorithms and machine learning techniques are used for length-scale dependent morphology, architecture and variability representations. Three-dimensional orthotropic viscoplasticity creep and fracture-mechanics damage models were developed. In September, a machine learning-based reduced order damage model was also developed, in collaboration with **Raytheon Technologies Research Center** in Waltham, Massachusetts, to increase computational efficiency. ★

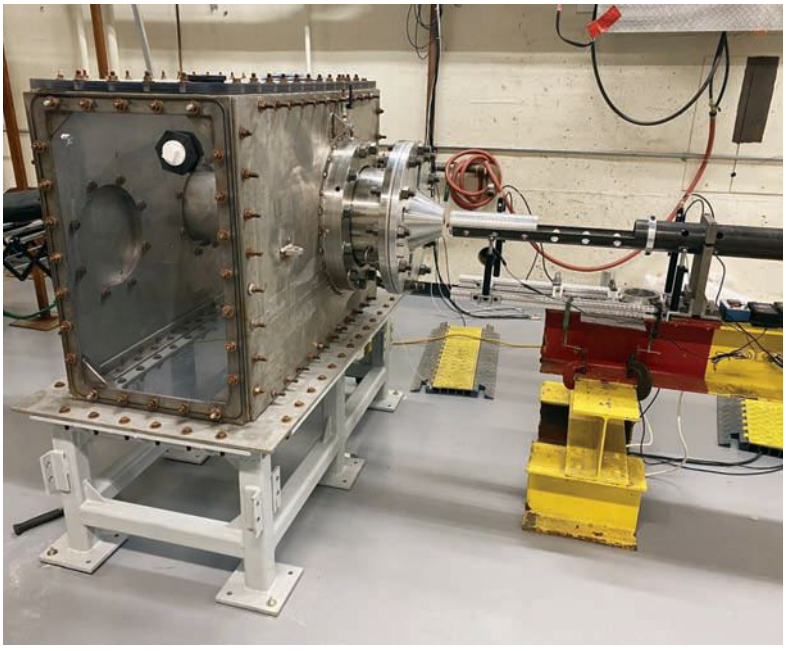


◀ Concurrent synergetic multiscale technology
Arizona State University

Military research focuses on improving survivability in both air and space

BY MARK E. ROBESON

The **Survivability Technical Committee** promotes air and spacecraft survivability as a design discipline that includes such factors as crashworthiness, combat and reparability.



▲ The black box in this image is the chamber of the Hydrodynamic Shock Test Apparatus that was tried out for the first time in January at the U.S. Air Force Aerospace Vehicle Survivability Facility in Ohio. Structural joints, such as those of fuel tanks and related components, can be tested in the HSTA to measure their resilience against hydrodynamic shocks caused by a crash or ballistic strike.

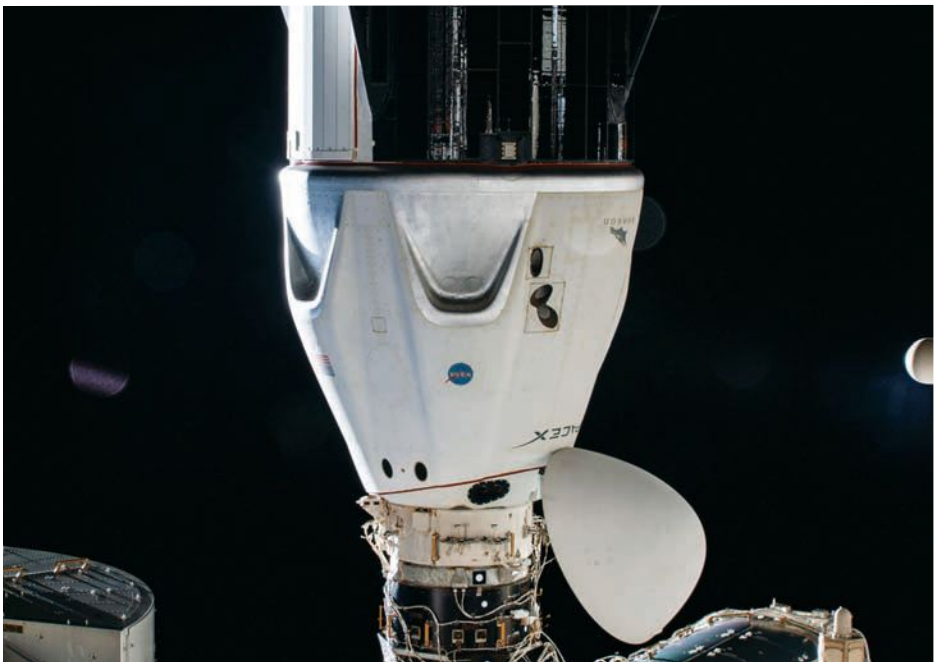
U.S. Air Force

The Aviation and Missile Center of the **U.S. Army Combat Capabilities Development Command** and **Lockheed Martin's Sikorsky** company in January notified the **Army's Future Vertical Lift Cross Functional Team** that they have advanced their system of **spaced armor** sufficiently to incorporate the technology into rotorcraft and other aircraft. This novel integrated system of polyethylene panels maintains threat protection while weighing less than alternatives. The two-part system consists of a striker panel, which causes the projectile to tumble and could be incorporated into an aircraft's outer skin, and a catcher panel, which stops the tumbled projectile and could be incorporated into a floor or inner wall. The developed capability was demonstrated in 2020 at Fort Eustis, Virginia. Ballistic testing on a representative rotorcraft fuselage, incorporating protection from an ultra-high molecular weight polyethylene fiber-based composite laminate for both the striker and catcher, showed the feasibility of the integration architecture and relevant protection levels at reduced areal density compared to traditional armors. To continue maturing the technology, different materials and ballistic threats were investigated throughout the year for improved performance-to-weight ratio, and rotorcraft integration will be further investigated to minimize weight impacts.

A **Hydrodynamic Shock Test Apparatus**, HSTA, was tested in January at **Wright-Patterson Air Force Base**, Ohio, in the Aerospace Vehicle Survivability Facility operated by the 704th Test Group. In the months since, HSTA has provided a foundation for studying structural skin/joint/spare component failure caused by ballistic impacts on aircraft fuel tanks, as well as on related functional components such as fuel lines and pumps. Testers and designers can now evaluate joint pull-off and shear failure due to both symmetric and asymmetric loading conditions. Visual data is collected by high-speed video cameras, which was not possible with the previous test device. The testing in January demonstrated that the new HSTA striker and fuel tank apparatus minimize noise in the collected test data, enabling more accurate pressure and strain measurements; repeatability in the testing also showed improvement. The improved capability provided by the HSTA is enabling **the design of more survivable aircraft fuel tank structural components**, as well as the functional components contained within the tanks, for both future aircraft and upgrades to current fleet aircraft.

In the space realm, the U.S. **Air Force Institute of Technology** at Wright-Patterson continues to expand its analytical purview to include spacecraft safety and survivability in the cislunar domain between the Earth and the moon in support of the growing U.S. space enterprise. Throughout the year, AFIT has delved into topics such as **space system survivability to hypervelocity debris impacts** originating from catastrophic breakup events within cislunar space, as well as assessing satellite survivability with respect to micrometeoroids and dust near the stable Earth-moon Lagrange points. AFIT research during July and August extended the topic of spacecraft survivability to lunar orbit, with efforts to simulate debris events with respect to an ephemeris-based gravitational field. The goal of this analysis is to ascertain the susceptibility risks of not only orbiting spacecraft, such as **NASA's planned lunar Gateway**, but also facilities that may be built on the lunar surface. The concept of formulating spacecraft fragility curves is also being explored, based on existing empirical vulnerability studies of space system components exposed to low- and high-velocity impacts. Looking ahead, spacecraft survivability research is planned to examine debris risks within the context of cislunar rendezvous and proximity operations, and the use of periodic cislunar orbits for Space Domain Awareness missions. ★

Contributors: *Brian J. Barlow, Robert A. Bettinger and Alex Q. Weintraub*



▲ This SpaceX Crew Dragon autonomously moved to a different docking port on the Harmony module in April.

NASA

Working on future missions with systems built over decades

BY JOHN GEBHARD AND PAUL C. LAMBERTSON

The **Systems Engineering Technical Committee** supports efforts to define, develop and disseminate modern systems engineering practices.

The year was marked by milestones and achievements in the commercialization of space, fueled by state-of-the-art systems engineering and detailed interface management.

On April 5, the Crew-1 astronauts aboard the International Space Station entered their **Crew Dragon Resilience** spacecraft and rode in the spacecraft as it **autonomously undocked and re-docked** to a different port, marking the first time a commercial spacecraft has performed such a maneuver. As of September, **11 commercial dockings, relocations and captures** were logged at ISS over the year.

Disciplined systems engineering applied since 2000 yielded benefit to the space exploration ecosystem. Boeing engineers designed and built standard interfaces into the ISS some 25 years ago, and Space X, Axiom and Blue Origin are now using those interfaces to commercialize spaceflight. This year's events demonstrate that those interfaces, designed and built leveraging legacy requirements from systems engineering work completed decades prior, not only accommodated past needs but also enabled future unknown needs.

Matt Duggan, Boeing's ISS mission operations manager, recounted some of this history to our committee: The **Common Berthing Mechanism** was designed to connect the original ISS modules together and found continued use with current ISS cargo vehicles. Duggan said that engineers designed the **International Standard Payload Rack** and its interfaces to allow large payload systems to be quickly installed in all the research modules on the ISS.

The **Expedite the Processing of Experiments to the Space Station, or ExPRESS, rack** accomplished the same purpose by hosting multiple smaller payloads within a single rack, enabling a new generation of commercial research. **Boeing** engineers designed the **NASA Docking System and the accompanying International Docking System Standard** for NASA. Docking systems built to this standard are used today by commercial spacecraft visiting the ISS.

In July, **Virgin Galactic** conducted its first suborbital flight with passengers when **VSS Unity** and two pilots carried founder Richard Branson and three other spaceflight participants to the edge of space.

Two weeks later, a **Blue Origin New Shepard** rocket boosted founder Jeff Bezos and three other passengers to the edge of space, marking another milestone in the commercialization of space. The New Shepard program "encourages system-level thinking across the entire organization and utilizes systems engineering processes for risk reduction during all life cycle phases of the program," Blue Origin said in a statement, referring to the company's vertical integration across the product development and operations processes. "This organizational structure yields systems engineering influence in all aspects of the project," the company said. "Leading up to the first human flight, the systems engineering team, tools, and processes were essential in evaluating the system design and compliance to the requirements by organizing and performing a series of System Verification Reviews," the company added.

Looking back on the year's milestones, these elegantly designed interfaces demonstrate the enduring value of thoughtful systems engineering. The space community greatly benefited from the ISS and the new commercial entrants enabled by those interfaces. Beyond this year, the challenges that remain for each of the new commercial entrants to scale up their ventures are influenced by systems engineers within each organization. Balancing the complex requirements of functionality, ease of use, product certification and operational cost may remain the significant factors as new space technologies move forward in 2022. ★

Addressing future noise requirements in civil aviation

BY JULIAN WINKLER AND REDA MANKBADI

The **Aeroacoustics Technical Committee** addresses the noise produced by the motion of fluids and bodies in the atmosphere and the responses of humans and structures to this noise.

▲ Researchers test the high-lift variant of the Common Research Model in the 14-by-22-foot (4.3-by-6.7-meter) subsonic wind tunnel at NASA's Langley Research Center in Virginia to substantiate that a slat-gap-filler design can effectively reduce the noise signature from the airframe.

NASA

The need to reduce aviation-related carbon dioxide emissions is driving the development of electric and hybrid-electric propulsion systems for smaller aircraft. In June and July, researchers tested a folding high-lift propeller prototype for the **X-57 Maxwell electric aircraft** in the Low Speed Aeroacoustic Wind Tunnel at **NASA's Langley Research Center** in Virginia. Researchers used laser vibrometry and digital image correlation techniques to measure the response of the folding propeller blades when they are subjected to an out-of-plane pressure disturbance, yielding damping values about the folding blade hinges and thereby providing critical insight into the propeller design requirements.

New York-based **Moog Inc.** and **NASA's Glenn Research Center** in Ohio are producing a publicly available **advanced air mobility noise database**. This database of AAM propeller and electric motor noise, acquired using Moog's **SureFly AAM vehicle**, will be the first experimental data available to independent researchers and regulators seeking to understand, predict and reduce AAM noise. A field test in May at Lunken Airport in Cincinnati focused on electric motor noise and the next test will measure the noise produced by the SureFly vehicle in hover.

Furthermore, as part of the **Advanced Air Mobility National Campaign**'s developmental test, NASA conducted multiple acoustic flight tests with California-based partner company **Joby Aviation** with a full-scale prototype of the S4 electric vertical takeoff and landing vehicle between late August and early September. The acquired data will initiate fundamental work in understanding expected noise levels for this new class of electric vehicles.

Airframe noise from deployed high-lift devices and landing gear during approach continues to be a dominant contributor to the noise footprint. Between November 2020 and March, researchers testing the high-lift variant of the Common Research Model in Langley's 14-by-22-foot (4.3-by-6.7-meter) subsonic tunnel confirmed that **a reconfigurable slat-gap-filler design reduced noise** significantly. Furthermore, the extensive aerodynamic data collected will aid in the development and validation of computational fluid dynamics and computational aeroacoustics tools.

In July, Boeing conducted a series of acoustic flyover tests in Glasgow, Montana, as part of the ecoDemonstrator program under the FAA Continuous Lower Energy, Emissions, and Noise, or CLEEN2, program and in partnership with Alaska Airlines. Boeing tested acoustic liner concepts in the thrust reverser to reduce community noise for future airplane products.

With the aim of building quieter turbofan engines, the FAA funded **Boston University** and **Raytheon Technologies Research Center** through its **Aviation Sustainability Center, or ASCENT**, to further develop **fan-stage interaction noise prediction capabilities**. In August, researchers trained a machine learning algorithm using 260 rotor CFD flow cases resulting from four scaled rotor geometries that were run at different speeds and mass flow rates. Beyond wake predictions afforded by the algorithm, researchers gained insight into the most relevant geometry and flow parameters driving the various wake parameters and will use it to guide the development of a faster, more applicable, low-order fan broadband noise prediction method.

Aeroengine combustion noise is becoming an increasingly important contributor to the overall engine noise signature in advanced aircraft designs. In a multiyear-funded ASCENT project, **Georgia Tech** and **Raytheon Technologies Research Center** are using a combination of experiments, high-fidelity simulations and mathematical modeling for combustion noise prediction to contribute to the design process for **next-generation combustors**. Fabrication and installation of two complementary combustion rig test beds were completed, and researchers acquired extensive test data in both rigs for relevant aircraft combustor cycle conditions. The data are being used to understand and quantify the combustion noise generation mechanisms and to validate the physics-based models used in the predictive noise tool. ★

Contributors: *Vishal Acharya, Clifford Brown, Sheryl Grace, David Lockard, Jeffrey Mendoza, Kyle Pascioni, Takao Suzuki and Nikolas Zawodny*

Innovative imaging methods bring new diagnostic capabilities

BY THOMAS P. JENKINS

The **Aerodynamic Measurement Technology Technical Committee** advances measurement technology for ground facilities and aircraft in flight.

In January, researchers at the **University of Michigan** developed a new diagnostic method for the detection of mid-infrared emission from species of interest in rotating detonation combustors. The technique, **upconversion imaging,** is based on a pulsed mid-IR light source. UCI is an alternative to direct mid-IR detection that uses nonlinear optical frequency mixing to shift mid-IR wavelengths carrying a target image to wavelengths of visible light that can be imaged at higher efficiency with high-performance silicon-based charged coupled device/complementary metal-oxide semiconductor, or CCD/CMOS, cameras. UCI has several favorable properties, including high-spectral selectivity, high-temporal resolution and superior low-light detectivity. Researchers applied this technique to the imaging of carbon dioxide emission from an RDC operated with a hydrogen-carbon dioxide-air mixture. They performed imaging in high-pressure and high-temperature regions associated with a detonation front. The resulting measurements demonstrated a high spatiotemporal resolution capable of imaging small structures near the supersonically propagating detonation wave front. The results show how this technique can be used to observe sharp gradients and millimeter-scale structures in the high-temperature, high-pressure zones of RDC flow fields with a temporal resolution of approximately 200 nanoseconds.

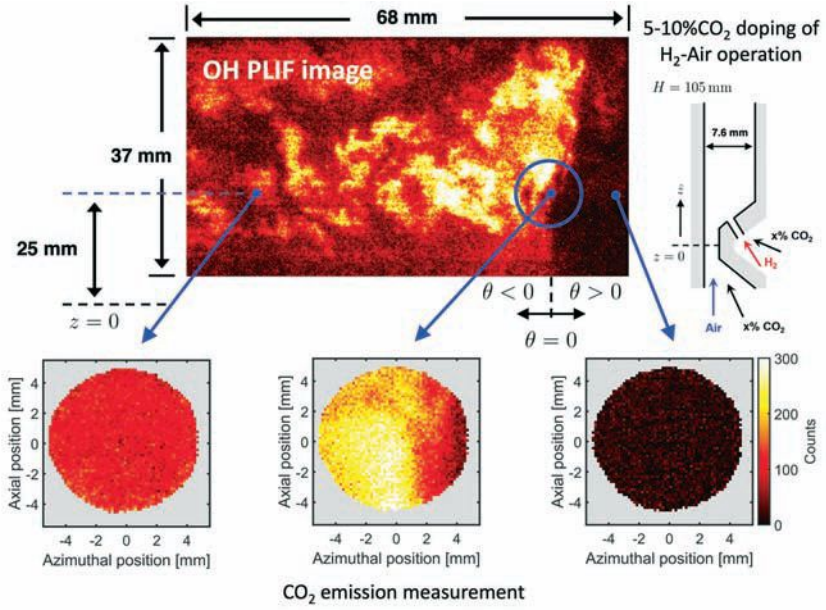
In March, California-based **MetroLaser Inc.** received a Phase II Small Business Innovation Research award from the U.S. Air Force to develop diagnostic tools and facilities to **characterize plasma-material interactions in high-enthalpy flows**. The program supports hypersonic flight applications and takes advantage of MetroLaser's expertise in laser-based diagnostics of combustion and aerodynamic environments.

Also in March, MetroLaser developed a **fieldable megahertz-rate digital holography system** that enables the study of ultrahigh-speed phenomena in three dimensions. Researchers used the system to study the collision of a supersonic projectile and its bow shock with water droplets for applications involving vehicle survivability in adverse weather conditions. They reconstructed and de-twinned (removed the conjugate twin image that always appears due to symmetry reasons) the holograms to probe complex shock wave dynamics and droplet breakup.

In October, MetroLaser was awarded a related Air Force program to develop evaluation tools to measure surface quality and chemistry of carbon-carbon composites and coatings. The company expects these two programs to contribute to the development of **hypersonic flight vehicles**.

Also in October, MetroLaser demonstrated a three-component velocity diagnostic being developed for supersonic aircraft exhaust flows called planar Doppler velocimetry. PDV enables spatially resolved distributions of the total velocity vector in particle-containing flows, such as combustion gases, and is useful for studying three-dimensional flow phenomena related to jet noise. The PDV method was demonstrated on a laboratory scale jet flow in preparation for a full-scale fighter jet engine test. ★

Contributors: *Mirko Gamba and Jacob George*



Measuring carbon dioxide emissions from a rotating detonation combustor through mid-infrared upconversion
Researchers conducted imaging in an RDC operated with a hydrogen-air-carbon dioxide mixture. Three instantaneous measurements of 200-nanosecond resolution (bottom) are shown in relation to the detonation front and visualized by laser-induced fluorescence of hydroxyl molecules (top). The three measurements are shown in a region before (right bottom image) and after (left) the detonation wave. The central bottom image corresponds to the detonation front. The resulting measurements demonstrate high spatiotemporal resolution capable of imaging small structures near the supersonically propagating detonation wave front.
Mirko Gamba

▲ Researchers covered the wings of the German Aerospace Center's Airbus A320 Advanced Technology Research Aircraft with a foil to optically measure deformations in flight.

German Aerospace Center

Computations, experiments, flight tests and additive manufacturing improve aerospace platforms

BY KEITH BERGERON AND ANDREW LOFTHOUSE

The **Applied Aerodynamics Technical Committee** emphasizes the development, application and evaluation of concepts and methods using theories, wind tunnel experiments and flight tests.

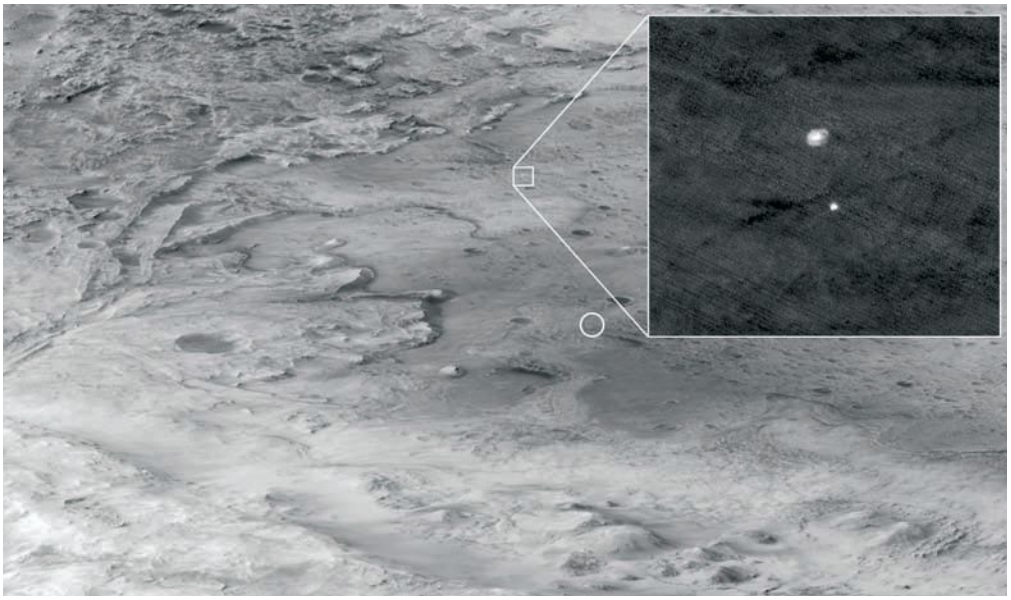
In January, researchers released the results of the multiyear **Virtual Aircraft Technology Integration Platform project**, which ended in December 2020. Researchers at the **German Aerospace Center, DLR**, developed a basis for the complete digital development and description of airplanes and helicopters based on validated high-fidelity numerical methods. For example, they simulated the noise of DLR's A320 Advanced Technology Research Aircraft high-lift system, its flight dynamics and its elastic behavior. They compared the high-fidelity simulations with real flight test data and used the validated multidisciplinary analysis and optimization methods to design a wide-body long-range aircraft. The completion of this project marked an important step along the path toward digital design and simulation-based certification.

In May and June, researchers tested new air data instruments for **NASA's X-59 Quiet SuperSonic Technology aircraft** in the 8-by-6-foot (2.5-by-1.8-meter) supersonic wind tunnel at **NASA's Glenn Research Center in Ohio**. The aircraft is designed to reduce the sound of a commercial supersonic aircraft's sonic boom and to measure human perceptions of the sound in flights over land. Among the instruments is the air data probe installed at the tip of the aircraft's nose. The probe was tested in the tunnel during simulated runs at takeoff, transonic and supersonic speeds. **Lockheed Martin Skunk Works** of California is scheduled to install the probe on the X-59 before flight tests begin in 2022.

In June, the U.S. Navy awarded **Sikorsky** a contract to build an additional nine **CH-53K King Stallion heavy-lift helicopters** ($878.7 million), and the program entered initial operational test and evaluation in August. The program had been delayed when the Navy found that the helicopters' engines were re-ingesting their own exhaust. In addition to re-ingestion, the exhaust gas impinged on the skin of the aircraft. Engine bay overheating was a third problem. To solve these problems, the **CH-53K Integrated Test Team** collected baseline aircraft airwake and thermal data that closely matched computational fluid dynamics predictions made by the CREATE-AV Helios, Siemens Simcenter Star-CCM+ and CharLES simulation codes. The team's digital design approach enabled the program to select several prototypes for fabrication and installation on flight test aircraft and to keep the program moving forward to meet performance, test and production milestones.

The **Boundary Layer Research Group** at the **University of Adelaide in Australia** continued exploring the use of additive manufacturing to fabricate microperforated surfaces with a backing cavity. This technology controls turbulent coherent structures in the boundary layer above the surface, thereby reducing the skin-friction drag. In September, the group reported direct numerical simulation results revealing that more skin-friction drag reduction is achieved in the wall-normal velocity fluctuations than in the streamwise velocity fluctuations, about 12% versus 5%. Researchers also observed that turbulent coherent flow structures responsible for the skin friction were progressively weakened as they passed over the microperforations and that overall drag was lowered by 6%. Even a small reduction in drag on transport vehicles reduces fuel requirements and emissions. ★

Contributors: *Maziar Arjomandi, Stefan Goertz, Jimi Russell and Andy Wissink*



▲ The Mars Perseverance lander (inset) dangles from a parachute as it approaches its target zone (the small square) as captured from a camera aboard the Mars Reconnaissance Orbiter. The circle indicates where the vehicle actually landed.

JPL-Caltech/University of Arizona

Mission milestones push the state-of-the-art in astrodynamics

BY BRIAN C. GUNTER

The **Astrodynamics Technical Committee** advances the science of trajectory determination, prediction and adjustment, and also spacecraft navigation and attitude determination.

After a seven-month cruise phase, **NASA's Mars 2020** mission reached the red planet in February to deliver its **Perseverance rover** with a sky crane landing, the touchdown system that brought Curiosity to Mars in 2012. The target for this mission was the Jezero Crater, with a final landing zone requirement allowing just 2.8 kilometers of position uncertainty. The orbit determination and trajectory maneuvers implemented by a navigation team at **NASA's Jet Propulsion Laboratory** in California landed the rover within 1 km of the target, well within the requirement, placing the rover in the precise location it needed to complete its mission objectives — all with most of the team working remotely due to covid-19 restrictions.

The year started with the celebration of the return of the first subsurface sample from an asteroid to Earth after the **Japan Aerospace Exploration Agency's**, or JAXA's, **Hyabusa-2** made the journey back from the asteroid Ryugu. The spacecraft released a capsule on its return flyby of Earth that was recovered in Australia in December 2020. Also in December, **China's Chang'e-5 lunar sample return mission** gathered and returned 1.7 kilograms of lunar material, marking the first lunar sample returned to Earth since the Soviet Union's Luna-24 mission in 1976.

Another asteroid sample return mission, **NASA's OSIRIS-REx**, initiated its return to Earth in May from the asteroid Bennu with a seven-minute thruster burn. The two-year journey will involve multiple orbits around the sun to synchronize with Earth's orbit in late 2023, where the samples will similarly reach the surface by a deployed capsule.

In April, **Northrop Grumman** continued to demonstrate the potential of **on-orbit servicing** by docking its **Mission Extension Vehicle 2 satellite** to **Intelsat's 10-02 commercial communications satellite**. This was the first time a servicing satellite had docked with a satellite in a geosynchronous orbit and will extend the operational lifetime of the Intelsat spacecraft by at least five years.

The need for improved international space traffic management policies was emphasized by the **uncontrolled reentry of the 18-metric-ton Chinese Long March 5B rocket body** in May. The piece of space debris ultimately landed in the Indian Ocean, but had this happened over a populated region, the expected 4 to 9 metric tons that would have survived reentry could have been much more destructive. The continued growth of several large constellations, to include **SpaceX's** plan to operate **4,408 Starlink** satellites, also underscores the need to develop improved prediction, monitoring and avoidance strategies to manage the increasingly crowded space environment.

In August, NASA's asteroid radar research program observed its **1,000th near-Earth asteroid** since radar tracking of asteroids began in 1968. Also that month, a separate group of astronomers **discovered asteroid 2021 PH27**, whose orbit takes it closer to the sun than any known object in the solar system, resulting in surface temperatures on the asteroid reaching 480 degrees Celsius.

Lastly, two ambitious planetary missions targeting asteroids reached milestones. **NASA's Lucy spacecraft** was launched in October and is now on its way to being the first spacecraft to explore the Trojan asteroids near Jupiter, with plans to visit eight asteroids over the next 12 years. In November, NASA planned to launch the **Double Asteroid Redirection Test** spacecraft to the binary asteroid system Didymos and attempt to redirect an asteroid's trajectory with a kinetic impactor, relying primarily on autonomous navigation techniques. ★

Sounding rockets, simulations advance understanding of complex environments

BY MILES T. BENGTSON

The **Atmospheric and Space Environments Technical Committee** encourages the exchange of information about the interactions between aerospace systems and their surroundings.

In May, the **U.S. Air Force Research Laboratory** concluded operation of the **Demonstration and Science Experiments, or DSX, satellite mission**. The spacecraft conducted 1,300 experiments to study the space environment in medium-Earth orbit. Satellites in this orbital regime encounter high-energy charged particles that are confined in the Earth's magnetic field. These energetic particles can damage and degrade spacecraft components, so scientists are seeking to learn more about their behavior and how to design satellites that can better withstand the radiation hazard. In addition to naturally occurring radiation, a nuclear device detonated at a high altitude could create a radiation hazard in Earth's orbit that could harm space-based assets. DSX conducted experiments using very low frequency radio waves that can interact with energetic particles and remove them from the space environment. The mission produced a trove of data on charged particles and how to remediate both natural and artificial radiation hazards in space. The very low frequency antenna on DSX extended approximately the length of a football field, making DSX the largest self-supporting structure ever flown in space. The DSX mission began development in 2003, and operations began in 2019 when the spacecraft launched from Cape Canaveral Space Force Station in Florida.

Two suborbital sounding rockets that were launched from **NASA's Wallops Flight Facility** in Virginia released vapor material into the sky as part of space environments experiments. Both experiments generated brightly colored clouds that were visible to many on the East Coast. The Air Force Research Laboratory, in partnership with the **Space and Missile Systems Center** and **NASA**, flew the first sounding rocket in March. The payload released material that generated pink clouds at more than 160 kilometers to study the ionosphere. In May, NASA launched a sounding rocket payload from the **University of Alaska Fairbanks** to study how energy and momentum are transported through regions of the Earth's magnetic field. The experiment, named **KiNet-X**, released barium vapors that were ionized by the sunlight and formed green and violet clouds. Scientists used observations of the clouds along with instruments on the sounding rocket to investigate how electrons in space are energized by the magnetic field. This mission is helping answer long-standing questions about how low-energy electrons from the near-Earth space environment are accelerated to the high energies found in regions like the aurora.

Aircraft icing researchers conducted a communitywide computer modeling campaign to assess simulation capabilities and establish future best practices. The campaign culminated at AIAA's first Ice Prediction Workshop, held virtually in July. In-flight icing is a safety consideration for design and certification of aircraft, and engineers require accurate computer simulation tools to reduce testing and design cycle times. Twenty-one participants representing businesses, research organizations and academia executed their icing codes against a set of defined test conditions, allowing direct comparison with each other and experimental results. By comparing results, scientists determined which specific models led to discrepancies in ice shape prediction. This endeavor, the first in 20 years, illuminated both technical achievements and future needs in icing simulation. ★

Contributor:
Andy P. Broeren

▼ The KiNet-X sounding rocket payload created bright clouds in the sky as part of an experiment to study the near-Earth space environment.

Geophysical Institute, University of Alaska Fairbanks

737 MAX flying again, progress in aircraft flight testing and much activity on Mars

BY CHRISTOPHER D. KARLGAARD, SOUMYO DUTTA AND CHRISTOPHER COTTING

The **Atmospheric Flight Mechanics Technical Committee** addresses the aerodynamic performance, trajectories and attitude dynamics of aircraft, spacecraft, boosters and entry vehicles.

Early in the year, **Boeing's 737 MAX** aircraft returned to commercial service worldwide after they were recertified for flight following extensive flight testing of improvements made to the Maneuvering Characteristics Augmentation System. The **737 MAX 10** variant made its first flight in June, starting its flight test and certification program.

In July, NASA's **X-57 Maxwell** all-electric aircraft underwent high-voltage testing at **NASA's Armstrong Flight Research Center** in California. This test demonstrated that the vehicle systems, including its propulsion system, could operate as designed at full power. The test paves the way for future flight testing of the experimental aircraft.

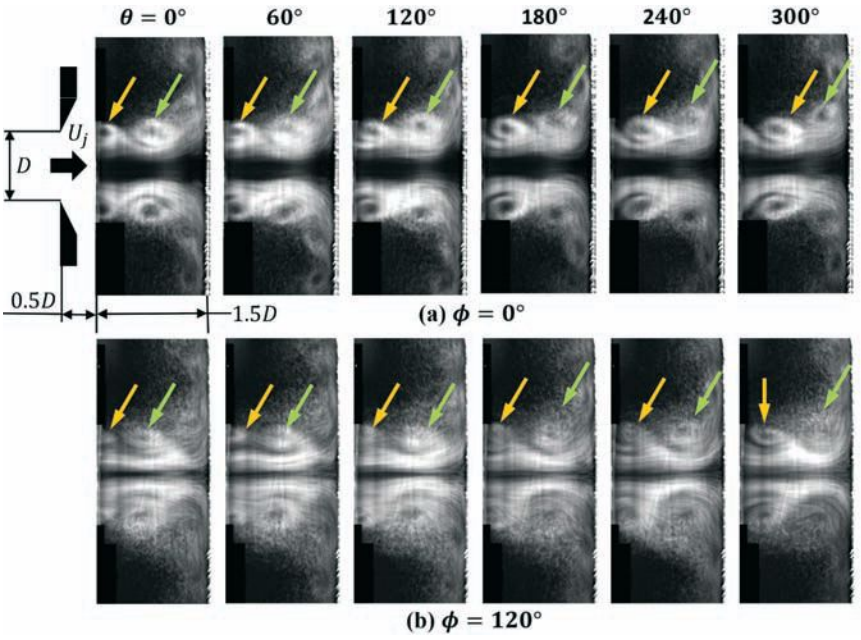
The **U.S. Air Force Test Pilot School** redesignated the NF-16D Variable In-flight Simulator Test Aircraft the **X-62A VISTA**. The Air Force Test Pilot School is upgrading the X-62A with a **new VISTA Simulation System** as well as a new System for Autonomous Control of the Simulation to include a **Lockheed Martin Legion Sensor Pod**. The upgrade also adds multiple data links for command and control as well as telemetry. The upgrades, sponsored by the Skyborg program, will enable future research projects to include **Air Force autonomous vehicle testing**. The X-62A can serve as a flying simulator to test prototype crewed and uncrewed aircraft and their control systems in a safe, sandboxed environment. The X-62A is poised to provide a flexible test bed to rapidly mature unproven systems for the next generation of Air Force aircraft.

The Air Force's **AGM-183A Air-Launched Rapid Response Weapon**, a hypersonic rocket-powered boost-glide guided missile, underwent a series of flight tests this year. In April and July, the Air Force **attempted two tests of the missile's booster system** over the Point Mugu Sea Range in California. In both cases, a B-52H Stratofortress from Edwards Air Force Base carried the AGM-183A test vehicle to the test range. During the first flight test, the test vehicle did not complete its launch sequence and thus was not released by the B-52H; the aircraft returned to Edwards. The second flight test attempt demonstrated safe release from the B-52H, but the solid rocket booster motor failed to ignite. The root cause of the failure was still under investigation as of mid-October. Although the booster flight tests were unsuccessful, a separate avionics test conducted in May during a B-52 flight test demonstrated the ability for the weapons systems to receive target data and conduct a simulated launch.

Spacecraft of three space organizations — United Arab Emirates Space Agency, NASA and the China National Space Administration — arrived at Mars this year after being launched in 2020. **UAE's Hope orbiter** reached the red planet first on Feb. 9, becoming the Arab world's first interplanetary mission. The **Chinese orbiter Tianwen-1** entered Martian orbit on Feb. 10. Finally, **NASA's Perseverance rover** landed on Mars on Feb. 18, becoming the ninth NASA mission to land on Mars. Perseverance also landed with the **Ingenuity Mars Helicopter**, a 2-kilogram robotic helicopter that in April flew the first powered flight on another planet. China's **Zhurong rover** joined Perseverance on the planetary surface on May 14, making China the second country to land and operate a spacecraft from the Martian surface. ★

▶ The U.S. Air Force Test Pilot School's Ione X-62A Variable In-flight Simulator Test Aircraft, or VISTA, has been upgraded to include multiple data links for command and control and telemetry.

U.S. Air Force



Enhancing capabilities to measure, analyze and control fluid flows

BY UNNIKRISHNAN SASIDHARAN-NAIR, REETESH RANJAN AND SCOTT DAWSON

The **Fluid Dynamics Technical Committee** focuses on the behaviors of liquids and gases in motion and how those behaviors can be harnessed in aerospace systems.

A team from **Sandia National Laboratories** in New Mexico completed in July a **multiyear computational fluid dynamics validation challenge** for a transonic flow over an axisymmetric body with shock-induced separation by implementing modern diagnostic capabilities for measuring surface pressure, surface shear stress and the off-body velocity field. The challenge kept participants "blind" to the experimental results and provided them only with the wind tunnel and model geometries and measured boundary conditions. Simulation results from Sandia and six participating teams, which used a variety of Reynolds-averaged Navier-Stokes and scale-resolving CFD techniques, highlighted the challenges of simulating separated flows when only minimal flow-field quantities are known. Researchers publicly released the validation dataset in August at AIAA's Aviation Forum so that additional computational teams could test their own capabilities.

The **DARPA Control of Revolutionary Aircraft with Novel Effectors, or CRANE**, program is developing unique **aircraft configurations that incorporate active flow control as the primary design consideration**. This year, CRANE research collaborators worked on Phase 0, a 12-month program phase focused on extensive trade studies, component testing, and system modeling and analysis. Researchers matured their design tools and selected active flow control technologies prior to selecting a conceptual aircraft design. By August, DARPA had chosen selected teams to proceed to Phase 1 of the program, in which they will complete preliminary reviews of their designs.

▲ This series of images shows flow structures identified within an unsteady jet of fluid impinging on a wall, which is excited using carefully selected frequencies. These orderly structures typically correspond to fluid vortices, as indicated by the arrows. Changing the phase offset between the excitation frequencies leads to different flow structures, as seen by comparing the top and bottom rows of images.

Michigan State University

Researchers at the **University of California San Diego** have developed a **novel modal decomposition technique**, the bispectral mode decomposition, which can identify nonlinear cascades in large datasets arising from experiments and computations. This technique gives insights into nonlinear triadic interactions among frequencies, as well as their causal relations, and computes interaction maps that indicate regions of nonlinear coupling. In August, the researchers presented the first practical applications of the method to turbulent jet acoustics and its use in the approximation of nonlinear transfer functions for real-time estimation.

At **Michigan State University**, researchers have demonstrated that the intermodal phase in a bimodal forcing scheme of an impinging jet can fundamentally alter the nature of vortex development in the jet, and this year, they incorporated **time-resolved visualization to examine the evolution of instantaneous vortex structures**. At certain intermodal phases, the jet vortices develop in a shear-layer-like manner, while at other phases, wake-like growth is observed. At yet other phases, more complex, intermittent behavior is found. These findings highlight the potential of using bimodal forcing as an effective tool for manipulating impinging jets in new ways to alter their effectiveness in cooling the impingement surface, or to change their noise signature.

In April, a team at the **University of Minnesota** demonstrated a unique measurement technique, **digital Fresnel reflection holography**, to quantify near-wall topology in three-dimensional flows. DFRH can achieve near-wall flow measurements at unprecedented spatial resolution and offers a new concept for designing highly compact digital inline holography probes. DFRH has discovered Kolmogorov-scale meandering motions that are responsible for stress events currently unresolved by state-of-the art direct numerical simulations. Based on these observations, researchers proposed a mechanism for drag reduction and flow control with roughness at a scale that is traditionally considered to be hydrodynamically smooth. ★

Contributors: *Ryan Hofmeister, Jiarong Hong, Nathan Miller, Ahmed Naguib and Oliver Schmidt*

Facility improvements, return to service and novel testing techniques showcase critical ground testing

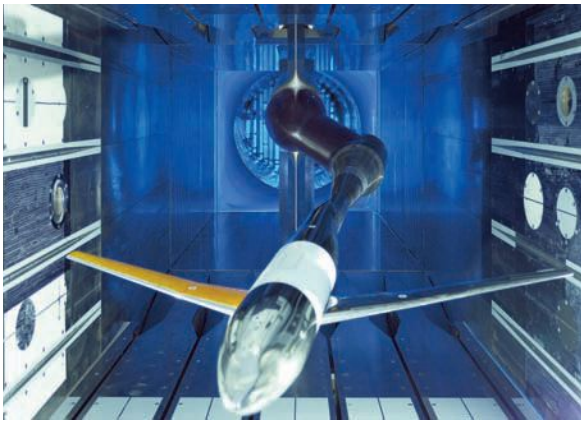
BY ROBERT C. GRIFFITHS

The **Ground Testing Technical Committee** focuses on evaluating aircraft, launch vehicles, spacecraft, structures and engines in wind tunnels and other facilities.

This past year, the **U.S. Air Force's Arnold Engineering Development Complex** maintained critical testing at its many geographically separated units. The **AEDC Propulsion Wind Tunnel 16S** in Tennessee demonstrated tunnel operability after a multiyear reactivation effort by testing an **AGARD-B standard model** in January. The supersonic wind tunnel has a 16-foot-by-16-foot (5-meter-by-5-meter) test section that operates from Mach 1.5 to Mach 4.75.

The **Unitary Plan Wind Tunnel** at **NASA's Ames Research Center** in California ran numerous tests during the ongoing pandemic, despite a maintenance outage from December 2020 to May. A notable upgrade included the installation of large optical windows in the 11-foot test section. These windows allow for a larger unobstructed view of any model using optical test techniques. Following the upgrade period, researchers tested the **Ames Check Standard Model** in the 11-foot section to establish new baseline performance data for the modified tunnel. Another multimonth upgrade that concluded in June was the demolition and replacement of the 45-foot-diameter aftercooler in the 9-foot-by-7-foot supersonic wind tunnel. An Integrated Systems Test followed the installation, and the 9-foot-by-7-foot tunnel has resumed production customer testing.

NASA completed its **Engineering and Safety Center** and **Space Launch System high Reynolds number test** in the **National Transonic Facility** in Virginia in April after a one-year delay due to the pandemic. The objective was to assess and characterize Reynolds number effects on the ascent aerodynamics of the SLS launch vehicle and use the results from the test to inform and update the SLS Ascent Aerodynamics Force and Moment Database and the SLS Ascent Aerodynamics Partial Derivatives Database.



▼ The Lean Secondary Roll Mechanism during a demonstration this year in the European Transonic Windtunnel High Reynolds number cryogenic facility in Cologne, Germany. The LSRM is designed for low interference, wings-level yaw measurements of transport aircraft configurations up to high yaw angles.

European Transonic Windtunnel

RUAG's Large Wind Tunnel Emmen, a 5-meter-by-7-meter tunnel, in Switzerland expanded the facility capabilities for testing both scaled and full-scale flight **urban air mobility** models. RUAG added provisions to ensure sufficient electrical power and more flexible means to perform aeroacoustic tests. The first specimen of a new compact hydraulic motor family, greater than 100 kilowatt (135 horsepower) and ranging from maximum speeds over 30,000 revolutions per minute, completed testing prior to being used to drive a scaled turbofan simulator in the Large Wind Tunnel Emmen as part of the **European Union-sponsored TRUflow project**.

The **Japan Aerospace Exploration Agency**, or JAXA, demonstrated a novel approach for efficiently **constructing single-structure wind tunnel models via application of additive manufacturing**. Single-structure models allow for a more accurate representation of structural characteristics due to aerodynamic and aeroelastic phenomena, thereby increasing confidence in the results. Using this approach, scientists fabricated half-span wing models for transonic testing in the JAXA 0.6-meter-by-0.6-meter flutter wind tunnel. The flutter test results showed good agreement with numerical aeroelastic solutions, validating this unique design approach.

The **European Transonic Windtunnel** in Germany expanded its unique cryogenic high Reynolds testing capabilities via demonstrations of the **Lean Secondary Roll Mechanism** and **Remote-Controlled Aileron Actuator**. The Lean Secondary Roll Mechanism is a double-knuckle roll mechanism designed for low interference, wings-level yaw measurements of transport aircraft configurations, thereby increasing sideslip testing capabilities with excellent productivity. The Remote-Controlled Aileron Actuator allows for complete control surface sweeps while the model remains in the pressurized cryogenic test section — no transport or manual rigging efforts needed.

The **Transport Canada Remotely Piloted Aircraft System task force** engaged the National Research Council to conduct wind tunnel experiments in the **Propulsion Icing Tunnel** in Ottawa this past year to **measure the magnitude of urban airflow fluctuations** on four representative Canadian cities: Vancouver, Toronto, Halifax and an artificial city. The objective was to support Transport Canada in the development of regulations for safe operation of RPAS within urban environments by providing knowledge on airflows within Canadian cities and the flight response of commonly used RPAS to these airflows. ★

Contributors: *Peter Aschwanden, David Chan, Luc Levasseur, Shinji Nagai, Eric Paciano, Rebecca Rought, Harold Quix and John VanHorn*

Autonomous operations take the forefront at Mars, in human spaceflight and aerial refueling

BY JULIE J. PARISH

The **Guidance, Navigation and Control Technical Committee** advances techniques, devices and systems for guiding and commanding flight vehicles.

The world was captivated by the entry, descent and landing of a **NASA Mars spacecraft** in February. Equipped with **new Range Trigger and Terrain Relative Navigation algorithms**, the **Perseverance rover** was able to autonomously touch down on the Martian surface. Together, these technologies reduced the uncertainty of the landing location and broadened the number of potential landing sites through hazard avoidance. When Perseverance landed, it was carrying the autonomous **Ingenuity Mars Helicopter**, which in April became the first powered aircraft to fly on another planet. Due to significant communication latency, Ingenuity cannot be flown remotely and consequently was designed for fully autonomous operation. Furthermore, this ultralight aircraft operates in harsh Martian conditions and must compensate for the uncertainty of flight in a sparsely modeled environment.

Earth-based autonomous flight continued to push limits as well. In July, **Blue Origin** flew civilian passengers on the fully autonomous **New Shepard rocket and suborbital capsule**. Then in September, **SpaceX** launched an all-civilian group to space on the Inspiration4 mission aboard the fully automated **Crew Dragon spacecraft and Falcon 9 rocket**. These passengers were provided limited training — relative to professional astronauts — in preparation for their missions. These launches advanced commercial space travel through demonstration of greater reliance on automated guidance, navigation and control systems rather than human pilots.

In April , Xwing of San Francisco announced the first fully autonomous gate-to-gate flight of a commercial aircraft with the company's Autoflight System on a Cessna 208B Grand Caravan. A month later, **Merlin Labs** of Boston announced that the Civil Aviation Authority of New Zealand had approved the agency's first certification basis for an autonomous flight system to Merlin Labs. Fully autonomous passenger and cargo flight vehicles require complex guidance and sensor fusion capabilities that must be evaluated to ensure the safety of passengers, bystanders and the environment. This is a key step toward **autonomous urban air mobility**, as are related tests underway around the world.

Autonomous guidance, navigation and control also had milestones in defense aircraft. A **Boeing MQ-25 demonstrator refueled** an F/A-18 Super Hornet, E-2D Hawkeye and F-35C Lightning II in June, August and September, respectively. The U.S. Navy tests were the **first demonstrations of air-to-air refueling with an uncrewed aircraft**.

An essential element for safe autonomous operations is reliable navigation technology. In June, SpaceX launched a previously flown Falcon 9 carrying the fifth **GPS III satellite**, the **first time a U.S. national security payload had been sent on a refurbished booster**, according to the U.S. Space Force. The fifth GPS III is the final Military-Code satellite required to make M-Code fully operational, which the Space Force says will provide data more accurately and more robustly prevent jamming. Alternatives to GPS also made strides. **NextNav** demonstrated precise timing and redundancy of its **TerraPoiNT GPS-free network** in a U.S. Department of Homeland Security evaluation in August. The U.S. Department of Transportation also named NextNav as the only vendor to "demonstrat[e] all applicable use case scenarios" in its January Complementary PNT and GPS Backup Technologies Demonstration Report. These efforts could improve autonomous localization, especially in challenging environments such as urban canyons. ★

▼ A Boeing MQ-25 test demonstrator autonomously transfers fuel to a piloted F/A-18 Super Hornet.

Boeing

Software releases, a corporate acquisition and advances in simulation propel meshing forward

BY ROMAIN AUBRY AND DAVID MCDANIEL

The **Meshing, Visualization and Computational Environments Technical Committee** explores the application of computer science to preprocessing, post-processing and infrastructure in support of computational simulation in the aerospace community.

Despite a lack of in-person interaction, this year has witnessed again numerous achievements in the meshing, visualization and computational environment realm.

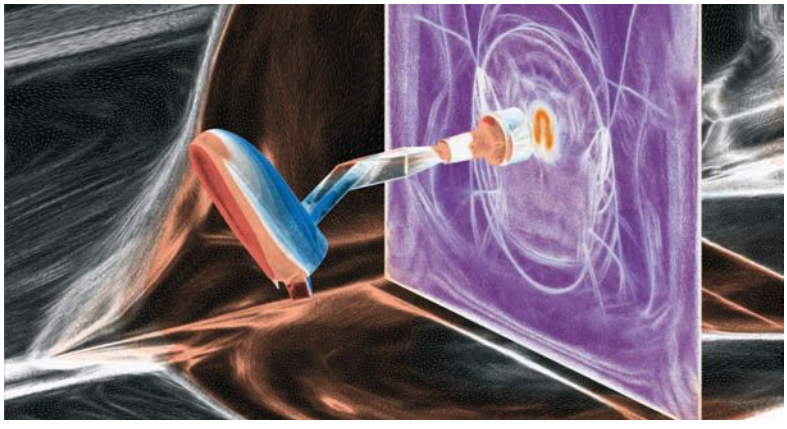
The recent computational fluid dynamics vision progress report shares the same trends, with a particular emphasis on the remarkable progress of adapted techniques.

The **U.S. Department of Defense** High Performance Computing Modernization (**HPMCP**) Computational Research and Engineering Acquisition Tools and Environments (**CREATE**) program continues to release new capabilities across its array of air vehicle simulation and mesh generation products. **Capstone v12** was scheduled to be released in December. The surface meshing has been fully parallelized on shared memory, including surface boundary layer generation. Adaptivity has been further developed in tight collaboration with the Kestrel CFD solver team, including boundary layer adaptivity, as well as with the **Helicopter Overset Simulations**, or Helios, team, regarding surface adaptivity. A large effort has been put to improve throughput, whether serial or parallel. **Kestrel v12** was released in May. It allows for more flexibility in multiphysics coupling by treating the fluid equation integration like other time-based actions in the simulation. This enables more efficient simulations along a trajectory, since the fluid solution can be updated only when specified or needed based on convergence criteria. It will also lead to future flexibility in variable-fidelity simulations, in which some physics are solved via full partial differential equation integration and others are solved with approximate methods or reduced-order models. **Helios v12** was released in October. This release continues to extend and improve the Cartesian-based Reduced Order Aerodynamics Solver, or **ROAM**, for automated meshing around complex geometries. ROAM combines an actuator line representation of the rotor with an immersed boundary representation of the fuselage and is implemented in Helios' SAMCart off-body Cartesian Adaptive Mesh Refinement solver. The reduced order solver provides automated meshing and runs up to 50 times faster than traditional body-fitted unstructured mesh approaches.

In April, **Cadence Design Systems Inc.** acquired CFD software developers **Pointwise Inc.** and **NUMECA**. These acquisitions continue the **electronic design automation** company's expansion into systems analysis and are expected to enable advanced CFD solutions where accuracy and reliability are required. Pointwise has been generating meshes for the CFD industry for three decades.

The application of **mesh adaptation in production workflows** was used this year to evaluate CFD as a surrogate for **Mach 2.4 to 4.6 wind-tunnel testing**. The evaluation included evaluation of expert-crafted meshes and multiple flow solvers. Simulations of high-speed leg of the wind tunnel with empty test section and models installed with support hardware created an extreme range of geometric scales. Simulations of vortices generated by structures upstream of the wind tunnel throat and the corners of the throat were propagated through the sonic throat to the supersonic test section. These simulated vortices impacted the model and support hardware to provide context for previously unexplained measurement anomalies. The **Space Launch System model** and support hardware had high-fidelity geometric detail, which indicates progress in accommodating complex geometry sources in production CFD environments with mesh adaptation.

Also this year, **Intelligent Light** announced **Kombyne**, a new in situ/in transit CFD data processing capability. As CFD simulations scale up as expected by 2030 under **NASA's CFD vision**, the ability to extract knowledge from the extremely large unsteady CFD simulation expected by 2030, file input/output will limit the ability to scale. In situ/in transit processing reduces the I/O constraints by processing the simulation data as the solver runs without writing out large CFD datasets. Under **PRESTIGE**, a research and technology project of the **DLR, the German Aerospace Center**, Intelligent Light worked with **Rolls-Royce Germany** to instrument the Hydra solver to enable Rolls-Royce to simulate and analyze an unsteady 5 billion element gas turbine compressor simulation. ★



▼ Mesh adaptation in wind tunnel for high-speed flows with extreme range of geometric scales.

William Kleb/Michael Park/NASA

Conducting traffic flow and urban air mobility simulations for future air transportation goals

BY CHRISTINE TAYLOR

The **Modeling and Simulation Technical Committee** focuses on simulation of atmospheric and spaceflight conditions to train crews and support design and development of aerospace systems.

▲ An electric vertical takeoff and landing vehicle makes a simulated approach to a vertiport on a parking garage in San Francisco in April during NASA's Revolutionary Vertical Lift Technology simulations in the Vertical Motion Simulator at NASA's Ames Research Center in California.

NASA

Effective **traffic flow management**, TFM, involves mitigating imbalances between traffic demand and airspace and airport capacity at the local, regional and national airspace levels. The collaborative decision making, CDM, community consists of representatives from government, flight operations, general aviation, industry and academia. A key aim of this community is to improve TFM efficiency through the timely exchange of information to support TFM decisions. Working with the FAA and CDM community, the Virginia-based **MITRE Corp.** developed a streamlined process and web-based tool to identify flight-specific alternate routes for departure fix demand balancing, which reduces pre-departure delay by matching demand with available capacity. By focusing on reroutes that have flight operator approval, the goal is to reduce the workload and delays associated with identifying these alternatives. From July to August, CDM stakeholders led field trials in the Washington, D.C., region that resulted in reduced delays and improved capacity utilization. By enabling the improved operation in today's environment, TFM will be better equipped to handle the operations envisioned for the future.

SimLabs at **NASA's Ames Research Center** in California conducted multiple **urban air mobility** simulation experiments in its **Vertical Motion Simulator, VMS**. In April, NASA's **Revolutionary Vertical Lift Technology project** conducted human-in-the-loop simulations to evaluate the handling qualities and establish flight control system design criteria of two **electric vertical takeoff and landing, or eVTOL, quadrotor vehicles**. One vehicle model used rotor blade pitch for control, as in conventional helicopters; the other model used rotor speed. The simulation demonstrated the connection between aircraft handling qualities and pilot workload during normal approach and landing operations. The flight control system design criteria will guide future control system designs for UAM vehicles.

Building on this progress, in June, the FAA and NASA compared two additional UAM vehicle models and corresponding flight control systems. One model was a six-person quadrotor; the other was a fixed-wing vehicle with separate lifting rotors and a pusher propeller. Test pilots and engineers from several FAA divisions participated in both VMS experiments. These VMS studies were the first in a series to help the FAA define a set of representative maneuvers and performance criteria for **evaluating the handling qualities and airworthiness of the new class of UAM vehicles**. These representative maneuvers, or mission task elements, will ultimately serve as a means of compliance for FAA certification of these novel vehicles.

In July, a ride-quality simulation in the VMS at Ames **collected physiological data and motion sickness questionnaires from 23 passengers** using a tablet-based vigilance task during flights with low- and high-intensity turbulence. This experiment provided valuable insights into how turbulence experienced in UAM eVTOL vehicles contributes to motion sickness. Experiments like this are essential to determine the effects of ride quality on passenger acceptance of UAM. ★

Contributors: *Bimal Aponso, Dave Klyde and Peter Zaal*

Fundamental advancements in plasmas and lasers propel the future of propulsion and energy

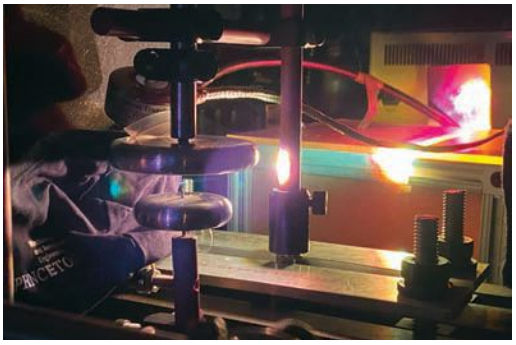
BY SALLY BANE, CARMEN GUERRA-GARCIA AND ANDREY STARIKOVSKIY

The **Plasmadynamics and Lasers Technical Committee** works to apply the physical properties and dynamic behavior of plasmas to aeronautics, astronautics and energy.

The U.S. Department of Energy-funded **Princeton Collaborative Low Temperature Plasma Research Facility** selected 21 projects in January to facilitate collaborations among scientists across the country. In April, researchers at the PCRF used a **Femtosecond Two-Photon Absorption Laser Induced Fluorescence diagnostic system** to image and monitor neutral atomic hydrogen densities in conditions relevant for fusion and Hall thrusters for the first time, with accuracy better than 10 billion atoms per centimeter cube.

The year brought several **advancements related to streamer discharges**, one of the most important processes encountered in nonthermal plasmas. In January, researchers at **Princeton University** and **the Moscow Institute of Physics and Technology** demonstrated pulsed generation of a beam of runaway electrons by a decelerating positive streamer, with possible implications in the X-ray radiation detected from various kilometer-long discharges (blue jets, red sprites) in the upper atmosphere. In May, researchers at Princeton University demonstrated self-focusing of a streamer in an external longitudinal magnetic field. In July, researchers from Princeton University, the **University of Notre Dame** and the **Massachusetts Institute of Technology** used the electric-field-induced second harmonic generation method to perform direct measurements of the electric fields inside streamer coronae.

Chemical kinetics researchers continued to advance in the quest for predictive understanding of plasma-assisted methods for combustion, catalysis, fuel reforming and carbon dioxide remediation. In June, researchers at **Ohio State University** developed a hybrid nonequilibrium plasma-generation method, combining high-voltage nanosecond discharges and sub-breakdown radio frequency voltage, applying it to control energy pathways and provide chemical selectivity of products. In July, researchers at Princeton University, in collaboration with the Moscow Institute of Physics and Technology, identified a new mechanism, based on positive hydrocarbon-water cluster ions, that controls the plasma recombination in hydrocarbon-air mixtures at temperatures below 1,000 kelvins. In August, Princeton University researchers achieved validation of kinetic models for plasma-assisted fuel pyrolysis and oxidation of n-alkanes through direct measurement of reaction rates and branching ratios of the singlet oxygen using mid-infrared laser absorption, integrated cavity output spectroscopy and faraday rotational spectroscopy. In September, researchers at **Bochum University** developed advanced laser diagnostics to measure carbon dioxide rotational-vibrational excitation, which is important for developing detailed kinetic models of carbon dioxide dissociation.



▼ A femtosecond laser-generated optical plasma in the center of an electrode gap can form a gasdynamic diode for high-voltage nanosecond discharges. Researchers showed that streamer propagation can be blocked by the streamer's interaction with both low and high gas densities in the layer formed across the propagation axis if its thickness is large enough. For a relatively small layer thickness, the gap exhibits selective conductivity: A negative discharge can develop up to a low-voltage electrode, while a positive discharge stops in a low density layer. Thus, the proposed mechanism forms a gasdynamic diode with asymmetric conductivity of the initially symmetrical air gap.

Princeton University

Hypersonics research was on the rise this year following the establishment of the **U.S. Department of Defense's University Consortium for Applied Hypersonics**. In January, **Ohio State University** researchers demonstrated that both cavity ring down spectroscopy and tunable diode laser absorption spectroscopy can be applied to measure the concentration of metastable excited molecular nitrogen N2(A3Su+) in nonequilibrium supersonic air flows at high-enthalpy pulsed test facilities. In March, New Jersey-based **Speckodyne Corp. and Plasma-Tec Inc.** implemented the femtosecond laser electronic excitation tagging technique for the first time in high enthalpy hypersonic flows at the **University of Texas Arlington Aerodynamics Research Center** arc-jet facility, providing kilohertz-rate imaging of velocity profiles. In April, researchers at the **University of Arizona** succeeded in incorporating the plasma sheath into numerical simulations of a Mach 10 flow. Researchers at the **University of Notre Dame** demonstrated an alternating-current-driven glow discharge sensor for measuring velocity in rarefied, high-speed flows and examined the effects of gas composition, pressure and plasma discharge frequency on the sensitivity.

Researchers also made progress in demonstrating plasma technologies for next-generation engines and combustors. In January, researchers at **CentraleSupélec** in France achieved agreement between experiments and simulations of stabilization of lean hydrocarbon flames by pulsed nanosecond discharge plasmas. They modeled the fully turbulent flame using large-eddy simulation techniques and developed a phenomenological reduced-order model for the plasma. In March, researchers at **Georgia Tech** and the **U.S. Air Force Research Laboratory** demonstrated for the first time plasma-stabilization and nitrogen oxides emissions reduction in ammonia-fueled flames. ★

Contributors: *Igor Adamovich, Arthur Dogariu, Christophe Laux, Stefan Löhle, Eric Matlis, Richard Miles, Bernard Parent, Suo Yang, Wu Yun and Joseph W. Zimmerman*

NASA advances atmospheric entry technology through spacecraft instrumentation

BY AARON BRANDIS, JONATHAN BURT AND SAVIO POOVATHINGAL

The **Thermophysics Technical Committee** promotes the study and application of mechanisms involved in thermal energy transfer and storage in gases, liquids and solids.

▲ NASA performed ground testing this year in preparation for the planned Low-Earth Orbit Flight Test of an Inflatable Decelerator in 2022.

NASA

NASA completed major components of the **Low-Earth Orbit Flight Test of an Inflatable Decelerator, or LOFTID**, between May and July. The LOFTID vehicle, which is dedicated in honor of United Launch Alliance aerospace engineer Bernard Kutter who died in 2020, will test an inflatable aeroshell for landing spacecraft on Mars and their reentry into the Earth's atmosphere. It is scheduled for launch in September 2022. An inflatable aeroshell has many advantages over conventional rigid aeroshell configurations, including the potential to efficiently decelerate large payloads while avoiding excessive fairing size requirements. Its potential applications include landing humans on Mars and recovering launch vehicles on Earth. The test aeroshell's large frontal area of around 30 meters squared produces comparatively low heat loads, so the aeroshell doesn't need an ablative heat shield. In May, manufacturer **Jackson Bond Enterprises** of New Hampshire shipped the LOFTID flexible thermal protection system — designed to protect against temperatures of up to approximately 1,900 kelvins (1,600 degrees Celsius) and consisting of silicon carbide fabric, carbon felts, aerogel and gas barrier layers — to **Airborne Systems Inc.**'s facility in California for connecting the thermal protection system to the inflatable structure. Airborne Systems then tested the combined assembly, packed it to a compressed launch configuration and shipped it to **NASA's Langley Research Center** in Virginia where the entire reentry vehicle will be assembled and tested.

In February, the **Mars 2020 spacecraft**, traveling at nearly 20,000 kph, entered the Mars atmosphere and delivered the **Perseverance rover** at Jezero Crater. In addition to the rover and its scientific payload, the Mars 2020 aeroshell included a sensor suite on the heatshield and backshell. That sensor suite, called **Mars Entry, Descent, and Landing Instrumentation 2, or MEDLI2**, had 28 sensors that measured the aerodynamic and aerothermal performance through a variety of pressure transducers, thermocouples, heat flux sensors and a radiometer. This instrumentation suite expanded upon the data collected by the MEDLI instruments flown aboard the Mars Science Laboratory mission in 2012. MEDLI2 represents NASA's most extensive backshell instrumentation suite flown on Mars to date. MEDLI2 was able to measure heatshield turbulent flow transition, high-altitude atmospheric density profiles, winds during supersonic flight and backshell infrared radiation from the wake flow. With the MEDLI2 dataset, researchers will be able to compare flight data with predictive simulations, to update analytical models and to learn how the thermal protection system responds throughout entry. Ultimately, this new dataset will lead to improved designs of future entry systems for robotic and crewed missions not only on Mars but also for other destinations, such as Venus, Titan and the gas giants.

NASA announced in March the establishment of the **Advanced Computational Center for Entry System Simulation, or ACCESS**, space technology research institute. ACCESS is a team of experts from six U.S. universities: **University of Colorado, University of Illinois at Urbana-Champaign, University of Kentucky, University of Maryland, University of Minnesota and University of New Mexico**. The institute will advance the design of NASA entry systems by developing a fully integrated, interdisciplinary simulation capability. The institute's efforts are divided into four tasks: focusing on theoretical chemistry to identify the key reactions and determine new rates of all gas-phase species encountered during entry; working toward a fully integrated simulation tool with exascale computing capability and new computational algorithms; developing multiscale models for thermal protection system materials; and tracking reliability and uncertainties of all processes. ACCESS' primary product will be the **Integrated Simulation Framework** that will provide a platform for multidisciplinary calculations that include physical effects related to chemistry, radiation, materials, structures and reliability. The institute will focus on the systems that protect spacecraft from aerodynamic heating, as well as prediction of the extreme environments experienced during atmospheric entry. This work is critical for the exploration of planets, such as Mars, that require high-reliability entry systems for safe placement of large payloads on their surfaces. ★

Contributors: *Charles Bersbach, Eric Stern, Adam Whelan and Todd White*

Improving accuracy of military airdrops, even without GPS

BY OLEG YAKIMENKO AND MICHAEL HENRY

The **Aerodynamic Decelerator Systems Technical Committee** focuses on development and application of aerodynamic decelerator systems and lifting parachutes, pararotators and inflatables for deceleration, sustentation and landing of crewed and uncrewed vehicles.

▲ The Military Free Fall Micro Light Weight precision aerial delivery system (bottom) can operate in environments without GPS. The U.S. Army is looking for a potential replacement for its T-11 parachutes (top).
U.S. Army

In May, after more than five months docked to the International Space Station, **SpaceX's Crew Dragon spacecraft Resilience** returned to Earth, landing in the Gulf of Mexico under four main parachutes. **Crew-1**, the first operational mission of NASA's Commercial Crew Program, launched to the ISS with four astronauts from Kennedy Space Center in Florida in November 2020. The second operational crew lifted off in April aboard the **Crew Dragon Endeavour,** docked with ISS and returned to Earth in November.

The **U.S. Army Combat Capabilities Development Command Soldier Center** conducted the final two operational demonstrations for the Autonomous Aerial Insertion and Resupply into Dense, Urban Complex Terrain, or **AAIRDUCT**, joint capability technology demonstration, sponsored by the Office of the Secretary of Defense in conjunction with U.S. Transportation Command, U.S. Special Operations Command and U.S. Central Command. The goal of this project was to rapidly develop precision aerial delivery technologies in the 23-kilogram to 230-kg range, with a focus on increased maneuverability in urban environments and areas without GPS. As part of the effort, the center developed a two-stage device known as the 230-kg **High Altitude Aerial Release System** that uses a small drogue to descend quickly from high altitudes and deploys multiple low-cost low-altitude parachutes closer to the ground for a low-velocity impact.

The Soldier Center also continued developing the next generation of **Joint Precision Airdrops Systems** in the 23- to 230-kg (ultralight) weight class and 11- to 23-kg (microlight) weight class. The center conducted demonstrations in March and May at **Yuma Proving Ground** in Arizona. It deployed systems from C-17A Globemaster III, C-130J Super Hercules and C-27J Spartan aircraft and a UH-60 helicopter from altitudes up to 7.6 kilometers. The Soldier Center worked with U.S. Central Command and Army Evaluation Command to conduct an operational evaluation and military utility assessment to determine the operational utility and effectiveness of the developed technologies. The center is working to transition these capabilities to programs of record to be incorporated into future Army products.

In February, the Soldier Center tested leading commercial and allied nations' **static line personnel parachute systems** to characterize the performance of potential replacements to T-11 parachute systems and to inform requirements generation. This data, and supporting analysis, will drive technical development efforts for a next-generation static line parachute system. ★

Contributors: *Eric Campagna, Jaclyn Fontecchio, Ricardo Machin and Ekaterina Prosser*

Air transportation systems recovering from pandemic's effects

BY DAVID THIPPHAVONG

The **Air Transportation Systems Technical Committee** fosters improvements to air transportation systems and studies the impacts of new aerospace technologies.

In October, the **International Air Transport Association** projected a **$51.8 billion net loss for the global airline industry** this year due to the ongoing covid-19 pandemic, after a $126 billion net loss in 2020. By comparison, global airline industry profits were $26 billion in 2019 and $27 billion in 2018. One bright spot for the industry was air cargo, which continued to experience strong demand this year, comprising one-third of revenues compared to 10%-15% pre-pandemic. In addition, domestic air travel rebounded, especially in the United States, where summer domestic bookings recovered to 85% of 2019 levels, compared to 36% of 2019 levels in 2020. However, in August, IATA cautioned that the rapid spread of the delta variant of covid-19 has increased the risk to continued airline financial recovery.

The faster-than-expected recovery of domestic air travel in the United States led to challenges that had not been fully resolved as of the end of September. For example, there was a **pilot shortage** because airlines encouraged early retirements and leaves of absence at reduced pay to cut costs. The latter, combined with **airlines changing the composition of their fleets**, resulted in an ongoing backlog of training to get pilots in the cockpit. The shortage of pilots prevented airlines from having the backup margin necessary to recover from weather, technical and other disruptions as quickly as they had been able to pre-pandemic.

Unrelated to the pandemic, **U.S. airlines started flying their Boeing 737 MAX aircraft** again following the FAA's approval in November 2020 for the aircraft to return to service. However, in April, Boeing announced issues with the electrical grounding inside a backup power control system that resulted in the grounding of 106 aircraft worldwide and more than 60 aircraft in the United States. The following month, though, the FAA approved a fix that the airlines were able to implement in time for the summer travel season.

Beyond traditional air transportation, progress was made toward the integration of small uncrewed aircraft systems into the national airspace system. In January, **the FAA approved American Robotics to conduct the first commercial drone flights without on-site personnel**. Although a human operator is still required to perform preflight safety checks, the drone is permitted to conduct automated flight to achieve missions. This represents another step toward fully autonomous drone flights for missions, including search and rescue, infrastructure inspection and package delivery.

▼ Airports in the United States were crowded as domestic air travel recovered to near-pre-pandemic levels.

U.S. Transportation Security Administration

Progress was also made toward the integration of advanced air mobility vehicles, such as two- to six-passenger electric vertical takeoff and landing aircraft, into the national airspace system. From Aug. 30 through Sept. 10, **Joby Aviation** remotely flew the prototype of its S4 eVTOL aircraft at its Electric Flight Base near Big Sur, California**.** These activities are part of **NASA's Advanced Air Mobility National Campaign**, which will take place at multiple locations across the country over the next several years. Joby's vehicle performance and acoustic data were collected for use in the modeling and simulation of future airspace concepts and the development of FAA regulations, standards and policies. ★

▲ Rolls-Royce's all-electric plane Spirit of Innovation was flown for the first time in the United Kingdom in September.

737 MAX 10, NASA's Ingenuity and others make first flights

BY MICHAEL LOGAN AND MICHAEL DRAKE

The **Aircraft Design Technical Committee** promotes optimization of aircraft systems, including analysis of their future potential.

First flights occurred this year across the spectrum of aircraft types, including commercial airliners, business jets, advanced air mobility, electric powered, uncrewed aircraft and subscale demonstrators. There was even the first powered flight of an aircraft on another planet.

The **Boeing 737 MAX 10**, the newest version of the venerable 737, made a 2½-hour flight from Renton Municipal Airport in Washington in June. The MAX 10 has an extended fuselage to carry up to 230 passengers and a projected range of 3,300 nautical miles (6,100 kilometers). The aircraft has a new landing gear concept that compensates for the longer fuselage body's adverse impact on takeoff performance, while still stowing in the same wheel well. Boeing expects to complete certification of the new jet in 2023.

In business aviation, the **Dassault Aviation Falcon 6X** took its first flight from the company's plant in Bordeaux-Mérignac, France, in March. The aircraft is a follow-on to the Falcon 5X with new engines and a longer fuselage. The aircraft carries 16 passengers, has a range projected to be 5,500 nmi (10,200 km), a long-range cruise speed of Mach 0.8 and a maximum speed of Mach 0.9. It is powered by two **Pratt & Whitney PW812D engines**. Certification is projected for 2022. The **Textron Aviation Denali** began ground runs in preparation for first flight. The Denali has the new **GE Catalyst turboprop engine** and carries up to 11 passengers. It has a range of 1,600 nmi (3,000 km) with four passengers and a maximum cruise speed of 285 knots (530 kph).

Among commercial supersonic aircraft companies, **Boom Supersonic** continued development of its **demonstrator XB-1**, and announced in June that **United Airlines would buy 15 of the full-scale aircraft**. However, **Aerion Supersonic** failed to obtain financing for continued development of its AS2 supersonic business jet and ended operations.

Companies continued to develop **advanced air mobility concepts**. In July, **Joby Aviation** remotely flew the full-scale prototype of its electric vertical takeoff and landing aircraft for 77 minutes on a single charge, its longest flight. The eVTOL's 11 circuits above Joby's California flight base was the equivalent of traveling 247 kilometers. From late August to early September, Joby conducted a series of remotely piloted flights with the same eVTOL S4 aircraft, the first under **NASA's Advanced Air Mobility National Campaign**. The aircraft flew over dozens of microphones placed by NASA engineers to gather acoustics data. **Rolls-Royce's all-electric Spirit of Innovation** also was flown for a short first flight in September in the United Kingdom. Rolls-Royce has said it wants to advance all-electric flight propulsion systems by developing an aircraft that will set electrified aircraft speed records.

Glasair Aviation's Merlin light sport aircraft was flown for an hour on its first flight in April. The Merlin was designed to ASTM standards for light sport aircraft and has a parachute recovery system.

Among uncrewed aircraft, the **Boeing Airpower Teaming System**, also known as the **Loyal Wingman**, prototype completed its first flight from the Woomera Range Complex in South Australia in February. It is designed to be flown with crewed military aircraft to offer flexibility for defense missions. Boeing said it is the first military combat aircraft to be designed, engineered and manufactured in Australia in more than 50 years.

As of November, the **NASA Ingenuity Mars Helicopter**, which made its historic first flight on Mars in April, had flown 15 sorties, the longest approaching three minutes. The first flight of the 1.8-kilogram helicopter lasted 39.1 seconds and was "the very first powered, controlled flight in the extremely thin atmosphere of Mars, and, in fact, the first such flight in any world beyond Earth," according to NASA .★

Aircraft operations begin to recover from covid

BY TOM REYNOLDS

The **Aircraft Operations Technical Committee** promotes safe and efficient operations in the airspace system by encouraging best practices and information-sharing among the community and government agencies.

▶ Airline passengers check themselves in at Raleigh-Durham International Airport in North Carolina in May. The number of passengers who flew this year did not fully rebound to pre-pandemic levels.

After a 70% drop in aviation operations and 90% drop in passengers during the first half of 2020 due to covid, there was a gradual recovery in domestic demand this year, with **U.S. flight and passenger numbers down about 20% compared to pre-covid levels** by mid-September. Cargo demand was robust, even higher in some global regions compared to before the pandemic, but international passenger traffic remained weak compared to 2019.

The **FAA** continued to move the air traffic control system toward **Trajectory-Based Operations**, which uses more time-based traffic control. In preparation for planned implementation of the **Terminal Sequencing and Spacing** component of TBO in 2022, testing continued at the Denver terminal radar approach control facility, which will be the first operational site. To address the impact of convective weather on Trajectory-Based Operations, preparation for a test of the **NASA-developed Dynamic Routes for Arrivals during Weather** technology continued at the FAA Technical Center.

Urban air mobility and advanced air mobility concepts continued to evolve. The FAA has been updating its UAM concept of operations and worked with NASA on its **Advanced Air Mobility National Campaign**. After completion of the National Campaign X3 simulations in 2020, NASA selected seven companies in July 2021 to participate in the next round of simulations — called X4 and scheduled for 2022 — to work toward integrating air taxis, cargo delivery aircraft and other new vehicle concepts into the national airspace system. The air taxi development sector continued to grow, with startups **Archer, Joby and Lilium** going public in September, August and September, respectively. A number of prospective air taxi operators announced plans to buy vehicles, including **UPS** in April and **American Airlines, Halo Aviation and United Airlines** in June. NASA spent considerable time engaging the community this year, establishing working groups focused on aircraft, airspace, community integration and cross-cutting topics. Most recently NASA completed a flight test with Joby Aviation to measure the acoustic signature of the company's S4 prototype.

Agencies around the world made steps toward putting **Unmanned Aircraft Systems Traffic Management** into operation. The **European Union U-Space regulatory framework** was published in April, the ASTM UTM standard went up for ballot in October, and the **FAA Unmanned Aircraft System Beyond Visual Line of Sight operations Aviation Rulemaking Committee** was formed in June. The committee will make recommendations to the FAA for performance-based regulatory requirements to normalize UAS beyond visual line of sight operations that are not under positive air traffic control.

NASA developed a concept of operations for an **In-Time Aviation Safety Management System** that was presented at numerous technical conferences this year. NASA is coordinating, with the FAA, the concept and developmental flight tests that could lead to immediate benefits during disaster response scenarios.

In the area of **supersonic civilian aircraft** operations, **Lockheed Martin** continued to build NASA's low-boom supersonic flight demonstrator; delivery of the **X-59 QueSST** experimental vehicle was scheduled for late this year and flight tests to assess the quiet boom technologies and gather community feedback are planned to start in 2022.

Commercial space operations hit a number of milestones this year. SpaceX followed up on its first crewed Crew Dragon flight in May 2020 with two more launches of crews to the International Space Station and the first all-civilian trip to orbit, **Inspiration4**, in September. As of mid-October, there had been 23 SpaceX Falcon 9 launches this year; the company planned 33 by the end of the year, compared to 26 in 2020. There were notable flights from other commercial space operators, with first passenger (non-test pilot) flights to space of both Virgin Galactic's SpaceShipTwo and Blue Origin's New Shepard vehicles in July. ★

Contributors: *Gabriele Enea, Antony Evans and John Koelling*

Altitude-controlled balloons in development for Earth and planetary missions

BY PAUL VOSS

The **Balloon Systems Technical Committee** supports development and application of free-floating systems and technologies for buoyant flight in the stratosphere and atmospheres of other planets.

NASA's **Jet Propulsion Laboratory** and **Near Space Corp.** completed a series of indoor flight tests of their subscale prototype Venus aerobot in August in the Tillamook, Oregon, airship hangar. The aerobot, or robotic balloon vehicle, is based on a metalized Teflon design in which helium pumping between an interior pressurized reservoir and an outside zero-pressure balloon modulates buoyancy and controls altitude. The testing is a prelude to a potential **future long-duration mission in the clouds of Venus**.

Following the ending of Project Loon, South Dakota-based **Raven Industries** continued to work on the technology of station seeking using variable-altitude balloons. This ability for a balloon to remain within a useful radius of a target area continues to improve as prediction algorithms improve. Raven is adding a fusion of weather data from multiple sources to its station-seeking system. In August and September, an **Aerostar** balloon completed a two-month mission over **wildfires in California and Colorado** to evaluate the effectiveness of these platforms in helping firefighting efforts.

▼ The prototype Venus aerobot floated in the Tillamook airship hangar in Oregon during indoor flight testing this year.

Jacob Izraelevitz/NASA's Jet Propulsion Laboratory and Near Space Corp.

The **NASA Balloon Program Office** and the **Columbia Scientific Balloon Facility** resumed balloon campaigns this year after the pandemic cancellations of 2020. Early in the year, NASA launched three balloons from Fort Sumner, New Mexico. NASA conducted its **Balloon-Borne Chirpsounder demonstration flight** on a new hand-launch system, and two Columbia Scientific Balloon Facility test flights carried numerous piggyback missions, including the **All-Sky Heliospheric Imager**, the **Balloon Observation of Microburst Scales** and the **Balloon-Based Observations for Sunlit Aurora**. NASA flew another eight missions later in the year. It flew the 15th High Altitude Student Platform in September.

JPL flew numerous missions, including the **Submillimeterwave Limb Sounder** (a heterodyne radiometer-spectrometer that measures the thermal emission spectra of gases in the Earth's upper atmosphere), **Remote** (an experiment to study stratospheric chemistry and stability of the ozone layer) and the **Water Hunting Advanced Terahertz Spectrometer on an Ultra Small Platform**. The second flight of the **Planetary Imaging Concept Testbed Using a Recoverable Experiment-Coronagraph** mission from **University of Massachusetts Lowell** imaged exoplanetary dust and debris around stars. This mission used the Wallops Arc Second Pointer, a gondola designed to assist pointing telescopes at specific astronomical objects.

The **Physical Science Laboratory at New Mexico State University** partnered with **Stratodynamics Aviation Inc.** of Canada and **UAVOS** of California to perform a series of stratospheric flights with **HiDRON, an autonomous aircraft dropped from a balloon**, at Spaceport America in New Mexico. The mission objectives were to advance new systems for forward-sensing turbulence detection on board aircraft at near-space and commercial flight altitudes. The Physical Science Lab provided launch logistics. The system includes a novel, high-altitude aerial platform with multihole wind probe and infrasonic microphone sensors. Researchers tested HiDRON in three balloon flight drop tests in restricted airspace in June. NASA's **Flight Opportunities Program** funded the campaign to advance turbulence detection sensors developed by the **University of Kentucky** and **NASA's Langley Research Center** in Virginia.

The French space agency **CNES** completed a series of **climate research balloon flights** at Esrange Space Center outside Kiruna in northern Sweden. Through four balloon flights in August, carrying a total of 17 research instruments, the researchers measured the concentration of greenhouse gases at different levels in the atmosphere.

In March, **Smith College** flew a major upgrade of its **Controlled Meteorological balloons** as part of the Isotopic Links to Atmospheric Water's Sources campaign to study cold-air outbreaks near Svalbard, Norway. These altitude-controlled balloons have accrued thousands of flight hours in diverse environments from the Amazon to Antarctica; their closed-cycle buoyancy control and high energy efficiency inspired the basic design for the prototype Venus aerobot. ★

Contributors: *Henry Cathey, Debora Fairbrother, Jeffery Hall, Mike Smith, Eric Waters and André Vargas*

Flight testing of commercial space vehicles and automation technology

BY ANDY FREEBORN, KARL GARMAN AND ED CANNON

The **Flight Testing Technical Committee** focuses on testing of aircraft, spacecraft, missiles or other vehicles in their natural environments.

▲ NASA's Ingenuity Mars Helicopter became the first powered aircraft to fly on another planet.

NASA

The **first powered flight test on another planet** took place in April when **NASA's Ingenuity Mars Helicopter** took off from near the Perseverance rover and hovered 3 meters above the surface of Mars. After a series of technology tests, the helicopter transitioned to operations demonstrations and contributing to the ongoing science mission.

SpaceX continued its aggressive flight test campaign by launching and landing its **Starship SN15 prototype** in May, with an eye on transportation to the moon and Mars. In January, **Virgin Orbit**'s Cosmic Girl aircraft launched the **LauncherOne rocket**, delivering 10 cubesats to low-Earth orbit while testing the main engines, upper stage and payload delivery systems. That flight cleared the way for Virgin Orbit's first commercial launch in June. Blue Origin maintained a high pace of test operations in January, April and August with suborbital payload flights of the reusable **New Shepard rocket**. **Virgin Galactic** received its **FAA commercial space transportation operator's license** after a May flight test of its SpaceShipTwo-class suborbital rocket-powered spaceplane Unity. Both companies followed their flight test campaigns with their first suborbital flights of private passengers. **Stratolaunch** returned its carrier aircraft Roc to flight in April, focusing on performance and flying qualities of the world's largest wingspan aircraft. The almost-590-metric-ton gross weight aircraft is a critical element of the company's plan to test launch hypersonic vehicles.

The **U.S. Air Force Test Pilot School** redesignated its **NF-16 Variable-Stability In-flight Simulator Test Aircraft, or VISTA**, as the **X-62A** in June, after replacing the airborne simulation system and adding components for autonomy research.

NASA began testing a shock wave-sensing probe and precision relative guidance display on an F-15 Eagle in September in preparation for the first flights of the **X-59 Low-Boom Flight Demonstrator** next year. NASA will use the instruments to measure the shock signature around the X-59 to validate low sonic boom aircraft design tools. An in-flight schlieren imaging camera will produce images of shock waves around the X-59.

In April, Oklahoma-based **Skydweller Aero** flew a **modified Solar Impulse 2 aircraft** out of Albacete, Spain, to continue to test **autonomous software for solar-powered flight**. The test further characterized flying qualities to improve models of flexible aircraft capable of bringing persistent communication and sensor coverage to remote areas.

In May, **Airbus** worked with the **Royal Singapore Air Force** to complete the developmental phase of the company's **automated air-to-air refueling** system. The A330 multirole tanker transport aircraft demonstrated fully automated refueling with another A330 and an F-16 Fighting Falcon aircraft as receivers.

Xwing, a California aerospace developer, tested its autonomously configured its Cessna Caravan aircraft in February from gate to gate, demonstrating autonomous flight and navigating ground traffic and obstacles.

In March, **Boeing** and the **Royal Australian Air Force** completed the first flight of their **Loyal Wingman uncrewed aircraft system**.

NASA's Advanced Air Mobility National Campaign began flight tests in March, evaluating **air mobility procedures**, approaches, test techniques and safety planning and a deployable test infrastructure using an OH-58C Kiowa helicopter surrogate. The tests were followed by flight tests with **Joby Aviation** in August and September to measure acoustic and operational performance at different flight conditions.

Kratos Defense and Security, with the **U.S. Air Force Research Laboratory**, completed a sixth **XQ-58A Valkyrie test and demonstration flight** in March. The test series for the Low-Cost Attritable Strike Demonstrator program included delivering the Altius-600 small UAS in flight.

Finally, Boeing tested its **MQ-25 Stingray's crewless air-to-air refueling** capability in June with a U.S. Navy F/A-18 Super Hornet receiver aircraft. The team followed up with a refueling flight test of an E-2D Hawkeye in August. ★

Contributors: *Paul Bolds-Moorehead, Brent Cobleigh, Starr Ginn and James Sergeant*

Influx of private capital marks another potential hypersonic inflection point

BY LIZ STEIN

The **Hypersonic Technologies and Aerospace Planes Technical Committee** works to expand the hypersonic knowledge base and promote continued hypersonic technology progress through ground and flight testing.

▲ Hermeus of Atlanta showed off a full-scale prototype of its Quarterhorse aircraft design in November.

Hermeus

The American academic hypersonic ecosystem continued to expand. Over the past year, 120 organizations joined the **University Consortium of Applied Hypersonics**, whose mission is to furnish the innovation and workforce to create modern hypersonic flight vehicles for national defense. Additionally, three collaborative centers were formed. In March, **University of Colorado Boulder** and **NASA** announced the **Advanced Computational Center for Entry System Simulation**, a multipartner collaborative institute, focused on researching hypersonic thermal protection systems. In July **Purdue University** announced the **Hypersonics and Applied Research Facility, or HARF**, a 65,000-square-foot research lab with the first Mach 8 quiet tunnel, a hypersonic pulse tunnel donated by **Northrop Grumman** and an **additive manufacturing for hypersonics lab**. In August the **Purdue Research Foundation** announced the creation of the **Hypersonic Ground Test Center,** with plans for the construction of test cells and labs for industry partners. The test center will be administered as a nonprofit consortium with **Rolls-Royce North America** as the foundational member. Of the two Purdue centers, HARF is more mature and is on track to be operational the first quarter of 2023.

The pace of flight testing for hypersonic research continued unabated, with mixed results. In June the **U.S. Air Force Office of Scientific Research's Boundary Layer Transition flight experiment failed** during a test in Sweden. In mid-July, Russia announced it tested its **Tsirkon (Zircon) hypersonic cruise missile**. In late July, the **U.S. Air Force's Air-launched Rapid Response Weapon** had its **second failed flight test**, but not due to the hypersonic design. The solid rocket motor failed to light — another instance in a trend of diminished solid rocket reliability. At the end of July, **JAXA, the Japan Aerospace Exploration Agency**, tested its **rotating detonation engine in space** on a sounding rocket. In August, China tested a hypersonic vehicle that first completed an orbit of the Earth before finding its target. In September, **DARPA's Hypersonic Air-breathing Weapon Concept** had its first flight test. The missile was designed by Raytheon, while the scramjet propulsion system was designed by Northrop Grumman. At the end of September, **North Korea** said it had tested a new **hypersonic glide vehicle**.

The year 2018 was an inflection point for military hypersonic systems, specifically in March when Russia announced its Avangard hypersonic boost glide vehicle. In the years since, the U.S., China, India and North Korea have all flown hypersonic gliders. For commercial hypersonics, this year may be a similar inflection point — momentum has been building, as gauged by the **influx of private capital investment into hypersonic startups**. In March, Houston-based startup **Venus Aerospace** closed a $3 million seed funding round, to demonstrate its patented propulsion technology and develop its hypersonic commercial aircraft design. In August, Atlanta-based startup **Hermeus** raised $60 million through **AFWERX's Strategic Financing program**, which receives government funds and matching venture capital funds. The award enables Hermeus to build an uncrewed aircraft to flight test its propulsion system across its operational envelope. In September, Beijing-based startup **Ling Air Skywalk Technology** closed a $15.5 million Series A financing round for the development of a **Chinese commercial hypersonic passenger aircraft**.

NASA's Langley Research Center in Virginia funded two independent review studies on **the business case for commercial high-speed flight**, supersonic and hypersonic. Completed in April by two consulting groups, SAIC/BryceTech and Deloitte/SpaceWorks/NIA, both reports said the business case for commercial hypersonic flight was positive without any need for government subsidies.

In September, Australia, the United Kingdom and the United States announced the **AUKUS working group**. While media attention has focused on maritime submarine development, the agreement will allow the countries to share technical information about **long-range hypersonic strike technology**. ★

Contributors: *Erik Axdahl, Joe Jewell, Dan Marren and A.J. Piplica*

Sergey Brin's zeppelin: The biggest, greenest aircraft in the world

BY ALAN FARNHAM

The **Lighter-Than-Air Systems Technical Committee** stimulates development of knowledge related to airships and aerostats for use in a host of applications from transportation to surveillance.

For three years rumors swirled: What could **Google billionaire Sergey Brin** possibly be building — in secret and far from public view — inside an old Navy blimp hangar at Moffett Field in California? The answer came in October: Brin's company, **LTA Research**, revealed **Pathfinder 1**, an all-composite, extremely green, extremely large 123 meters long by 20 meters in diameter new-age zeppelin the size of four Goodyear blimps.

Alan Weston, CEO of LTA Research, said that the craft portends "the rebirth of an era when giant lighter-than-air vehicles circled the world" and "a new future for aviation, travel, [and] freight that uses less energy, is quieter, lower cost, [and has] a much smaller carbon footprint than any other form of transportation." Since Pathfinder 1 needs no airport or runway to land, its initial mission will be delivering humanitarian aid and disaster relief to regions of the world inaccessible to conventional aircraft.

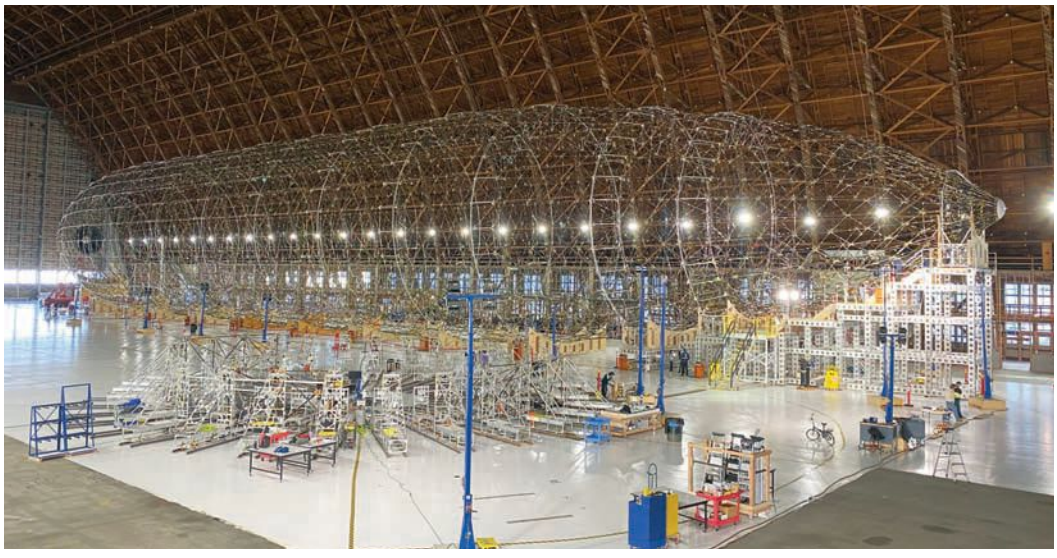
Made of girders digitally printed from carbon fiber, Pathfinder 1 was assembled with unprecedented speed using a patented jig ("the roller coaster") that allowed the airframe to be rotated on its horizontal axis during construction on the floor. All previous zeppelins have been built by suspending components from the ceiling and then joining them using ladders and scaffolding — a slow, labor-intensive and more dangerous process.

Pathfinder 1 will lift 28 tons, cruise at 60 knots and have a range in excess of 2,500 nautical miles. For propulsion, Weston said in September that LTA was exploring a variety of options, including **solar-electric, hybrid and hydrogen fuel cells**, any combination of which would produce "very small to zero carbon emissions."

The company plans to manufacture larger craft. In March, it negotiated a deal to buy the **Akron (Ohio) Airdock** — 360 meters long, 99 meters wide, 64 meters tall — in which the U.S. Navy built its airplane-carrying airships Akron and Macon of the 1930s.

United Kingdom-based **Hybrid Air Vehicles** in May unveiled a **100-seat cabin configuration for its Airlander 10** that HAV said was suited to such intercity trips as Liverpool to Belfast or Seattle to Vancouver. Assuming hybrid-electric propulsion, the craft would operate with **90% fewer carbon emissions** than conventional aircraft in the same role. In June, HAV announced that **Collins Aerospace** of North Carolina had begun fabrication of a **500-kilowatt electric motor** and said in July that **ILC Dover** of Delaware would fabricate the hull. The company and the **U.S. Navy's Naval Postgraduate School** in August signed a cooperative research and development agreement to explore what impact hybrid aircraft might have on Navy and Marine Corps logistics capability. Also this year, investment firm Global Emerging Markets made a $200 million commitment to help HAV eventually go public.

AIAA and Explorers' Club member Don Hartsell's quixotic dream of an around-the-world airship race drew closer to reality when he secured the support of French dirigible-maker **Flying Whales** and of **Air Liquide**, among the largest suppliers of helium. His **World Sky Race** involving seven Airship Industries Skyships and other dirigibles, would start from London in September 2023 and end in Paris in May 2024. ★



▶ This photo of the completed internal airframe of the Pathfinder 1 airship was released in October by LTA Research, owned by Google billionaire Sergey Brin. The vehicle, in construction at Moffett Field in California, will measure 123 meters by 20 meters.

LTA Research

◀ UPS announced in April that it was buying up to 10 Beta Technologies Alia-250c electric vertical takeoff and landing aircraft, shown in an artist's rendering.

Beta Technologies

Flying on Mars and developing V/STOL and eVTOL programs continue apace

BY ERASMO PIÑERO JR.

The **V/STOL Aircraft Systems Technical Committee** is working to advance research on vertical or short takeoff and landing aircraft.

NASA's autonomous **Ingenuity Mars Helicopter** became the first aircraft to fly on another planet in April after landing on Mars in February with the Perseverance rover as part of the Jet Propulsion Laboratory's Mars 2020 Mission. Until then, only spacecraft powered by rockets have flown on other planets and celestial bodies. This time, the flying was with electrical motors and aerodynamic lift, or rotors, opening a new, but long-sought, era of planetary exploration.

The number of **F-35B Lightning II** aircraft in operation expanded as the Italian Navy began flying its fleet of F-35Bs from the aircraft carrier Cavour. An F-35B landed aboard the carrier in July; eventually, 18 to 20 F-35Bs will operate from the Italian flagship. The Italian Navy joined the British and U.S. navies as oceangoing operators of the F-35B.

In May, a **U.S. Marine Corps F-35B detachment operated from the British aircraft carrier HMS Queen Elizabeth** for the first time. The Marines were to spend up to seven months on the Queen Elizabeth, demonstrating the aircraft's operational commonality with F-35Bs of other NATO nations. The squadron mix consisted of 10 Marine Corps F-35Bs and eight F-35Bs from the Royal Air Force.

The **Bell Boeing V-22 Osprey** began operating with both the Japanese Self-Defense Force (the first non-U.S. operator) and the U.S. Navy's carrier onboard delivery aircraft fleet. CMV-22Bs operate regularly from aircraft carriers performing resupply missions on open-ocean missions. The CVM-22B replaced the Grumman C-2A Greyhound. One highly visible change on the CVM-22B airframe is the inclusion of higher-capacity sponson fuel tanks to extend the baseline range of the aircraft.

The U.S. Army Future Vertical Lift program made progress. The **Bell V-280 Valor tilt-rotor demonstrator** completed a three-year, 200-plus-hours flight test program in April at the Bell Flight Research Center in Texas. The **Sikorsky-Boeing SB-1 Defiant compound helicopter and S-97 Raider proof-of-concept test aircraft** completed demonstrations to outgoing U.S. Army Secretary Ryan McCarthy in February. Operating from Sikorsky's test facilities in Florida, additional demonstrations included an SB-1 sling load test in July and other high-speed flight milestones. Lessons learned from these demonstrators are being applied to Raider X and Defiant X, which are Sikorsky offerings for the U.S. Army's Future Vertical Lift competition.

Throughout this year, investors funded the expanding electric vertical takeoff and landing aircraft industry. At least **16 eVTOL aircraft have entered preliminary or detailed design phases**, with at least nine projects aimed at carrying passengers and cargo. Two eVTOL aircraft made strides on their flight test programs. **Joby Aviation's S4 Generation 2.0 multitilt propeller design** performed a series of full transitions to forward flight early this year, culminating in a long-duration flight (77 minutes) in late July. The S4 has six tilting electric-powered propellers and is designed to cruise at an airspeed of 322 kph. **Beta Technologies Alia-250**'s first eVTOL prototype performed an up-and-away piloted test flight in January, and a second prototype is under construction at the Beta Tech facilities in Vermont. In April, UPS announced that it will buy up to 10 Alia-250c aircraft with an option to buy 150 more to expand its delivery network. Both the S4 and the Alia-250 are scheduled to enter operations in 2024. ★

Contributor: *Paul Park*

Low-Earth orbit megaconstellations reach record capacity

BY TOM BUTASH

The **Communications Systems Technical Committee** is working to advance communications systems research and applications.

▲ The low-Earth orbit communications satellite megaconstellation in this illustration includes orbital satellite shells at multiple altitudes.

ESA Science Office

The year was the first in which the aggregate throughput capacity of all operational low-Earth orbit communications satellites eclipsed that of all geosynchronous Earth orbit communications satellites. Indeed, **SpaceX Starlink** and **OneWeb** alone were conservatively expected to have launched 1,016 and 316 LEO satellites by the end of the year, bringing their megaconstellation totals to 1,969 and 420 satellites, respectively, with a total gross aggregate capacity of more than 36 terabits per second. Even if this gross capacity were derated by 75% to reflect the percentage of Earth's surface covered by water or in remote regions and reduced another 66% to conservatively account for LEO satellites without access to an uncongested ground station or optical intersatellite link, the net aggregate throughput capacity of these LEO megaconstellations was to conservatively exceed 3 Tbps by year's end. This easily eclipses the 2.7 Tbps aggregate throughput capacity of the 400 GEO communications satellites in orbit.

The predominance of these megaconstellations is unlikely to end soon. The total numbers of LEO broadband satellites planned, approved and under development by SpaceX Starlink (42,000), OneWeb (7,088), **Amazon Kuiper** (3,236), **China GW** (12,992), **Telesat Lightspeed** (298) and **Inmarsat Orchestra** (150-175) for deployment before the end of this decade ensure this. As of mid-November, Starlink reportedly had 140,000 users across 20 countries.

The specter of LEO megaconstellations' impending growth, together with ceaseless expansion of terrestrial broadband networks' reach and capacity, undoubtedly explains, in part, **commercial GEO broadband satellite system operators' continued hesitance** to add fleet capacity. As of the end of September, only six GEO awards had been made: two to Airbus Defense and Space, two micro-GEOs (each with less than one-tenth the mass and capacity of full-sized GEOs) to San Francisco-based Astranis and two digital radio broadcast satellites to Colorado-based Maxar Technologies (one to replace a predecessor that failed in orbit in December 2020 before it could be placed in service). This downturn in GEO awards began in 2015, before which the average annual GEO award rate during 2012-2014 was 26 satellites.

Given the LEO communications satellite industry's dramatic manufacturing and launch efficiency advances in deploying unprecedented numbers of small satellites, and the inherent flexibility, responsiveness and resilience of LEO megaconstellations, the U.S. Department of Defense's **Space Development Agency issued an August request for proposals** for the development and production of 144 LEO communications satellites. These satellites will form Tranche 1 of a Defense Department "Transport Layer" — a space-based mesh network for reliably transmitting data from sensors to end users.

For 60 years, the communications satellite industry has developed and leveraged innovative technologies to repeatedly extend the reach, expand the capacity and increase the reliability of terrestrial communications networks. Aware of the 5.2 billion worldwide cellular subscribers at the start of 2021 and the 1.7 billion 4G and 5G mobile phones to be shipped this year, the industry again innovated to meet a clear need: the provision of service to these phones when they are beyond the reach of terrestrial networks.

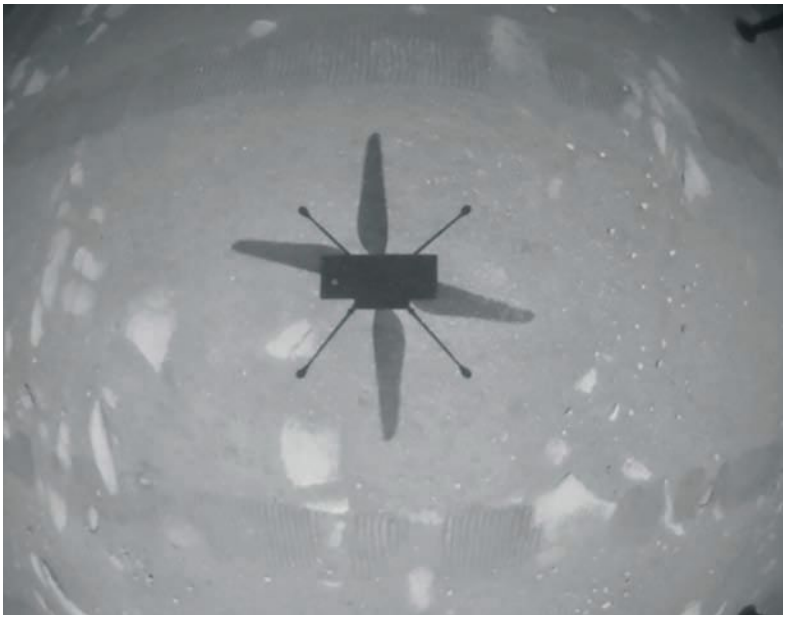
Virginia-based **Lynk** and Texas-based **AST SpaceMobile** are developing LEO communications satellite constellations to provide cellular service directly to standard (unmodified) mobile phones, thus expanding terrestrial cellular network coverage without the need for new phones or towers. Lynk deployed its production design satellite in July and planned to launch the first of its 4G text messaging LEO communications satellites in December to initiate commercial service in 2022. AST SpaceMobile is developing **communications satellites with 64-meters-squared deployable antennas** to provide 5G broadband cellular service directly from its LEO constellation. Its first demonstrator satellite was scheduled for launch in March 2022. ★

Contributor: *Roger Rusch*

A drone on Mars hints at space computing things to come

BY RICK KWAN

The **Computer Systems Technical Committee** works on advancing the application of computing to aerospace programs.



▲ The navigation camera on NASA's Ingenuity Mars Helicopter shot this photo of its shadow as it hovered over the Martian surface.

NASA

NASA's **Ingenuity Mars Helicopter** had made 15 flights on Mars through mid-November. Originally carried as a technology demonstrator, it produced scouting images for the Perseverance rover. Ingenuity employs a three-level avionics computing stack. A quad-core Qualcomm Snapdragon 801 running a version of Linux developed for the drone market handles the helicopter's high-level functions. A pair of TI Hercules TMS570 high-reliability processors that operate in lockstep handles real-time flight control. Sensor and actuator signals are fed through a MicroSemi ProASIC3L radiation-tolerant field-programmable gate array. Ingenuity can also power-cycle either of the Hercules processors in case of a detected fault.

NASA's High Performance Spaceflight Computing project made progress in software but suffered a setback in hardware. NASA's **Goddard Space Flight Center** in Maryland and **Jet Propulsion Laboratory** in California completed **HPSC Middleware Release 4** midyear. The middleware handles such functions as resource allocation, configuration, power and performance, and sharing hardware resources. NASA expected a prototype radiation-hard dual quad-core ARM Cortex-A53 chiplet in April. However, given the retirement of the intended 32-nanometer fabrication line, NASA is reformulating HPSC.

JPL is leading a design study that considers requirements from advanced mission concepts as well as earlier use cases. While the overall assessment continued to favor general purpose central processing units, a new direction involving artificial intelligence and machine learning emerged. JPL published a request for proposals in May asking vendors to submit detailed implementation plans but also allowing for proposals of low-risk features that show market adoption.

The primary radiation-hard processor in U.S.-based designs was the **BAE Systems RAD750**, based on the Power/PowerPC architecture. In Europe, it was the **Gaisler LEON3FT** (FT for fault tolerant), based on the SPARCv8 architecture. However, the IEEE Space Computing Conference in August showed that a lot of researchers were looking at **RISC-V, RAD5545 and LEON5**.

The fastest supercomputer in the world remained **Japan's Fugaku**, reaffirmed in June and November by Top500.org. In fact, its High Performance Linpack rating rose from 415.5 to 442 petaflops (million billion floating-point operations per second). This made it three times faster than the second-fastest machine, Oak Ridge National Laboratory's Summit in Tennessee, which was rated at 148.8 petaflops. Built by Fujitsu, Fugaku is based on the ARMv8.2-A architecture with Scalable Vector Extension. By contrast, Summit combines two architectures: IBM Power9 CPUs and Nvidia Volta graphics processing units. The largest aerospace computational fluid dynamics simulations take a few days on Summit.

A **global microchip shortage** delayed the manufacturing of a wide range of products and drove up prices. General Motors and Ford made deep cuts in manufacturing due to the shortage. Observing the impact on automotive, aerospace manufacturers began to look more closely at their supply chain vulnerabilities. Responding to the shortage, the leading chip manufacturer Taiwan Semiconductor Manufacturing Co. ramped up production by 30% between January and June over 2020 levels. It prioritized orders such as automotive. Following order cancellations in 2020 due to economic slowdown, several industries placed production orders simultaneously against limited fabrication capacity. However, chip fabrication and packaging normally take several months.

In June, **TSMC** began construction of a $12 billion fabrication facility in Arizona, but it won't start production until 2024. Intel is also building two new facilities in Arizona but will also use some TSMC facilities for CPU tiles that are later sewn together to create a chip package. AMD was expected to complete its acquisition of Xilinx, a leading manufacturer of FPGAs, before the end of the year. Intel acquired FPGA manufacturer Altera in 2015. Both Xilinx and Altera produce radiation-hard FPGAs used in aerospace. ★

Digital avionics guide accomplishments in aeronautics and astronautics

BY MARK DARNELL AND ERIK THEUNISSEN

The **Digital Avionics Technical Committee** advances the development and application of communications, navigation and surveillance systems used by military and commercial aircraft.

The U.S. Navy and **Boeing** demonstrated in June the first **air-to-air refueling** between a crewed vehicle and an autonomous tanker. Using a hose and drogue fuel-transfer system, an **MQ-25 T1 test vehicle** transferred the scheduled volume of fuel from its aerial refueling store to a Navy F/A-18 Super Hornet aircraft. The operation was the culmination of 25 preceding flight trials in which the test team evaluated the performance and stability of the system before the actual refueling. From autonomous guidance and navigation to embedded control of the fuel delivery system, digital avionics makes it possible for the MQ-25 to perform its primary aerial refueling mission. By replacing the Navy's F/A-18s in the tanker role, the MQ-25 will extend the range of a carrier wing. Handling trials aboard an aircraft carrier were scheduled for later in the year.

Digital electronics also made it possible for ground vehicles to perform complex missions in space this past year. In February, **NASA's Perseverance rover** landed in the Jezero Crater on Mars. To search for ancient signs of life, the car-sized rover is fitted with sensors and embedded systems that control a robotic arm for collecting rock samples and sealing the material in tubes. The tubes are scheduled for return to Earth in the 2031 time frame. Another NASA-developed instrument, the **SuperCam**, uses laser light to disintegrate rock samples and assess the composition of the resulting vapor. The scientific data and samples will help researchers learn about the environment for planning future red planet missions.

As part of NASA's **Commercial Crew Program** to demonstrate safe, reliable and cost-effective transportation to and from the International Space Station, four astronauts returned to Earth in May after performing the first of many planned science and research experiments on the ISS, including a study to understand the effect of microgravity on human health and diseases. Digital avionics guided **SpaceX's Crew Dragon spacecraft Resilience** back to Earth autonomously after it took the astronauts to the ISS in November 2020 for a six-month stay — the longest human space mission launched from the United States. It was the first use of a NASA-certified commercial spacecraft for human flight and another example of embedded system technology enabling new horizons in space.

To make digital avionics economically viable, consensus-based industry standards are needed to efficiently integrate the diverse systems that together implement a complex system. Sharing the airspace with new users such as drones requires avionics that enable a ground-based pilot to remain well clear of other traffic. In March, the **RTCA** released **Revision B of DO-365**. This latest edition of the performance-based standard enables the use of ground-based collision detect-and-avoid systems for autonomous and remotely piloted aircraft that have insufficient payload to carry the required equipment. In Europe, the **SESAR URClearED** project, short for **Single European Sky Air Traffic Management Research URClearED,** is addressing the requirements for a vehicle to remain well clear in airspace Classes D through G. To realize the maximum benefit of a universal standard, NATO Study Group SG-268 commenced validation of these standards with the goal of a multilateral agreement among the NATO member nations that operate military aircraft. ★

▶ The SpaceX Crew Dragon spacecraft Resilience prepared to undock from the International Space Station's Harmony module.

NASA

Human-machine teaming involved in current and future challenges on Earth and on Mars

BY ZARRIN CHUA AND JOHN-PAUL CLARKE

The **Human-Machine Teaming Technical Committee** fosters the development of methodologies and technologies that enable safe, trusted and effective integration of humans and complex machines in aerospace and related domains.

Developments in systems to enable human-machine teaming continued despite challenges posed by the pandemic. In January, Boeing agreed to pay $2.5 billion in a settlement with the U.S. Department of Justice over **Boeing's 737 MAX**, which began flying again in December 2020. The FAA cleared Boeing and other international aviation agencies to resume commercial flights after a two-year suspension. The FAA previously grounded the aircraft due to a design flaw involving the **Maneuvering Characteristics Augmentation System** that affected the positive control of the aircraft. More than 300 737 MAX aircraft are flying worldwide, providing better real-time situation awareness to the flight crew regarding the aircraft state, in addition to other system improvements.

In February, **NASA's Perseverance rover** landed on Mars and demonstrated the next generation of robotic teleoperation and supervisory control. Human rover drivers on Earth previously planned routes and major tasks on each Martian day, or sol. The communication between rover and drivers is slow due to an average communication delay of 20 minutes. The new onboard automatic navigation system enabled "Percy" to self-drive by mapping the local terrain, identifying hazards and planning a route, while the drivers focused on planning the overall path and mission objectives. This level of **rover autonomy** enables Perseverance to travel 120 meters an hour, as compared to the predecessor Curiosity rover's speed of 20 meters an hour. The drivers again used **3D goggles to visualize the terrain scans** that their robotic teammate provided, offering the drivers an immersive environment from another planet.

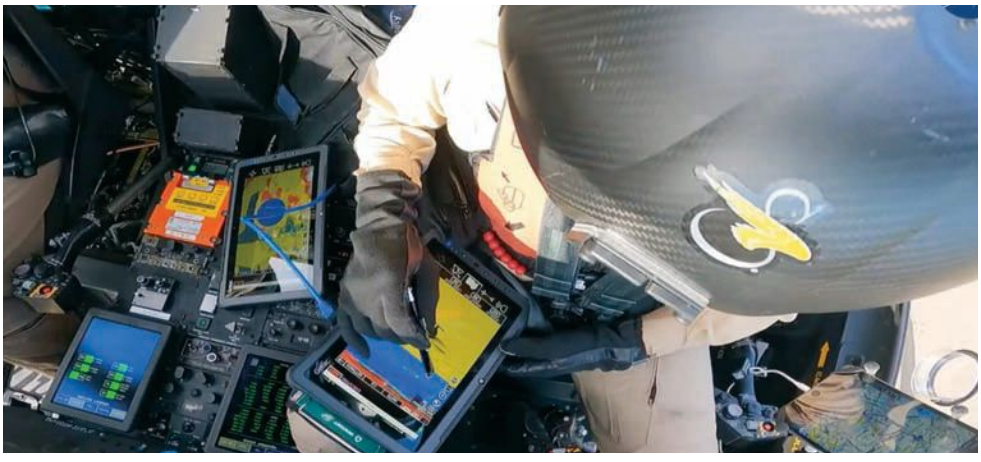
Sikorsky demonstrated its **Aircrew Labor In-Cockpit Automation System, or ALIAS** — developed under **DARPA** — on an **S-70 Black Hawk helicopter** in March. The onboard pilot conducted a supervised level of control using a tablet, commanding the aircraft to perform an autonomous takeoff and landing as well as two simulated obstacle-avoidance scenarios. The program aims to support **optionally piloted levels of control**, ranging from two, one or zero pilots controlling the aircraft.

In April, the **Institute for Defense Analyses**, a nonprofit based in Virginia, published "Characterizing Human-Machine Teaming Metrics for Test and Evaluation," a framework for **measuring the effectiveness of human-machine teams** and a timely contribution given the increase of such demonstrations. The research focused on a team's general effectiveness rather than performance in tested scenarios. This framework also relies on research on team dynamics to help determine possible failures, whether due to intrinsic shortcomings, poor interactions or potential vulnerabilities.

The **U.S. Air Force** conducted two flight tests of the **Skyborg autonomy core system** in June. The Skyborg ACS flew on two unmanned aerial vehicles this year — **UTAP-22 Mako** in May and **MQ-20 Avenger** in June; a third, **Boeing Airpower Teaming System**, is planned for 2022. During these tests, ground control station operators monitored aircraft behavior to validate foundational capabilities such as respecting geo-fencing, performance within aircraft flight envelopes and coordinated maneuvers. Future tests will feature human-machine aerial teams.

In September, California-based **General Atomics Aeronautical Systems** and Massachusetts-based **Autonodyne** demonstrated **aerial control of an MQ-20 Avenger combat drone** from the cockpit of a modified King Air 200. A ruggedized tactical control tablet, integrated with Autonodyne's RCU-1000 Advanced Human Machine Interface, provided real-time situational awareness combined with complex behavior tasking.

DARPA's Air Combat Evolution program collected data on **human pilot trust in artificial intelligence algorithms**, measuring a suite of physiological responses, in preparation for ACE's next major demonstration, which is to feature dogfights involving actual subscale aircraft with AI pilots. ACE is aimed at enabling humans to focus on battle management decision-making while the AI pilot manages combat maneuvers. ★



▼ An onboard pilot with a tablet told an S-70 Black Hawk helicopter to perform an autonomous takeoff and landing in a demonstration this year of Sikorsky's Aircrew Labor In-Cockpit Automation System, or ALIAS.

YouTube/Lockheed Martin

Demonstrating and testing artificial intelligence applications in aerospace

BY KERIANNE HOBBS

The **Intelligent Systems Technical Committee** works to advance the application of computational problem-solving technologies and methods to aerospace systems.

The aerospace community saw many novel applications of artificial intelligence this year, including demonstrations of artificial intelligent flight control, multiagent planetary exploration vehicles, autonomous navigation on Mars, aids to crewed missions and research into novel detect-and-avoid systems.

In March, the **U.S. Air Force Research Laboratory's Autonomy Capability Team 3** and the **U.S. Air Force Test Pilot School** flew the first deep reinforcement learning flight control agent on a jet aircraft as part of the **Autonomous Air Combat Operations Program**. The flight testing, which Test Pilot School students named "Have Cylon," included a series of two-hour flights using either a single ship (Calspan LJ-25 Learjet) or two ships (Calspan LJ-25 Learjet and an F-16 Fighting Falcon). The artificial intelligence agents were trained using reinforcement learning in simulation and then transferred to the Learjet. Researchers designed the flight tasks to identify simulation-to-real-transfer challenges associated with a zero-shot transfer approach; the tasks culminated in a series of flight maneuvers.

Also in March, the **University of Cincinnati's Aerospace Engineering and Engineering Mechanics Department** and **NASA's Ames Research Center** in California developed a novel small unmanned aerial systems traffic management system that can **autonomously identify, track and manage large-scale sUAS operations**. This research primarily focused on developing an intelligent conflict detection and resolution system that uses high-level heuristics and a low-level fuzzy controller to keep sUAS separated, known as the **Tactical Intelligent Detect and Avoid System for Drones, or TIDAS-4D**. Using only current-state information, the TIDAS-4D system can resolve potential conflicts with and without knowledge of intruder intent. When compared to other state-of-the-art systems, such as ACAS-Xu, the performance of TIDAS-4D was similarly effective at preventing near-midair collisions.

In April, the **Autonomous Pop-Up Flat Folding Explorer Robot team** demonstrated multiple autonomous **PUFFERs** cooperatively exploring an environment without a map. A series of tests focused on the new multiagent technologies: a mapping database for storing and synchronizing cost maps that supports updating cost maps in response to new localization estimates; pose graph optimization using ultrawideband ranging radios when visual loop closures are not present; and a modular exploration pipeline that allows multiple rovers to explore an environment while satisfying recurrent connectivity constraints. The team completed testing with three PUFFER v4.0s in the mini-Mars Yard at NASA's Jet Propulsion Laboratory in California.

Since June, novel AI software developed at JPL enabled the **Perseverance rover to drive itself autonomously on Mars**, over much greater distances than can be achieved with humans alone. This Enhanced Autonomous Navigation software creates a 3D map of the environment using the navigation cameras' stereo images and generates a path optimized to reach the goal in minimal time while avoiding hazards. ENav enables Perseverance to drive itself beyond the terrain human operators on Earth can see and thus make much faster progress toward the mission's scientific destinations.

In October, **Campaign 6 at the Human Exploration Research Analog** facility began at NASA's Johnson Space Center in Houston. For 45 days, a crew of four subjects were to live in this confined space while conducting scientific experiments, with a focus on increased crew autonomy. Experiments included a technology demonstration for an AI assistant called Daphne, which assists astronauts with diagnosis and resolution of spacecraft anomalies during long-duration exploration missions, when long communication delays preclude timely communications from mission control. This experiment will help NASA develop standards and guidelines for development of similar AI assistants for space exploration. ★

Contributors: *Brandon Cook, Jean-Pierre de la Croix, Daniel Selva and Olivier Toupet*

▼ In October, volunteers began a six-week stay in NASA's Human Exploration Research Analog structure at the Johnson Space Center in Houston to simulate humans' capacity to adapt to a trip to deep space. An artificial intelligence assistant called Daphne is part of the trial. NASA

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COLLINS AEROSPACE | PRATT & WHITNEY | RAYTHEON INTELLIGENCE & SPACE | RAYTHEON MISSILES & DEFENSE

▲ The German Aerospace Center, DLR, this year flew its superARTIS uncrewed research helicopter with a cargo-dropping system for relief supplies.

German Aerospace Center

Sending drones to disasters; making history on Mars

BY CHRISTOPH TORENS

The **Software Systems Technical Committee** focuses on software engineering issues for complex and critical systems, including requirements, design, code, test, evaluation, operation and maintenance.

The German Aerospace Center, DLR, started the Drones4Good project in January with the United Nations, World Food Program, German Federal Agency for Technical Relief, International Search and Rescue Germany and the Netherlands-based Wings for Aid. The project will fly drones with artificial intelligence to deliver relief supplies in disasters. The goal is to process images in real time on board the drones to assess damage to buildings, scout supply routes and detect people on the ground. The drone could automatically drop supply packages if it detects a clear area and safe drop site.

In March, software for the **F-35 Joint Strike Fighter** program was delayed again. A report assessed that the goal for finalizing the modernization is not achievable. In its original development, the software was repeatedly delayed due to the unprecedented complexity. The current upgrade program is called **Continuous Capability Development and Delivery**, or C2D2, and began in 2019. The new delay does not show a positive trend, although C2D2 placed greater emphasis on agile software development to enable quicker releases.

The **European Organization for Civil Aviation Equipment, or EuroCAE**, published in April its first document regarding artificial intelligence. The statement of concerns covers challenges and a gap analysis regarding the use of AI in the safety critical aviation domain. Potential next steps and use cases are detailed. In the same month, the **European Union Aviation Safety Agency, EASA,** published the first **regulatory guidance for machine learning applications**. This document details objectives that must be fulfilled to ensure the safety of AI applications in aviation systems.

Also in April, **NASA's Ingenuity Mars Helicopter** needed a software update before lifting off for its first flight on Mars. Ingenuity is a drone with a mass of 1.8 kilograms. The **autonomous control software detected a problem** during the spin-up test of its rotors. NASA issued a software fix that resolved a command sequence issue, and Ingenuity performed the first powered flight in the atmosphere of another planet.

EASA published a follow-up in May to its concept of **design assurance for neural networks** report. After the first report in 2020, the second version provided details on learning assurance, expandability and safety risk mitigation for AI applications. Additional standards organizations and regulatory bodies are working on similar guidance materials. These efforts indicate that regulatory bodies will eventually accept AI and autonomous software in general, even for safety-critical applications.

The **International Space Station** inadvertently **moved off course** in July after the **new science module Nauka** docked to it. The flight director of the Russian space agency, Vladimir Solovyov, said, "Due to a short-term software failure, a direct command was mistakenly implemented to turn on the module's engines for withdrawal, which led to some modification of the orientation of the complex as a whole." The software problem pushed the space station out of position for 47 minutes before a NASA ground crew fixed the problem.

Microsoft announced in August that it will incorporate the **air taxi VoloCity**, Germany-based Volocopter's vision for urban air mobility, into the **Microsoft Flight Simulator**. The new capability will enable gamers and enthusiasts to experience personal air traffic and the future of urban air mobility, likely leading to a host of new ideas for developing and expanding the UAM sector. ★

Contributors: *Stephen Blanchette and Chris Thames*

Photovoltaic-powered exploration punctuates the year

BY GIANG LAM

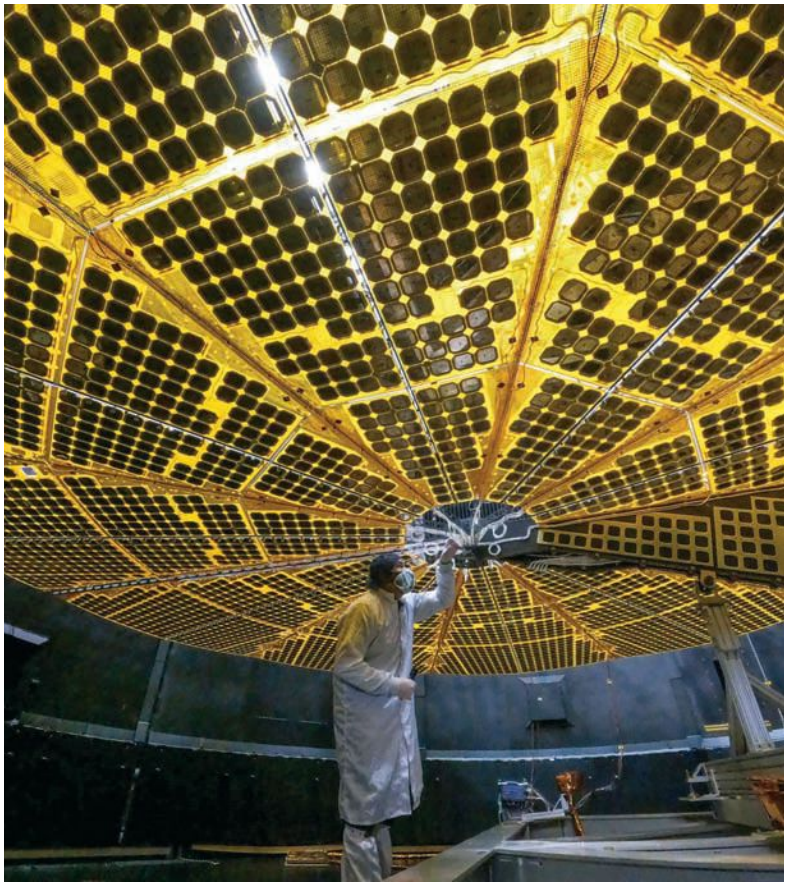
The **Aerospace Power Systems Technical Committee** focuses on the analysis, design, test or application of electric power systems or elements of electric power systems for aerospace use.

Astronauts in June installed two **Roll-Out Solar Arrays** — of six planned new solar arrays — on the **International Space Station**. The ROSAs are solar cells on flexible carriers for stowage and will supplement the ISS' aging flexible solar arrays in operation since 2000. The ROSA arrays, which are smaller and use higher-efficiency triple-junction solar cells than the original arrays' silicon solar cells, are positioned in front of the original arrays. When fully deployed, each ROSA will stretch 19 meters long by 6 meters wide. Once completed, the electrical power capability on the ISS will be boosted by 20% to 30% from its current 240 kilowatts in direct sunlight. Deployed power output of the ROSA arrays has been per analytical predict on-orbit, accounting for environmental conditions.

NASA's Lucy spacecraft was launched from Cape Canaveral in Florida in October to begin its mission of studying the Trojan asteroids as they trail and lead in the orbit of Jupiter. Lucy's first asteroid stop will be in 2025, followed by flybys of an additional seven Trojan asteroids between 2027 and 2033. The spacecraft is powered by two **flexible solar arrays** that stow about 4 inches thick and each solar array was supposed to unfurl into a 24-feet diameter circular wing. The solar arrays were commanded to deploy about an hour after launch, but NASA received confirmation that one of the solar arrays was fully deployed and latched, while the **second array was only partially unfurled**. Both solar arrays will supply about 500 watts at the approximate radial distance of Jupiter from the sun. The solar arrays are designed to provide varying voltages at solar distances from less than 1 astronomical unit to 5 AU on its trajectory from launch to the Trojan asteroids.

In August, NASA installed a ROSA and a **Didymos Reconnaissance and Asteroid Camera for Optical** navigation, or DRACO, onto its **Double Asteroid Redirection Test spacecraft** as part of the final assembly prior to launch scheduled for November. DART's mission is to demonstrate the kinetic impactor technique to change the motion of an asteroid, Didymos, by hitting its moonlet, Dimorphos, in space. A small portion of the DART solar arrays is configured to demonstrate Transformational Solar Array technology, which uses reflective concentrators to increase the solar intensity by a factor of three onto high-efficiency solar cells.

NASA set the launch date for the **James Webb Space Telescope** for no earlier than Dec. 22 on an Ariane 5 launch vehicle out of Kourou, French Guiana. After almost two decades of development and construction, the JWST arrived via ship in French Guiana in October. The telescope will use longer infrared wavelengths to look much closer to the beginning of time and hunt for the unobserved formation of the first galaxies. The JWST will operate near the Earth-Sun L2 Lagrange point, approximately 1.5 million kilometers beyond Earth's orbit, where the telescope will stay in line with the Earth as it moves around the sun. The orbital position will allow the satellite's large sunshield to protect the telescope from the sun-Earth's light and heat. JWST's electrical power systems consists of rigid solar panels producing 2 kilowatts of nominal power, rechargeable lithium-ion batteries, a solar array regulator with redundant buck converters for peak power tracking, a power control unit and a telemetry acquisition unit. ★



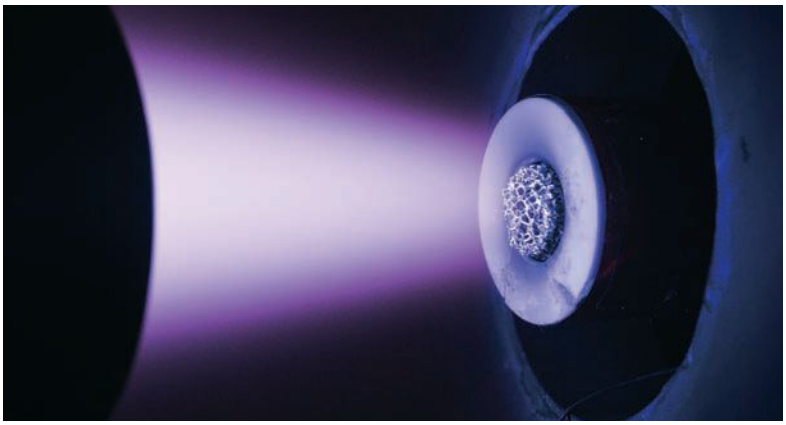
▼ Researchers test the solar arrays for the Lucy spacecraft in preparation for a thermal vacuum test ahead of its launch in October.

NASA

Electric propulsion: An expanding capability and community

BY JOHN W. DANKANICH

The **Electric Propulsion Technical Committee** works to advance research, development and application of electric propulsion for satellites and spacecraft.



▲ The Wirz Research Group at the University of California, Los Angeles, this year discovered plasma-infused materials exhibiting significant reduction in material erosion.

Wirz Research Group

The electric propulsion community had a landmark year with new discoveries, flight systems deployed at historic levels and multiple first flights of novel technologies.

The **Wirz Research Group** at the **University of California, Los Angeles**, discovered plasma-infused materials that may enable higher energy density systems. NASA also initiated the **Joint Advanced Propulsion Institute**, or JANUS, with team members from **Georgia Tech, the University of Michigan, UCLA, the University of Illinois, Colorado State University, Pennsylvania State University, the University of Colorado, Stanford University** and **Western Michigan University**, to address challenges with implementation and testing of high-power devices.

Massachusetts-based **Busek** completed the **BET-MAX electrospray system design** with two flight units awaiting qualification. **Applied Ion Systems** of New York demonstrated a 26-watt Hall system using sublimated adamantane. North Carolina-based **Froberg Aerospace** and the **University of Illinois** demonstrated a chemical-electric multimode thruster. While **NASA's Marshall Space Flight Center** in Alabama, working with part Canada-based **Espace Inc., Georgia Tech, the Massachusetts Institute of Technology and Alabama-based Plasma Processes**, demonstrated an integrated multimode system with both a refillable electrospray system and combustion engine using advanced spacecraft energetic nontoxic propellant.

The **European Space Agency** initiated the **Mars Sample Return Earth Return Orbiter**, building on the BepiColombo mission with a 35-kilowatt system of four **Arianegroup RIT-2X radiofrequency ion thrusters**. BepiColombo accumulated 5,000 hours of thruster operation partway through its journey to Mercury.

NASA **Jet Propulsion Laboratory's lanthanum hexaboride hollow cathodes** demonstrated 500 amperes discharge currents sufficient to support 200kW Hall thrusters, while JPL's Ascendant Sub-kW Transcelestial Electric Propulsion System thruster demonstrated 1.3 meganewton-seconds total impulse, processing 82 kilograms of xenon over 6,300 hours of operation, targeting 100 kg Xe throughput this year.

The assembling and testing of **NASA's Psyche spacecraft** with the SPT-140-based subsystem began in March. **NASA's Power and Propulsion Element**, using **Aerojet Rocketdyne's 13kW** and **Busek's 6kW Hall thrusters**, completed the spacecraft preliminary design review. The engineering hardware completed qualification-level testing on a path to propel the PPE, built by Colorado-based **Maxar Technologies**, to lunar orbit, critical toward building NASA's lunar Gateway.

Busek completed a 3,500-hour test of its iodine BIT-3 thruster in January; two units are ready for launch aboard NASA's **Space Launch System**.

NASA and the **U.S. Space Force** worked to modify NASA's Evolutionary Xenon Thruster Commercial technology to double power and increase thrust density by 40%. The current system, built by **Aerojet Rocketdyne**, and its power processing unit, built by **ZIN Technologies**, were joined to **NASA's Double Asteroid Redirection Test spacecraft** at the **Johns Hopkins University Applied Physics Laboratory** and shipped to Vandenberg Space Force Base in California for a scheduled November launch.

T4i of Italy saw its **REGULUS** iodine thruster launched on the UNISAT-7 cubesat dispenser in March, following France-based **ThrustMe**'s demonstration of an **iodine electric propulsion system** in space in 2020.

As of August, the community had doubled all operating electric propulsion systems in a single year. **Northrop Grumman's Mission Extension Vehicle-2** reached geosynchronous orbit propelled by **Aerojet Rocketdyne's 3kW XR-5 thrusters** and docked with an Intelsat spacecraft for life extension. By November, the **SpaceX Starlink constellation** had deployed more electric propulsion spacecraft than all previous electric propulsion flights combined, for a total of about 1,800 satellites on orbit. Finally, the June launch of the SpaceX Falcon 9 **Transporter-2** mission included electric propulsion systems from **Accion, Apollo Fusion, Enpulsion, Exotrail and Phase Four**. These included, respectively, micro-electrospray propulsion, a magnetic shielded Hall thruster, a field emission thruster, a cubesat Hall thruster and the first electrodeless commercial radiofrequency thruster operated in space. ★

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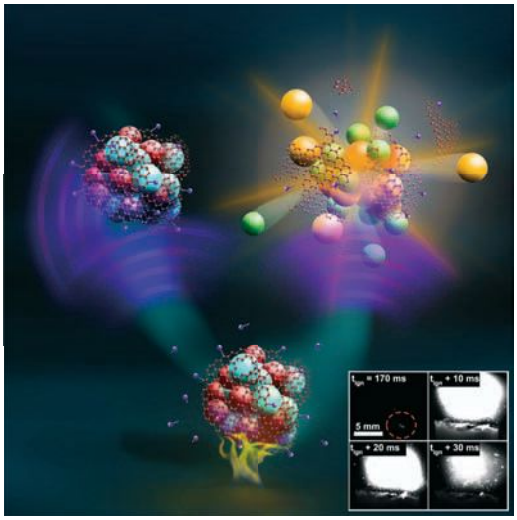
Smart thermites enter the scene; progress seen on thermography for ballistics and electric propulsion for nanosatellites

BY JOHN F. ZEVENBERGEN

The **Energetic Components and Systems Technical Committee** provides a forum for the dissemination of information about propellant and explosive-based systems for applications ranging from aircraft to space vehicles.



Microwave igniting solid rocket fuel: This artist's rendering and the accompanying high-speed imaging sequence capture the process of thermally switching the microwave ignitability of graphene oxide (GO)/thermites by striking the bundle with microwaves. The drawing at top left shows a graphene oxide/thermite unignitable by microwaves represented by the curved purple lines striking and reflecting off the bundle — the blue (fuel, aluminum particles) and red (oxidizer, iron oxide) balls. At bottom center, heating of the thermite turns the graphene oxide in reduced graphene oxide (rGO) represented by the red cage structure. The yellow represents absorption of heat energy, and the small purple dots represent the functional groups on graphene oxide that are knocked off the carbon cage structure by adding heat to convert graphene oxide to reduced graphene oxide. At top right, the thermite now readily absorbs the microwave radiation and the thermite is readily ignited.

Adapted from "Smart Electromagnetic Thermites: GO/rGO Nanoscale Thermite Composites with Thermally Switchable Microwave Ignitability," in the Aug. 25 issue of ACS Applied Materials & Interfaces, with permission of the American Chemical Society

The **University of Iowa** and **Iowa State University** this year began planning for experiments at the **Argonne National Laboratory Advanced Photon Source** to investigate the ability to dynamically control, via microwave radiation, the porosity within an explosive. The team plans to observe this process using in-situ high-speed synchrotron X-ray imaging. This research will be a follow up to work by Iowa State University featured on the cover of the Aug. 25 issue of ACS Applied Materials & Interfaces describing the ability to make "smart thermites" with a switchable electromagnetic function, opening the door to new ignition possibilities for explosives and solid rocket propellants. The initial research and forthcoming experiments, both funded by the **U.S. Air Force Office of Scientific Research**, demonstrate how the addition of graphene oxide to a thermite can give the thermite on-demand controllable "off-on" microwave ignitability. Until this research, ignition was thought to be only possible on a surface of an energetic material. Embedding the reduced graphene oxide thermites into such a material and penetrating this material with microwave energy could allow new ignition modalities or dynamic control of porosity/damage formation in explosives, enabling on-command control of explosive sensitivity. The ability to thermally "switch" the microwave ignitability of the formulation from unignitable to ignitable is game-changing and could enable selection of one of many ignition sites, and hence enable selection of one of multiple possible energy output modes.

Researchers at **Texas Tech University** this year made advances in thermal imaging technology to **thermally map a ballistic impact event**. The researchers applied filters and software to turn a high-speed visual camera into a thermography system. The design of the camera's sensor was completed in April. The camera's optics can capture the spatial distribution of temperature with millimeter spatial and microsecond temporal resolution. The high-resolution images show the plasma generated from the kinetic energy produced when a projectile impacts a steel plate at 1,200 meters per second by recording the event with a frame speed of 0.03 milliseconds. Subsequent images show temperatures of the fragmenting debris field as it disperses and continues to react through the chamber. The highest temperatures are localized toward the leading edge of the flame spreading. High-speed thermography will advance the science of ballistics by providing the temperature information needed to enable design of new projectile materials that can be exploited for their thermal rather than mechanical properties.

For the **Netherlands Organization for Applied Scientific Research**, TNO, the year was one of progress for a nanosatellite propulsion system that promises to **drastically increase the maneuverability of nanosatellites** while occupying only a fraction of the available volume. In February, TNO received funding for a proof of principle experiment of this **Liquid Metal Pulsed Plasma Thruster**, or LiMe-PPT. The concept adapts the principle of an exploding bridge wire, a type of detonator, into what TNO calls a **Liquid Metal Regenerative Bridge**. Inside a nanosatellite, this microscopic bridge reforms after ignition to deliver near continuous thrust. In June, TNO completed the first of these regenerative bridges, and by August bridges were generated having the correct electrical characteristics required for test firings. Test firings of the conceptual LiMe-PPT started in September. The propulsion system has the potential to deliver a delta-V to a nanosatellite of several kilometers per second. This is orders of magnitudes greater than most micro-propulsion systems currently on the market, and almost twice as high as the current state of the art in micro propulsion technology. The LiMe-PPT is characterized by a high delta V (change in velocity), low power consumption, low complexity and the use of a high density metal, inert and non-pressurized propellant. ★

Contributors: *Stuart Barkley, Sem de Maag, Alfons Mayer, Michelle Pantoya and Travis Sippel*

▲ Rolls-Royce tested a 100% sustainable aviation fuel on the Pearl 700 at a test stand in Dahlewitz, Germany. SAFs are "drop-in" replacements for petroleum-based fuels that are compatible with existing fueling infrastructure and made from sustainable sources such as cooking and vegetable oils, fats or municipal wastes. The test represented the first petroleum-free-fuel test on the Rolls-Royce business jet engine.

Rolls-Royce

Gas turbine industry commits to sustainable aviation fuel research

BY MICHAEL G. LIST

The **Gas Turbine Engines Technical Committee** works to advance the science and technology of aircraft gas turbine engines and engine components.

Demonstration of sustainable aviation fuel in several flight and ground tests represented a major development in the gas turbine engine community. SAFs comprise fuels from a variety of sources, such as cooking or plant oils, with characteristics suitable for use with jet fuels and consistent with existing air transportation infrastructure. Use of SAFs can also enable an up to 80% reduction in carbon footprint over the lifecycle of the fuels relative to petroleum-based fuels, driving a large global investment. Current policies allow up to a 50-50 blending of an SAF with existing jet fuels. Flight tests with SAFs require material compatibility, endurance, safety and performance evaluations to ensure all components work with the alternate fuels.

The United Kingdom's **Rolls-Royce** announced in February that it tested a **100% SAF with a Pearl 700 business jet engine** in its Dahlewitz, Germany, facility. The Pearl 700 powers the Gulfstream G700 aircraft. The test followed a late 2020 test of the Trent 1000 engine with a 100% SAF. **Airbus**, headquartered in the Netherlands, flight tested an **A350 fueled by a 100% SAF** in March in Toulouse, France, as part of the collaborative Emission and Climate Impact of Alternative Fuels project. Ground and flight testing on the A350's Trent XWB engine continued throughout the year to characterize emissions. Williams International of Michigan also tested the FJ44-4 engine using a 100% SAF in a 3.5-hour flight over Michigan. The FJ44 engines power a variety of business aviation aircraft.

Safran Helicopter Engines of France announced that an Airbus H145 rescue helicopter was flown with a 40% blend of biofuel in Munich in June. The helicopter used Safran Arriel 2E engines. Safran also announced in July that researchers ran an Arrano helicopter engine with a 38% SAF blend and that they ran a Makila 2 on a 100% cooking oil SAF in September. The flight tests represented an increasing application of SAF usage in Safran's French facilities over the course of the year and a focus of the helicopter engine industry on SAF adoption.

In September, **GE Aviation**, based in Ohio, announced a new $55 million, five-year partnership under **FAA's Continuous Lower Energy, Emissions and Noise program** that will include research into standards for 100% SAFs. Additionally, U.S. President Joe Biden signed executive actions planned to increase SAF production and reduce emissions 20% by 2030. Coupled with previous tests by GE Aviation and Connecticut-based Pratt & Whitney, the past year's tests, research investments and policy announcements represent substantial investment in SAFs from the global engine supplier community and substantial work that regulatory bodies may use to standardize SAFs and reduce aviation emissions in both business jet and large civil transport applications.

In July, GE Aviation celebrated shipment of the 100,000th ceramic matrix composite turbine shroud and the 100,000th additively manufactured fuel nozzle. CMC components consist of ceramic fibers oriented in a ceramic matrix and are lighter and enable temperatures that are hundreds of degrees higher than competing metal alloys, resulting in increased efficiency and reduced emissions. GE has used additive manufacturing of fuel nozzles to reduce part counts and machine labor for production of the complex part. Ohio-based **CFM International's LEAP engine** employs both technologies. Also in July, **Pratt & Whitney** opened a facility in Carlsbad, California, for development of CMC components, joining Rolls-Royce's nearby facility in Cypress, California. ★

Hypersonic flight systems: From research and testing to business analysis

BY KHALED A. SALLAM

The **High-Speed Air-Breathing Propulsion Technical Committee** works to advance the science and technology of systems that enable supersonic and hypersonic air vehicle propulsion.

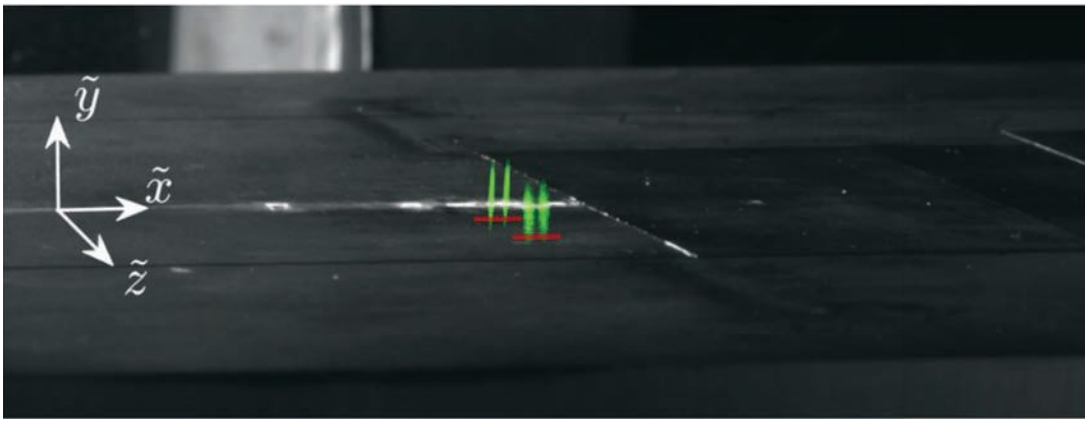
In September, **DARPA**,working with the U.S. Air Force, completed a free flight test of its Hypersonic Air-breathing Weapon Concept. **Raytheon Technologies** built the missile, which is powered by a **Northrop Grumman supersonic combustion ramjet**, or scramjet, engine. Test goals included vehicle integration and release sequence, safe separation from the launch aircraft, booster ignition and boost, booster separation and engine ignition, and cruise. Researchers met all primary test objectives.

The **Hypersonic Technology Project**, part of NASA's Aeronautics Research Mission Directorate Advanced Air Vehicles Program, conducted fundamental research on dual-use technologies, analytical tools, test techniques and capabilities to enable routine, reusable hypersonic flight for point-to-point travel and space access associated with commercial and U.S. Department of Defense hypersonic missions. NASA HTP funded two studies that were completed in April by teams led by United Kingdom-based Deloitte and Virginia-based Science Applications International Corp. These studies indicated that there are **viable markets for high-speed/hypersonic point-to-point vehicles** for certain long-distance city pairs.

As part of a collaborative effort with the **University of Maryland, the Office of Naval Research and Air Force Office of Scientific Research**, NASA HTP researchers developed new **flow-field measurement techniques** to provide data on fluid-structure interactions needed by designers of hypersonic flight systems. Researchers developed this new focused laser differential interferometry system to provide non-intrusive, high-speed (megahertz) density fluctuation measurements in hypersonic wind tunnel facilities. In addition to characterizing the tunnel freestream environment, researchers measured the near-surface boundary layer flow over the test model and validated it with high-speed schlieren imaging. The two separate laser lines with 16 points distributed evenly along each allowed for spatial evolution and velocity measurements of the fluctuations, providing data for comparison to surface-mounted pressure probes.

In August, **Space Engine Systems**, based in Canada, developed a scale-model engine and a three-degree-of-freedom thrust test cell to validate engine thrust, moments and flow characteristics across the full range of simulated flight speeds (Mach 1.8-5). Over seven months, SES also developed, prototyped and constructed its **uncrewed demonstration vehicle**, designated as Sexbomb. The goal, pending FAA approval, is to air-launch at 57,000 feet and Mach 1.8, from which it would accelerate over five minutes to Mach 5 and then glide to land. Current testing focuses on the vehicle body's cooling capabilities for Jet-A, cryogenic and other fuels, validating the technology for larger vehicle bodies and informing the design of the company's **commercial turboramjet-rocket demonstrator, Hello-1**.

The **Institute of Space Propulsion of the German Aerospace Center, DLR,** operates a hydrogen/oxygen air vitiator test bench in Lampoldshausen that is capable of simulating Mach 5.5 to Mach 8 high-speed flight combustion chamber inlet conditions. In September, DLR finished the composite material test campaign for scramjet engines, which started in 2020 and had some covid-19-related delay. The update of the bench's data acquisitioning and optical measurement technique systems is embedded into the European multinational project on multidisciplinary design and optimization and regulations for low-boom and environmentally sustainable supersonic aviation, or MORE&LESS. The project started this year as a successor of **Stratofly** and investigates pollutant generation, atmospheric impact and combustion processes for high-speed flight and supersonic transport with a focus on the application of bio-fuels for high-speed air-breathing propulsion. The results of this four-year project will be vital for a European legal framework on supersonic flight regulations that accompanies the U.S. efforts on this topic from FAA, NASA and others. ★



▼ A new focused laser differential interferometry technique allows for boundary layer profile measurements (currently 16 points) in hypersonic wind tunnel facilities. The green laser lines indicate location of the boundary layer profile measurements.

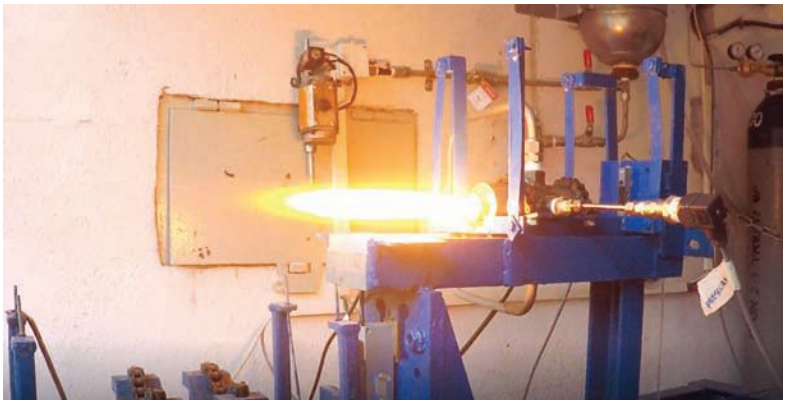
NASA

Contributors: *Jesse Kadosh, Mary Jo Long-Davis, Daniel Paxson and Friedolin Strauss*

A defining year for hybrid rocket innovation

BY JOSEPH MAJDALANI

The **Hybrid Rockets Technical Committee** studies techniques applied to the design and testing of rocket motors using hybrid rocket systems.



A demonstration of a water-augmented hybrid ducted rocket showed that adding a secondary stream of water can increase the thrust and specific impulse by as much as 70%. The static test was at the Fine Rocket Propulsion Center of the Technion-Israel Institute of Technology.

Alon Gany/Technion-Israel Institute of Technology

Researchers at **Utah State University's Experimental Rocketry and Propulsion Laboratory** developed a **low-erosion nozzle system** by leveraging the anisotropic thermal conduction properties of two synthetically derived materials. Between January and May, the researchers designed materials that give their nozzle throat, fabricated from pyrolytic graphite, a high-thermal conductivity radially and a low conductivity axially. The conduction axes for the surrounding boron nitride insulator were arranged perpendicularly to the throat, thus leading to effective radial insulation. As such, heat from the motor plume conducted away from the nozzle throat and into the high-heat-capacity boron-nitride insulating layer. Two dozen tests were performed with different motor prototypes. When compared to a monolithic-graphite nozzle under identical burn conditions, the low-erosion system exhibited a fivefold decrease in erosion rate. A third-generation nozzle system that replaces the boron-nitride insulator with carbon-reinforced-epoxy-composite was also developed and shown to produce erosion rates that are approximately 20% higher with better thermal stress resistance.

Researchers at the **Fine Rocket Propulsion Center of Technion-Israel Institute of Technology** published in January the results of a breakthrough in hybrid rocket conceptualization. They built a novel concept of a ducted, water-augmented, hybrid-gas generator rocket for high-speed underwater propulsion. This motor is augmented by a water stream that can enter the chamber through an inlet channel and then course its way to the mixing chamber. The underwater stream is naturally aspirated due to the motion of the vehicle. In this manner, incoming water can mix with the hot products and evaporate, thus generating a higher mass flow exhaust jet. In February, these researchers demonstrated through thermochemical calculations as well as static firing tests of an oxygen-polyester hybrid gas generator that the mere addition of water can increase the thrust and specific impulse by as much as 70%. Experiments conducted in June to August showed that by adding to the fuel 30% aluminum particles the thrust and specific impulse can be increased by over 100%.

Members of the **Stanford Propulsion and Space Exploration Group** continued to study multidimensional flame propagation effects on hybrid fuels using slab samples of poly (methyl methacrylate), acrylonitrile butadiene styrene and polycarbonate in gaseous oxygen. In July, they published their results for a small-scale poly (methyl methacrylate)/gaseous oxygen motor with a transparent combustion chamber; the latter was modified with a laser igniter to permit ignition at any location along the motor axis. The block of fuel, which also served as the combustion chamber, was augmented by a blackened fuel on the port surface to absorb the energy from the laser and to provide the spark needed for ignition. This modification allowed the characterization of flame ignition dynamics during the initial combustion transients. Preliminary studies validated this design and demonstrated linear flame propagation rates from ignition stations located at the halfway point of the fuel port.

Turkey announced its plan to land a hybrid rocket on the moon by 2023; its program started with the founding of **Delta V Space Technologies** and the first testing of a hybrid rocket in April. In May, **Vaya Space**, a Florida-based hybrid propulsion and orbital launch provider, announced its intention to create a Brazilian subsidiary. Also in May, **HyImpulse** conducted a test series of its paraffin-liquid oxygen hybrid engine at the Shetland Space Centre in Scotland. Meanwhile, the **German Aerospace Center** continued its hybrid engine developments with the Compass and Hy-FIVE-2/3 rocket series. Along similar lines, companies such as **Nammo, TiSpace, Gilmour Space, T4I, SpaceForest and SpaceLink**, continued to develop and promote hybrid rocket technologies involving paraffin-based, HTPB and 3D-printed acrylonitrile butadiene styrene fuels. ★

Contributors: *Brian J. Cantwell, David Dyrda, Alon Gany, Mario Kobald, Veronika Korneyeva and Stephen A. (Tony) Whitmore*

New techniques and results enhance physical understanding

BY JONATHAN S. LITT

The **Inlets, Nozzles and Propulsion Systems Integration Technical Committee** focuses on the application of mechanical design, fluid mechanics and thermodynamics to the science and technology of air vehicle propulsion and power systems integration.

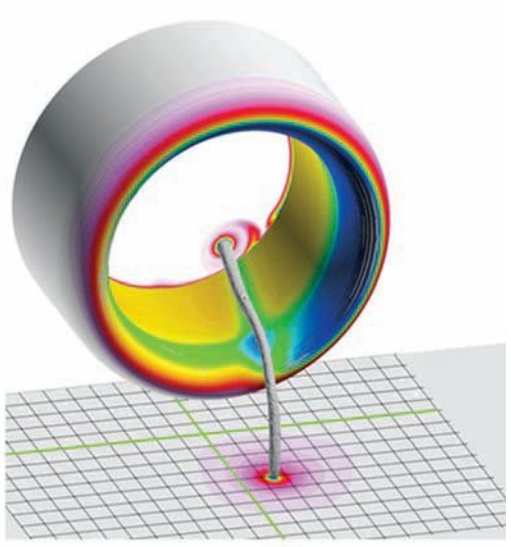
In January, researchers at the fifth AIAA Propulsion Aerodynamics Workshop demonstrated **novel computational fluid dynamics methods on two test cases** that were chosen to identify **shortcomings in CFD modeling practice** and thereby direct future research. The test cases provided rich datasets that enabled new multiphysics approaches to be validated. The results were vastly superior to the use of simpler models. Participants studied grid generation, turbulence and physical modeling, and boundary condition modeling and identified preferred practices. For one test case, participants predicted deck surface temperatures and boundary-layer profiles for a film-cooled non-adiabatic nozzle with an aft deck. Results showed that conjugate heat transfer modeling is critical to predicting temperature profiles and that scale-resolving simulations enable better agreement with experimental measurements than steady-state calculations for temperatures in the wall boundary layers. For the second test case, researchers assessed the ability of their CFD methods to predict ground vortex formation at the engine inlet under different crossflow conditions. This test case showed that CFD can contribute to the understanding of this problem. Guidelines for grid generation were among the outcomes of this important set of simulations.

Early this year, researchers at **NASA's Glenn Research Center** in Ohio analyzed experimental data to improve the knowledge of flow physics associated with a boundary-layer ingesting, distributed propulsion system. The experiment, conducted in 2019-2020 in a subsonic wind tunnel with a 20-by-30-inch (50-by-76-centimeter) test section, specifically examined the influence of incoming boundary-layer thickness on the performance of the system. Researchers mounted the propulsion model, integrated with electrical fans, on a flat plate and tested it at subsonic speeds. Hot-wire anemometry and static pressure measurements enabled detailed characterization of the incoming boundary layer and the downstream flow field. Trip rods placed near the leading edge of the flat plate modified the boundary layer. The researchers assessed the overall system performance by estimating thrust, flow power and input power to the fans. Results indicated that **ingestion of a thicker boundary layer yielded a net improvement in the performance of the system**.

In May, the **EcoPulse distributed propulsion hybrid aircraft demonstrator**, developed by Europe-based **Airbus**, **Daher** and **Safran** completed wind tunnel testing at the Airbus facility in Filton, England. The tests evaluated the performance characteristics of the propeller and electrical engine cooling concepts. Propeller performance testing included thrust and force measurements for different engine power levels and rotations-per-minute settings, as well as propeller wake flow visualization behind the engine, which helped characterize the interaction between the propeller and the wing. Researchers recorded dedicated engine and air temperature measurements to assess the effectiveness of the cooling technologies. The wind tunnel tests will enable estimation of the propulsion system's power and the aircraft demonstrator's overall energy performance.

In July, **Pratt & Whitney Canada** said it would continue work on its hybrid-electric propulsion technology and flight demonstrator program as part of a $131 million ($163 million Canadian) investment, with funding from the governments of Canada and Quebec. The **new hybrid-electric propulsion technology**, to be integrated into a **De Havilland Canada Dash 8-100 flight demonstrator**, will deliver a 30% reduction in fuel burn and carbon dioxide emissions, compared to a modern regional turboprop airliner. The demonstrator features technologies already developed by P&WC and Collins Aerospace, including an advanced electric motor and controller. This program is a successor of the Project 804 joint development program between P&WC and Collins Aerospace. ★

Contributors: *Dyna Benchergui, Nicholas J. Georgiadis, Puja Upadhyay, Chad M. Winkler and Khairul B. Zaman*



▶ The results of this computational fluid dynamics simulation show a ground vortex in an inlet in crossflow. The prediction of the existence of the vortex is notoriously sensitive in CFD to boundary conditions, crosswind and grid resolution. The results provide guidelines for setting up problems based on actual test data.

Boeing

Many companies and agencies achieve new launch capabilities with more to come

BY BRANDIE L. RHODES

The **Liquid Propulsion Technical Committee** works to advance reaction propulsion engines employing liquid or gaseous propellants.

NASA's **Stennis Space Center** in Mississippi conducted a series of **green run tests** of the first **Space Launch System** core stage, culminating with a hot fire of the stage's **four RS-25 engines** in March. It marked the most powerful test conducted at Stennis in more than 40 years. In addition, Stennis conducted a series of RS-25 single-engine tests, collecting data for production of new engines for future SLS missions. The site also continued testing work with companies such as **Relativity Space, Virgin Orbit and Launcher**, all based in California, and **Firehawk Aerospace** of Florida.

Virgin Orbit conducted its first commercial launch in June when LauncherOne, a two-stage expendable RP-1/liquid oxygen rocket, was dropped from the wing of a modified Boeing 747. **Virgin Galactic**'s first fully crewed flight with SpaceShipTwo VSS Unity was launched into suborbital space in July. SpaceShipTwo uses a **hybrid nitrous oxide/hydroxyl-terminated polybutadiene rocket motor**. In July, **Blue Origin** completed **New Shepard**'s first human flight with four passengers on board, passing the Kármán line. Powering this flight was the **BE-3PM, a liquid hydrogen/LOx engine** designed for restart and deep throttle operation.

NASA awarded its **Human Landing System** contract to **SpaceX**, with **Starship** intended to take astronauts from lunar orbit to the surface of the moon. A three-engine prototype was launched and landed in May. Alabama-based **Dynetics** also completed significant development testing milestones on its lunar lander propulsion system prior to the contract down-select in April, including taking the full design to preliminary design review-level maturity.

The **European Space Agency** awarded **ArianeGroup** a contract in July to develop **a new kick stage called Astris for the Ariane 6** launcher. Astris will be powered by a 5 kilonewton storable hypergolic nitrogen tetroxide/monomethylhydrazine engine. A demonstrator of this engine, SPE/Berta, was predeveloped in the frame of ESA's Future Launcher Preparatory Program. First hot fire tests were completed in August.

In February, the **German Aerospace Center, or DLR**, received the first upper stage of the European Ariane 6 launcher. The fully functional test module was subjected to extensive testing at **DLR's Lampoldshausen P5.2 test stand**. This stand is one of the largest projects in the history of the DLR site and will allow DLR to qualify not only engines and individual components but also entire cryogenic upper stages.

In May, **Prometheus motor M1**, the first European LOx/methane precursor engine, entered assembly and integration. An upgraded motor version with a 20% increase in thrust is under development.

Isar Aerospace Technologies GmbH was announced as winner of the main round of the **German microlauncher competition** in April. The company will receive $12.8 million for qualification and two demonstration flights of its **Spectrum launcher**.

Stellar Exploration of California supplied a novel **micropump-fed cubesat propulsion system** that was used to raise the orbit of an Echo Star spacecraft. This system featured a Georgia-based Flight Works-developed electric micropump that was used to power the eight small hydrazine thrusters. NASA's CAPSTONE, short for Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment, and Lunar Flashlight CubeSat missions will use similar micropumps.

ZBOT-NC, the second in series of the **Zero Boil-Off Tank Experiments**, passed its preliminary design review. **NASA's Glenn Research Center** in Ohio is developing this microgravity experiment to investigate the effect of noncondensable gases on propellant tank self-pressurization and pressure control. ★

Contributors: *Eric Besnard, Miranda Caserta, David Coote, Andy Crocker, Mohammad Kassemi, Christoph Kirchberger, Anne Lekeux, Bogdan Marcu, Ken Philippart and Dieter Preclik*

▼ Blue Origin's New Shepard launch vehicle lifts off carrying four passengers. It was powered by a BE-3PM, a liquid hydrogen/liquid oxygen engine.

Blue Origin

Focusing on nuclear propulsion and power for Mars missions

BY BRYAN PALASZEWSKI

The **Nuclear and Future Flight Propulsion Technical Committee** works to advance the implementation and design of combinations of chemical and high-energy megawatt-class nuclear propulsion systems using electric thruster systems.

Nuclear power and propulsion will allow faster and more effective human missions to Mars, Aerojet Rocketdyne engineers reported at the AIAA virtual Propulsion and Energy Forum in August. Nuclear electric propulsion, or NEP, uses the fission reactor power to ionize and accelerate xenon propellants to very high exhaust velocities. Nuclear thermal propulsion passes hydrogen through a nuclear reactor core; the hydrogen becomes very hot and provides rocket thrust.

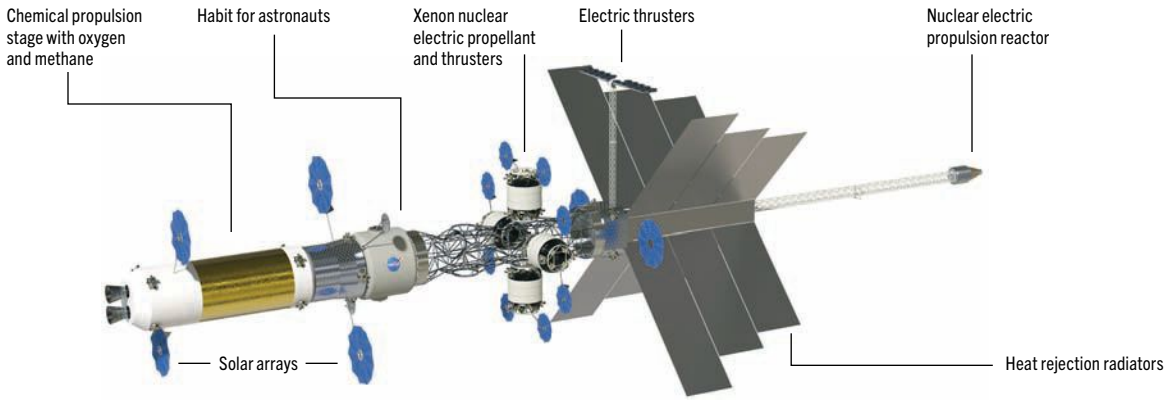
Also at the AIAA event, NASA and a group of research partners reported that **low enriched uranium, or LEU, reactors for human Mars space vehicles are affordable and feasible.** Research showed that nuclear propulsion — either electric power from a fission reactor or a nuclear thermal rocket using hot hydrogen — would be effective in carrying large chemically propelled landers and humans to Mars. The research focused on LEU cores. NASA's partners were DARPA, the U.S. Department of Energy, Aerojet Rocketdyne, the Aerospace Corp., BWX Technologies and Ultra Safe Nuclear Corp.

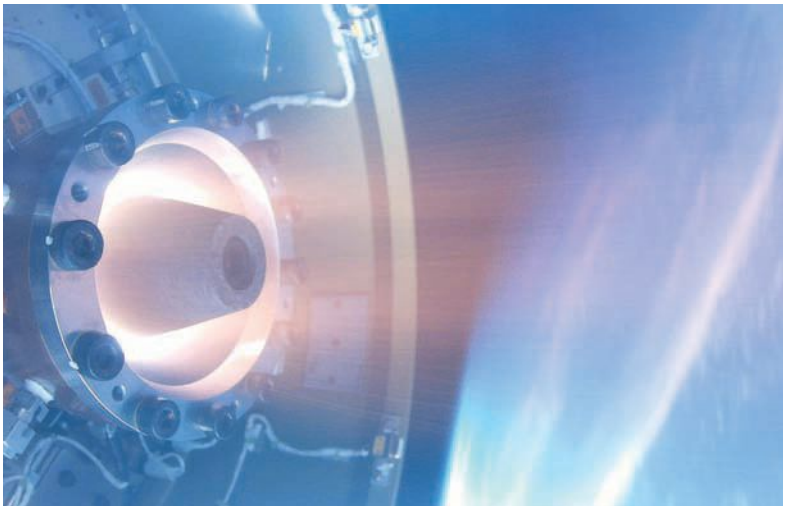
The Aerojet Rocketdyne team assessed near-term missions for the 2030s and **long-term human Mars bases for the 2040s**. It designed two NEP space vehicles for separate human transport and cargo transport. The simulated cargo transport carried several chemically propelled Mars landers. The human transport used both NEP and chemical propulsion; this propulsion combination created significant trajectory benefits, including faster missions, exposing the human crew to less of the deep space radiation.

The research also showed that **human Mars bases can be resupplied with the fast NEP transports**. The human transport used a 1.9-megawatt electric NEP stage with 20 100-kilowatt electric Hall-effect thrusters (18 active thrusters, with 2 spares), four Xenon Drop Tanks attached to a drop tank truss, a deep space habitat where a crew would live during the in-space portion of the mission, and a liquid oxygen/liquid methane chemical stage with two 25,000-pound thrust pump-fed engines. Ejecting empty drop tanks after their propellant is consumed would allow improved Mars payload performance. The research showed that the **chemical propulsion system would make the Earth departure and entry into Mars orbit faster than using NEP alone**. The transport design is flexible and would accommodate many human Mars exploration campaigns. Aerojet Rocketdyne assessed many Mars flights, improving our knowledge of the technology gaps that must be filled for mission success.

Nuclear propulsion is also critically important for outer planet exploration and exploitation. In August, NASA's Glenn Research Center in Ohio reported new results for the **mining requirements for outer planet moons**. Given the large fraction of water ice that's available on the moons of Uranus and Neptune, that ice is crucial to refueling mining vehicles. The mass of the mined water would be only a small fraction of the total mined matter. The water ice would be used to make oxygen and hydrogen for both chemical rocket engines and refuel nuclear electric propulsion orbit transfer vehicles to carry helium 3 and deuterium from additional nuclear mining vehicles working in Uranus' and Neptune's atmospheres.

In August, the Limitless Space Institute reported on dynamic vacuum research. **Extracting energy from the vacuum of space** is not yet practical on a large scale. However, the institute's research focused on potential applications to propulsion, communications, sensors and optics. Researchers visualized potential space-warp fields and theorized new insights into a negative vacuum energy density. They discovered warping space-time requires enormous energy, usually far beyond present human and world scales.★





Expanding the potential benefits of rotating detonation engines

BY DON FERGUSON AND JOSHUA GRAY

The **Pressure Gain Combustion Technical Committee** advances the investigation, development and application of pressure gain technologies for improving propulsion and power generation systems and achieving new mission capabilities.

▲ The Japan Aerospace Exploration Agency this year demonstrated a rotating detonation engine on a sounding rocket at an altitude of 165 kilometers.

Japan Aerospace Exploration Agency

Pressure gain combustion, achieved through either deflagration or detonation, is an area of great interest for both propulsion and power generation applications as it offers access to greater work availability compared to conventional constant pressure combustion. **Rotating detonation engines** remained the primary focus this year; however, RDEs with nontraditional configurations and other detonation-based systems were also of interest.

In July, the **Japan Aerospace Exploration Agency, JAXA**, and its collaborators demonstrated **in-space operation of an RDE and multiple pulse detonation engines** on board a sounding rocket at an altitude of approximately 165 kilometers. While these were not primary engines, multisecond operation of each engine resulted in positive thrust and permitted the recording of critical data while operating on gaseous methane and oxygen.

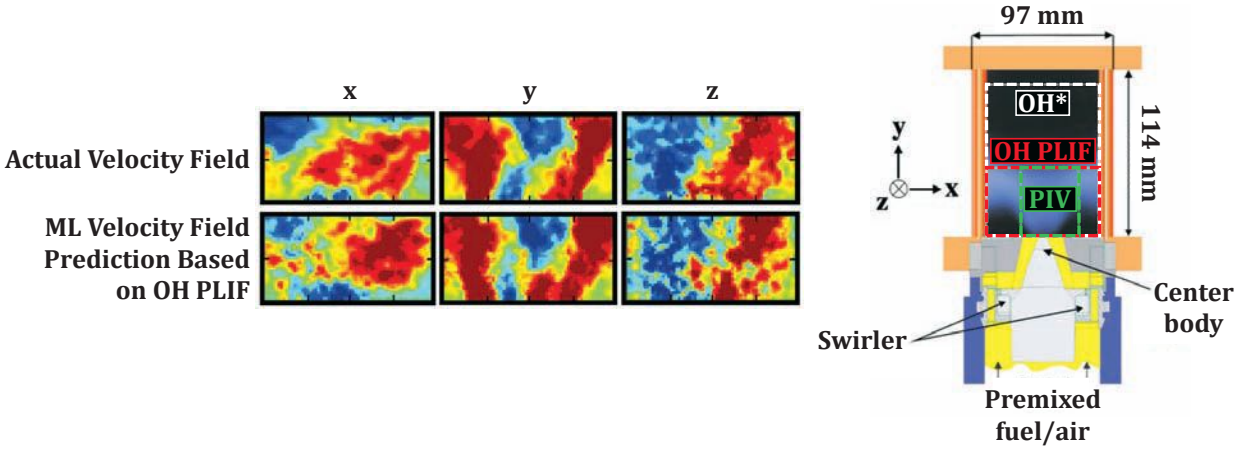
In January, **Tsinghua University in China** completed experimental and numerical studies on liquid fuel injection to explore the influence of droplet size, pre-evaporation equivalence ratio and mixture uniformity on RDE thrust performance. Domestically, researchers at **Aerojet Rocketdyne**, based in California, engaged in **multiple test campaigns to develop air-breathing RDEs for new flight systems** during 2020 and early in the year. Flight was also a consideration at the **University of Central Florida** as demonstrated by a May article in the Proceedings of the National Academy of Sciences detailing research on stabilizing oblique detonations that could address some of the unique challenges associated with hypersonic propulsion. Researchers at the **University of Texas at Arlington** also explored the use of **RDEs in high-speed flight vehicles** through computational models of streamline-traced inlets.

Fundamental and applied research continued to be an area of interest for government agencies, including **NASA, the U.S. Air Force Research Laboratory, the Naval Research Laboratory and the Department of Energy's National Energy Technology Laboratory**. The establishment of standardized testing and modeling has been a major focus for AFRL at Edwards Air Force Base in California in its **RDE Model Validation Program**. As part of this effort, 15 teams composed of academia, industry and federal laboratories were participating in a joint computational and experimental study of a baseline laboratory-scale rocket RDE. AFRL reported updates on the results from these studies at AIAA's SciTech Forum in January.

In January and August, multiple organizations presented research results. The **University of Michigan** reported on RDE operational parameters such as elevated inlet temperatures and exhaust gas recirculation to control detonation wave characteristics. Research at the **Naval Postgraduate School** focused on **RDE injector and combustor geometry**. Similar studies at **Purdue University** explored relationships between pressure gain and combustor geometric parameters while simultaneously developing megahertz-scale laser diagnostics, including OH planar laser-induced fluorescence and coherent anti-Stokes Raman scattering in a collaborative effort with Ohio-based **Spectra Energies** and **NASA's Glenn Research Center** in Ohio. Characterizing the unsteady supersonic/subsonic RDE exit flow is a critical element for propulsion and power applications. The **University of Alabama** has worked to address this need using its 100 kilohertz particle image velocimetry capability. Alternative RDE geometries such as centerbody-less and disk-shaped continued to be of interest as were novel concepts like South Korea's **Pusan National University's tri-arc RDE cross section.**

In January, the **Technical University of Berlin** initiated the Marie-Curie Innovative Training Network. It is composed of 15 early stage researchers from eight hosting institutions across Europe and is to focus on several key topics associated with pressure gain combustion over a few years.

Advancement and innovation continue to expose more of the underlying physics and push the technology envelope confirming pressure gain combustion to be a well-qualified candidate for realizing more efficient propulsion for high-speed vehicles, space exploration and land-based power generation. ★



Testing ways to reduce emissions, increase speeds and create smarter combustion

BY TIMOTHY OMBRELLO AND CLARESTA DENNIS

The **Propellants and Combustion Technical Committee** works to advance the knowledge and effective use of propellants and combustion systems for military, civil and commercial aerospace systems.

▲ The images on the left show machine learning predictions (bottom row) of actual velocity fields (top row) trained by using hydroxyl planar laser-induced fluorescence data, where x/y/z represent the different cross-sectional planar velocity components in the experimental configuration schematic on the right.

Venkat Raman, University of Michigan; Adam Steinberg, Georgia Tech

The aviation community continues to emphasize sustainability — with many efforts focused on thermal and propulsive efficiency — while also urging higher-speed flight regimes. This has motivated researchers to use disruptive technology with fundamental and applied efforts to tackle the new and extreme operating conditions. One such movement is the adoption of hydrogen as fuel, which was a pillar in the August establishment of the **Combustion and Propulsion for Aviation Research Center at the University of Tennessee Space Institute**. The center's goals are to improve flame stabilization and injector design and to reduce nitrogen oxide emissions in hydrogen-fueled gas turbine combustors.

A joint experimental and computational research program of **Georgia Tech, General Electric** and the **FAA's Center of Excellence for Alternative Jet Fuels and Environment, or ASCENT**, in January began investigating **novel low-emission gas turbine combustors for supersonic civil transport**. The unusual conditions that occur in the combustors of supersonic transports make it challenging to control pollutant emissions. The team is leveraging advanced manufacturing techniques and the high temperature air created at supersonic flight speeds to rapidly premix the fuel and air prior to combustion. The researchers are using laser-based measurements of the fuel/air mixing, velocity field and nonvolatile particulate matter to explain the flame stabilization process within and beyond the design-intent parameter space. Large-eddy simulations are both supplementing the experimental data and exploring the cost/accuracy tradeoff for this type of combustor. The effort is helping to enable the rapid pursuit of higher speed civil propulsion systems while also aligning with the aviation sector's sustainability goals.

In January, researchers at the **University of Michigan** and **Georgia Tech** published the results of their experiments using a machine learning model to look for a smarter means of mitigating combustion behavior that can lead to catastrophic mechanical failure. They trained the model using existing swirl combustor experimental data, which exhibited two flame states, lifted and attached, for the same operating conditions. While the transition between states was spontaneous, the machine learning approach captured the key features in the flame velocity field when trained using only one of the states. Moreover, a prediction of the impending transition between states was also possible using a different machine learning tool based on clustering of data, which enables a reduced probabilistic interpretation of the system state. Researchers are using the results for real-time prediction of extreme events that ultimately lead to mechanical failure in combustors. Due to the small timescales associated with extreme events, predictions must occur in real time. This motivates a combination of reduced order models and low-latency hardware, which in turn motivates machine learning. As such, the fusion of probabilistic modeling, unsupervised learning and low-energy — for example, graphics processing unit — computing is key to extreme event prediction. By extracting patterns from experimental data with machine learning algorithms, researchers are using low-overhead probabilistic models to map the evolution of patterns to extreme event identifiers in interpretable ways. Essentially, the input is a flow pattern obtained from operational sensors, and the output is the likelihood of observing an extreme event in the near future. ★

Contributors: *Shivam Barwey, Michael Benjamin, Daniel Jacob, Ellen Mazumdar, Joe Oefelein, Paul Palies, Venkat Raman, Jerry Seitzman, Adam Steinberg and Krishna Venkatesan*

Launch industry sees a defining year for interceptors, hypersonic boosters and space orbiters

BY CLYDE E. CARR JR. AND JOSEPH MAJDALANI

The **Solid Rockets Technical Committee** studies techniques applied to the design, testing and modeling of rocket motors based on solid propellant grains.

Overall, this year thrived with high-speed interceptor missile tests, hypersonic booster demonstrations and satellite launchers.

In the tactical-rocket category, the **U.S. Navy and Air Force** awarded **Lockheed Martin** two substantial contracts to produce scores of **AGM-158C Long Range Anti-Ship Missiles**. Lockheed Martin announced that from March into May it conducted tests of the **Extended-Range Guided Multiple Launch Rocket System** at White Sands Missile Range in New Mexico. These demonstrations confirmed the missile's enhanced range, trajectory and robust interfacing with its launcher. Lockheed Martin also used the same launcher in May to launch a surface-to-surface **Precision Strike Missile weapon demonstrator**. Meanwhile, **Northrop Grumman** announced that the Navy in July completed a live fire test of the company's newly upgraded **Advanced Anti-Radiation Guided-Missile-Extended Range**, when an F/A-18E/F Super Hornet fired the air-to-surface missile.

In related news, the **Missile Defense Agency** this year announced its selection of **Northrop Grumman, Raytheon and Lockheed Martin** as the main contractors for development of the nation's **next-generation interceptor**. From May to July, the agency conducted two live interceptor tests involving six **Standard Missile-6 solid-boosted rockets**. The U.S. Army took delivery from **Aerojet Rocketdyne** of its **1,000th Patriot Advanced Capability-3 Missile Segment Enhancement booster** with hit-to-kill capability. Then, in April, Lockheed Martin said it supplied Sweden's first package of **PAC-3-MSEs**. In the interim, Lockheed Martin conducted two PAC-3-MSE flight tests at White Sands; both missiles intercepted the incoming target using hit-to-kill technology.

▼ The Advanced Anti-Radiation Guided-Missile-Extended Range was launched this year from a U.S. Navy F/A-18 Super Hornet aircraft during a live-fire test at Point Mugu Sea Test Range in California.

U.S. Navy

In the strategic and hypersonic rocket categories, the Navy's Strategic Systems Program said that in February it conducted a **UGM-133A Trident II flight test from a nuclear-powered submarine**. This marked at least 165 launches for Trident II since 1989. In May, Lockheed Martin announced it **tested a hypersonic strike system first-stage booster** in Utah. Also in May, Aerojet Rocketdyne said it demonstrated the effectiveness of **DARPA's Operational Fires technology** that enables a missile to adjust its speed "on the fly." This static test included a medium-range, ground-based, hypersonic weapon that relied on a second-stage throttleable motor. Further, the Navy completed its evaluation of both first- and second-stage motors in Utah, first in May and later in August, as part of its ongoing development of a **Conventional Prompt Strike hypersonic offensive capability** in concert with the Army's. Both programs enable long-range service-specific weapon delivery with hypersonic boost-glide capability from ships, submarines and mobile launchers.

During a January static test, **United Launch Alliance's Vulcan Centaur's strap-on GEM-63XL boosters** delivered 2,000 kilonewtons (449,000 pounds) of thrust, the company said. In April, **ULA's Delta IV Heavy** launched from Vandenberg Space Force Base in California and placed the NROL-82 satellite into orbit. In May, ULA said its Atlas V rocket lifted off from Florida with the **Space Based Infrared System Geosynchronous Earth Orbit Flight 5 spacecraft** for the U.S. Space Force. This marked Atlas's 87th launch using Aerojet Rocketdyne and Northrop Grumman strap-on and separation boosters.

In March, NASA selected a two-stage solid booster and spin-up/spin-down motor system for the **Mars Ascent Vehicle**. In June, Northrop Grumman said it completed the **28th Minotaur I launch for national reconnaissance** using a decommissioned Minuteman III. In addition, Northrop Grumman launched the Tactically Responsive Launch 1 into orbit using a three-stage Pegasus XL.

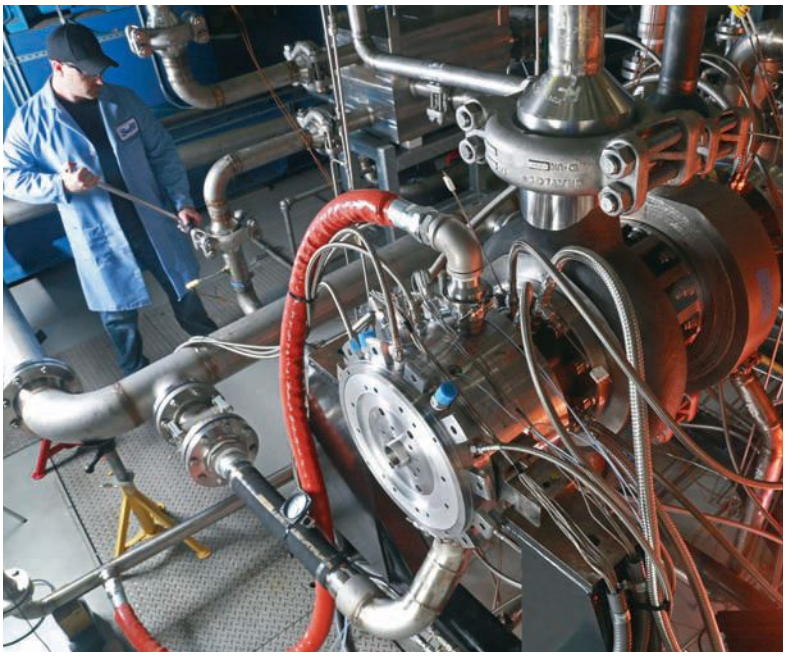
On the international stage, in April **Arianespace** said it launched its **18th Vega rocket** from the Guiana Space Center in French Guiana to deploy the **Pléiades Neo 3 Earth Observation constellation**, along with numerous light satellites. This was followed by the 19th Vega launch in August, which orbited Pléiades Neo 4 and four innovative cubesats. Furthermore, an **Ariane 5** in July placed two telecommunications satellites into orbit for **Embratel** and **Eutelsat**. In September, **South Korea** fired a submarine-launched ballistic missile from a submarine. In February, an **Indian Polar Satellite Launch Vehicle** orbited **Brazil's geosynchronous Amazônia-1 and 18 smaller payloads**. This rocket, equipped with two solid strap-on boosters, lifted off from the Satish-Dhawan Space Center in Sriharikota, India. An identical launch in September inserted the Earth-observation satellite RISAT-1A into orbit. ★

Contributor: *Wesley J. Ryan*

Progress in carbon-neutral technologies for power generation

BY TAKU TSUJIMURA, KEIICHI OKAI AND REZA SHEIKHI

The **Terrestrial Energy Systems Technical Committee** works to advance the application of engineering sciences and systems engineering to the production, storage, distribution and conservation of energy for terrestrial uses.



▲ Supercritical carbon dioxide power generation systems consist of compact, more efficient components. The desk-sized 10-megawatt-electric supercritical carbon dioxide turbine designed by General Electric and Southwest Research Institute yields the highest power density of any industrial turbine at higher efficiency, according to Southwest Research Institute.

Southwest Research Institute

Japan published the **Sixth Strategic Energy Plan** in October, laying out Japan's approach to achieving **carbon neutrality by 2050**. In December 2020, Japan released its Green Growth Strategy to achieve carbon neutrality by 2050. It includes action plans for 14 growth sectors. Five of them are strongly related to the technologies employing combustion of hydrogen and ammonia. As an example, the National Institute of Advanced Industrial Science and Technology's Fukushima Renewable Energy Institute, or FREA, is developing **an internal combustion engine using hydrogen and ammonia as the fuel**.

In January, **Mitsubishi Heavy Industries Engine and Turbocharger Ltd.** announced **joint research with FREA of a hydrogen engine**. MHIET aims to make a 1 megawatt-class hydrogen engine available for the introduction of the hydrogen economy in the 2030s. FREA also achieved gas turbine power generation of 50 kilowatts firing 100% ammonia. These results could contribute to significant reductions in greenhouse gas emissions.

Another promising technology is biofuels for aviation. Projects on the production of bio-derived aviation fuels using waste wood and microalgae started in 2017 as the consignment business of the **New Energy and Industrial Technology Development Organization**. Biomass-based production fuel met the requirements for the ASTM International standard. In May 2020, Japan-based IHI Corp. obtained a new ASTM standard for algae-based sustainable aviation fuel. These SAF were used on regular flights of Japan Airlines and All Nippon Airways in June.

Supercritical carbon dioxide power generation was another carbon-neutral technology attracting much attention. These systems, using supercritical carbon dioxide as the working fluid within their power cycle, offer higher efficiency, compact components as well as reduced emissions and construction costs. This past year, the **Advanced Research Projects Agency-Energy** funded several projects that promote cleaner, more efficient power generation using this technology. In February, **General Electric** received a grant to optimize a direct-fired cycle for electricity generation on a grid with highly intermittent input from renewable energy sources, seeking to achieve lower electricity cost with near-zero carbon emissions. Direct-fired supercritical carbon dioxide cycles provide high-purity carbon dioxide as a combustion product that is readily available for reuse or storage. In March, **Southwest Research Institute** received funding to implement renewable energy storage using liquid oxygen besides the air separation unit in a direct-fired system. In June, **Raytheon Technologies** was awarded a contract to develop an ultra-efficient, lightweight gas turbo-electric engine using this technology with waste heat recovery to enable designing a **narrow body commercial aircraft with net-zero carbon emissions**.

Funded by the U.S. Department of Energy's National Energy Technology Laboratory, the **Supercritical Transformational Electric Power program** is a project for the design, construction, operation, evaluation and performance demonstration of a 10-megawatt-electric pilot plant using an indirect-fired cycle. **Indirect-fired supercritical carbon dioxide cycles** offer the benefit of heat source flexibility by separating the supercritical carbon dioxide working fluid from the heat source. A team led by **Gas Technology Institute** together with **Southwest Research Institute, General Electric** and several international partners is developing this facility, located at the Southwest Research Institute campus in San Antonio, Texas. The Gas Technology Institute announced in August that it had completed mechanical assembly of the supercritical carbon dioxide process heater. Further advancement of this technology continued throughout the year focusing on designing combustors, turbines, heat exchangers and turbomachinery shaft end seals along with developing pilot power plants. ★

3D-printed tissues, freeze-dried sperm and gene editing

BY JONATHAN METTS

The **Life Sciences and Systems Technical Committee** advances technologies required to keep people healthy and safe as they explore space.

Competing research teams from **Wake Forest University** in North Carolina claimed first place and second place in **NASA's Vascular Tissue Challenge** in June by **replicating liver function in a long-lasting artificial tissue**. Using different methods and materials, both teams 3D-printed scaffolds with vascular channels to mimic blood flow in human tissue. NASA is interested in the technology's potential to provide artificial tissue or even functional organs for transplant into astronauts who cannot quickly or safely return to Earth for emergency treatment.

Both teams created artificial tissues housing human liver cells that remained functional through at least 30 days, producing albumin and bilirubin. They 3D-printed the macroscale tissues with a volumetric envelope over 1 cubic centimeter. The challenge required that these tissues be maintained only by perfusion of blood (or other fluid) to provide nutrients and oxygen while disposing of waste products, without leakage into the surrounding tissue.

A spaceflight demonstration of Team Winston's winning technology is in development with the **International Space Station National Laboratory**, with the goals of enabling tissue research in space by modeling human biology under precisely controlled conditions, as well as studying the benefits and challenges of biomanufacturing such tissues in microgravity.

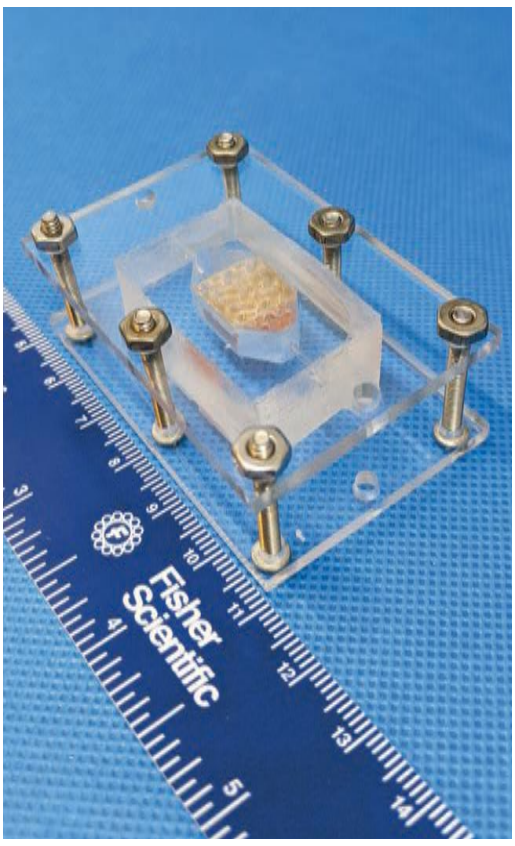
Freeze-dried mouse sperm first launched to orbit in 2013 were stored on the ISS in a long-term fertility study on space exposure, according to results from the **University of Yamanashi in Japan** that Science Advances published in June. The samples were returned to Earth after increasing intervals, up to nearly six years later. After landing and recovery, the sperm were rehydrated and used to fertilize mouse eggs that had not been flown to space. All mice born of the study, a total of 168 pups over the years, developed normally. Genetic analysis of the space-flown sperm and the resulting mice showed no defects. These results support the prospects for off-world storage and transport of mammalian genetic material.

The researchers also exposed nonflown sets of both fresh and freeze-dried mouse sperm to high doses of X-rays, finding the freeze-dried sperm to be equally fertile with no radiation and more tolerant than fresh sperm when exposed to radiation up to 10 Gray (1,000 rad) of an absorbed dose. Freeze-drying also allows for long-term storage at room temperature, which has operational benefits for in-space research and storage.

NASA has long understood that increased exposure to ionizing radiation in space, particularly beyond Earth's magnetosphere, such as during lunar exploration, can damage DNA and lead to health problems. In results published by PLOS One in June, **researchers demonstrated gene editing technology aboard the ISS for the first time**.

In the experiment, devised by a team of Minnesota high school students with support from researchers at the **Massachusetts Institute of Technology**, the team used the **CRISPR-Cas9 method** to sever both strands of the double helix in yeast DNA. They then allowed test samples to repair themselves, which can occur by two natural processes — one of which, nonhomologous end-joining, can result in an altered gene sequence with increased risk of mutation and cancer.

By preparing and testing the samples in space, this research shows that microgravity can be isolated as the only variable for such experiments, thus **introducing a new genetic research capability on the ISS**. Results also showed that the method of repair can be effectively determined using ground-based gene sequencing of lab results obtained on orbit. Future studies will investigate whether spaceflight affects either or both double-strand DNA repair processes. ★



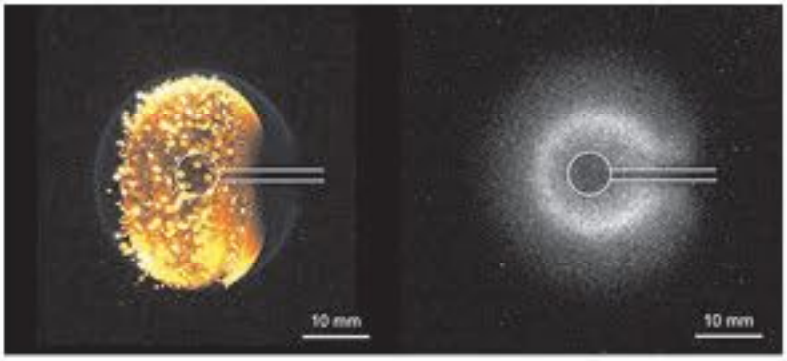
▶ Artificial vascular tissue was 3D-printed into this chamber as a support structure for human liver cells by a team of researchers at Wake Forest University. NASA held a competition to develop technology to produce artificial tissues in space for astronauts who may not be able to return to Earth quickly.

Wake Forest Institute for Regenerative Medicine

Steady progress in microgravity research leveraging diverse flight platforms

BY PETER B. SUNDERLAND, HENRY K. NAHRA AND SUNIL CHINTALAPATI

The **Microgravity and Space Processes Technical Committee** encourages the advancement and public awareness of low-gravity studies in physics, materials, biological sciences and related fields.



▲ Photographed this year during the Cool-Flame Investigation with Gases aboard the International Space Station, a hot flame (left) burns n-butane and then extinguishes, leaving a spherical cool diffusion flame (right), a phenomenon never before photographed in the act of spherical burning of gases. A better understanding of cool flames should improve the internal combustion engines of the future such that they have the high efficiency of diesel engines and the clean emissions of gasoline engines. The cool flames could also play a role in the ignition of fires in microgravity.
University of Maryland

Researchers on Earth, watching via a remote camera, for the first time observed spherical, cool diffusion flames burning gases aboard the International Space Station in June. Unlike hot flames with peak temperatures of 830-1,930 degrees Celsius (1,520-3,500 Fahrenheit), cool flames have peak temperatures of 330-730 degrees Celsius (620-1,340 Fahrenheit). The flames were observed during tests of the Cool Flames Investigation with Gases experiment. The burner was a 6 millimeter porous sphere fed by n-butane diluted with nitrogen. The ambient gas was 40% oxygen in nitrogen at 2 atmospheres. Researchers at the University of Maryland, Washington University in St. Louis, University of California San Diego and NASA's Glenn Research Center in Ohio noticed that after the hot flames extinguished radiatively, cool flames were quickly established. The cool flames were too weak to detect except with sensitive radiometers and an intensified video camera. Measurements in these flames could help improve the internal combustion engines of the future.

The Flow Boiling and Condensation Experiment, or FBCE, flight hardware was launched to the ISS in August. Researchers from Purdue University and Glenn Research Center designed the FBCE testbed to obtain long-duration microgravity data for two-phase flow research with emphasis on the flow boiling and condensation. Any long-duration space missions would be constrained by high power and heat dissipation requirements, while maintaining low size and weight. Researchers aim to use FBCE to advance understanding of flow boiling and flow condensation prior to designing future two-phase thermal management systems with reduced size and weight.

Participants in the NASA Flight Opportunities program of the Space Technology Mission Directorate conducted some notable suborbital experiments. Among them were:

- Researchers flew the Ring Shear Drop experiment conceived by NASA's Marshall Space Flight Center and Rensselaer Polytechnic Institute in late April and early May on a Zero-G aircraft. The parabolic flights produced data about the formation of potentially destructive amyloid fibrils, or protein clusters, like those found in the brain tissue of patients with neurodegenerative diseases including Alzheimer's and Parkinson's. A different version of a ring-sheared drop payload was sent to ISS in 2019 but needed hardware modifications to function properly. The parabolic flight campaign proved that the modified hardware was functioning as designed with no issues.

- A University of Florida plant experiment was flown to suborbital space in July aboard the VSS Unity spaceplane during the Unity 22 mission, Virgin Galactic's first fully crewed flight with passengers in addition to pilots. The whole genome gene expression experiments were conducted using plants as test organisms and the Kennedy Space Center Fixation Tubes for containment. The KFTs were activated by Sirisha Bandla, vice president of government affairs and research operations at Virgin Galactic, to release a preservative that captured the plant's biochemistry at specific points during transitions into and out of microgravity.

- The third generation of Southwest Research Institute's tapered Liquid Acquisition Device, or LAD, flew aboard an unoccupied Blue Origin New Shepard spacecraft in August in the NS-17 mission. Long-duration space missions would require storage of large amounts of fuel at low temperatures, and a LAD would need to function properly to deliver the fuel to the rocket engine. Current LADs have straight channels and fuel moving through these channels could potentially contain vapor bubbles that could severely damage engines during ignition. The goal is to develop a tapered LAD that can eliminate bubbles via surface tension.

- In September, SpaceX's Inspiration4, with four passengers, completed a three-day orbital spaceflight. The passengers submitted skin samples pre- and post-flight to investigate the potential effects of radiation, as the orbital altitude reached 590 kilometers, a higher radiation profile than at the space station. Other biomarkers were also measured throughout the flight to evaluate microgravity effects on human bodies. ★

The AGM-88G Advanced Anti-Radiation Guided Missile Extended Range missile was launched from a U.S. Navy F/A-18 Hornet aircraft during a live-fire test this year.

Northrop Grumman

Companies report a number of firsts for missile tests

BY DUSTIN OTTEN

The **Missile Systems Technical Committee** focuses on technologies associated with the design, development, operations and utilization of strategic and tactical missile systems.

In July, Lockheed Martin intercepted a surrogate cruise missile threat with a PAC-3 missile at White Sands Missile Range in New Mexico. The flight marked the first time in a live-fire event that an **F-35 Lightning II aircraft contributed to the tracking of a target**.

Also in July, at Yuma Proving Grounds, Arizona, **Raytheon Missiles and Defense** used a **nonkinetic Coyote Block 3 effector to defeat a swarm of drones**. A significant first was the demonstrated ability to recover, refurbish and reuse the Coyote Block 3.

In April, the European **MBDA Group** and France-based **Nexter**, as part of the French defense procurement agency, conducted the **first lock-on live firing of the Missile Moyenne Portée medium-range missile from a Jaguar armored reconnaissance and combat vehicle**. The Missile Moyenne Portée hit a fixed target, which is the first step in integrating the missile onto the Jaguar platform.

Lockheed Martin had a string of flight tests of two different ground-to-ground missile systems. In March, the **Extended-Range Guided Multiple Launch Rocket System demonstrated a range of 80 kilometers** at White Sands, confirming the missile's performance with the M142 High Mobility Artillery Rocket System launcher system. In May, the **Precision Strike Missile demonstrated a range of 400 km** at White Sands. In October, the Precision Strike Missile completed its fifth consecutive flight test, achieving its longest flight to date. The missile had an extended range flight over the Pacific Ocean, validating range and performance requirements, but the company did not release the exact distance.

As part of the U.S. Navy's **Conventional Prompt Strike program**, Lockheed Martin and **Northrop Grumman** conducted a live-fire ground test in May of the first-stage solid rocket motor. Conventional Prompt Strike is designed as a hypersonic boost glide system to carry a non-nuclear payload. It is a joint Army-Navy program with each service tailoring its design for different launch environments.

In September, the Navy authorized Northrop Grumman, as the prime contractor for the **AGM-88G Advanced Anti-Radiation Guided Missile Extended Range missile,** to begin low-rate initial production.

In August, the **U.S. Marine Corps** and **Raytheon Missiles and Defense**, launched a Naval Strike Missile from shore and hit its target ship at sea using the **Navy Marine Expeditionary Ship Interdiction Systems**. The cruise missile is designed to destroy heavily defended land and maritime targets. According to Kim Ernzen, the vice president of Naval Power at Raytheon Missiles and Defense, "This was the first time NMESIS has been used from shore to strike a target at sea during an operational exercise." ★

▲ This first stage of a SpaceX Falcon 9 flew NASA's Crew-2 astronauts to space and landed on a drone ship for its return to Port Canaveral, Florida.

SpaceX

Pace of reusable rocket launches picks up

BY RYAN DIBLEY, PETRAS KARUZA AND BOB SEIBOLD

The **Reusable Launch Vehicles Technical Committee** promotes the development and implementation of operationally responsive and economically viable commercial, military and civil reusable launch vehicles and systems for space access and global reach.

In March, **Virgin Galactic** released images of **VSS Imagine**, its updated air-launched reusable rocket spaceplane. The first of the Spaceship III series, Imagine is designed to make construction and maintenance easier as the company increases its flight tempo. Virgin is also working on its Delta class of vehicles to increase its flight tempo toward the company's goal of 400 flights per year. Virgin Galactic completed its first spaceflight with passengers in addition to pilots in July from Spaceport America in New Mexico, when the two pilots took four passengers to an altitude of about 86 kilometers.

In January, **Blue Origin** flew its human-outfitted capsule on a **reusable suborbital New Shepard rocket** from the company's West Texas facility. Blue Origin progressed toward its goal of human spaceflight with the second launch of the year in April, during which Blue Origin employees standing in for spacefligh participants entered the capsule prior to launch and after landing to perform a series of tests and evaluate operations. In July, Blue Origin made its first human flight with four people on board, culminating 20 years of development.

Blue Origin also continued to participate in research payload operations. In March, **NASA's Flight Opportunities program** contracted with the company to develop and fly a mission to simulate lunar gravity during a suborbital flight by spinning a capsule. Demonstrating a quick turnaround of its reusable launch capability, Blue Origin conducted a flight in August carrying NASA, industry and academic payloads.

SpaceX continued to reuse boosters to reduce cost and improve launch turnaround times. Booster 1051, originally built and flown for NASA's Crew Demo-1 mission, had made 11 total flights (10 reflights) as of November. And B1061, originally flown for Crew-1, was launched again for the Crew-2 mission in April.

The **National Security Space Launch program** approved SpaceX to use previously flown boosters. B1062, originally flown for GPS-III-4 in 2020, carried the **GPS-III-5 satellite** into orbit in June, saving tens of millions of dollars in launch costs. In November, Falcon 9 booster 1058 took flight for the ninth time to lift 53 Starlink internet communications satellites into low-Earth orbit. Efforts are underway under the NASA Commercial Crew Transportation Capability contract to allow multiple reuses of Falcon 9 rockets for crewed missions. As of November, SpaceX had reflown its Block 5 boosters 61 times for 80 total launches.

In November, **Rocket Lab** of California completed the third ocean recovery of the first stage of its **Electron** rocket under a parachute. The company retrieved it as part of a test of its reusability plan. Japanese car maker **Honda** announced in September that it is developing a partially reusable launch vehicle for small satellites.

In July, the **China Aerospace Science and Technology Corp.** announced completion of a secret first test flight of a reusable suborbital vehicle. The Russian space agency, **Roscosmos**, said in July that it plans to develop a **two-stage rocket called Amur**, whose first stage will return to Earth for vertical, powered landings. In August, Russia said that it will create a reusable space freighter to replace Progress resupply ships. In October, Russia announced that it will build a **prototype of a Krylo-SV reusable wing-deployable space rocket** by late 2022. ★

Small-satellite launches and opportunities increase

BY MICHAEL SWARTWOUT, PAULA DO VALE PEREIRA AND RAVI DEEPAK

The **Small Satellite Technical Committee** works to advance the science and engineering of satellites, launch vehicles and ground systems to enable the development of small and highly capable spacecraft.

▲ The TechEdSat-10 small satellite was released from the International Space Station and deployed its exo-brake precision deorbit system. The spacecraft remained in low-Earth orbit for seven months before making a deliberate reentry this year.

NASA

More than 1,100 small satellites were placed in orbit, and national governments and private investors increased their investments in the field this year.

Two small-satellite broadband constellations took concrete steps toward full operability. **OneWeb** emerged from bankruptcy protection in November 2020 and added 248 spacecraft to its network this year. SpaceX launched **889 Starlink spacecraft** as of November, and its 1,800-spacecraft network achieved 90,000 subscribers.

Although those two companies were responsible for most of the small satellites launched this year, other constellations also started services or expanded their orbital fleets. Sixteen companies placed 160 of their own spacecraft into orbit, and 100 other small satellite missions were flown, covering a range of educational, scientific and technology-demonstration objectives.

In June, the **U.S. Space Development Agency** put its first spacecraft in orbit, the **Laser Interconnect and Networking Communication System** and **Mandrake II** missions. These technology demonstrators are intended to advance the SDA toward its goal of proliferated low-Earth orbit — hundreds or thousands of LEO spacecraft for data relay and detection. In July, the SDA issued a request for proposals for 150 more data-relay satellites.

There were also many mergers and acquisitions within the industry, especially through special purpose acquisition companies, SPAC. In July, the Earth-imaging companies **Planet** of California and **Satellogic** of Argentina announced plans to go public via mergers with SPACs. In August, the satellite-service company **Momentus**, based in California, completed its own SPAC merger and went public, as did the remote-sensing company **Spire Global** of Virginia. Also in August, SpaceX announced that it was acquiring **Swarm Technologies**, a California company that has fielded a low-data-rate store-and-forward constellation of 90 spacecraft.

Historically, small satellites take care of excess capacity on launch vehicles, reaching orbit as secondary payloads. The relatively low cost of being a secondary payload made space accessible, but this advantage was often offset by the constraints of the primary payload's schedule and orbit. Small satellites now have the option of dedicated launches through small launchers such as **Rocket Lab** of California's **Electron**, but increasingly, large launchers are manifesting many small satellites without a prime. In January, the **SpaceX Transporter-1** dedicated small satellite launch carried a record 143 spacecraft into orbit, and **Transporter-2** launched 85 payloads in June. But even on shared launches, new services are allowing small satellites to have customized orbits. Transporter-1 carried the **Spaceflight Sherpa-FX 1** spacecraft tug, which in turn deployed 14 small satellites into specific orbits. Similarly, the **D-Orbit ION-SCV 002** carrier was deployed from Transporter-1 and delivered eight Planet Doves and 12 Swarm Technologies SpaceBEEs to custom orbits.

The Small Satellite Mission of the Year was the **TechEdSat-10** from **NASA's Ames Research Center** in California. The 6-unit cubesat deployed from the International Space Station in July 2020 and demonstrated increased power capabilities and deployable tunable brakes before its reentry in March. The umbrella-like exo-brake increased the drag faced by the satellite, making it deorbit faster, but unlike typical drag sails, the amount of drag could be adjusted by altering the sail geometry. Such technology could not only help mitigate the orbital debris issue but could also provide a new targeted reentry method to sample return missions. TechEdSat-10 also hosted eight radios, four cameras and a virtual reality experiment.

Small satellites continued to be an effective means for universities and even nations to start their space programs. A dozen universities put their first spacecraft in orbit. In March, **Tunisia's** first space mission, **Challenge ONE**, was launched. It will serve as a technology demonstrator for a planned commercial constellation. ★

▲ ICON Technology Inc. received a contract to 3D-print the Mars Dune Alpha analog habitat as part of the Crew Health and Performance Exploration Analog project at NASA's Johnson Space Center in Houston.

ICON Technology

Space architecture projects building on space station experience

BY BARBARA IMHOF, THEODORE W. HALL AND MARIA JOÃO DURÃO

The **Space Architecture Technical Committee** focuses on the architectural design of the environments where humans will live and work in space, including facilities, habitats and vehicles.

The International Space Station and the Tianhe core module of the Chinese Tiangong space station are the only habitable structures in outer space. But the pace and variety of flights, construction and contracting foretell that space will soon be inhabited by more people, including commercial workers and tourists as well as government employees.

Tianhe reached orbit in April, a cargo module joined it in May, and its first crew of three taikonauts took up residence in June. The ISS, the largest and longest-inhabited orbital outpost in human history, showed more signs of its age and suffered more wear and tear, but it also offered a base from which to spawn a new generation of space stations. In March, cosmonauts again floated tea leaves to pinpoint the locations of air leaks in Russia's **Zvezda module**, following some success with that strategy in 2020. In July, controllers used a Progress spacecraft to detach and deorbit the Pirs module after nearly 20 years attached to Zvezda. A few days later, controllers attached the new **Nauka module** where the Pirs had been. But shortly after, Nauka's reverse thrusters began to push away, causing the entire station to rotate 540 degrees before opposing thrusters on Zvezda and on a docked Progress cargo spacecraft eventually stopped it and restored the station's nominal attitude. The already leaky Zvezda carried the brunt of these forces. Space station partners are assessing the structural implications.

Nevertheless, the replacement of Pirs with Nauka illustrated the potential of the modular ISS to survive and support new growth. In June, Roscosmos Director General Dmitry Rogozin suggested that Nauka might ultimately detach as the core of **a new Russian station**.

Texas-based **Axiom Space** continued efforts toward establishing the **first commercial space station**. In May, Axiom finalized an agreement with NASA for the company's four-person Ax-1 mission to arrive at the ISS aboard a SpaceX Crew Dragon in 2022. In June, Axiom contracted with SpaceX for additional Ax-2, Ax-3 and Ax-4 missions. In July, Axiom contracted with Italy-based **Thales Alenia Space** for the development of the first two pressurized elements of its new station, to be launched and initially docked to the ISS in 2024 and 2025, but ultimately to detach as an independent station when the ISS is decommissioned.

Other space architecture projects looked further toward the moon and Mars.

In July and August, Iceland hosted a 15-day simulation campaign dubbed **Construction of a Habitat Inside a Lunar-analogue Lava tube in Iceland, or CHILL-ICE**. The analog was organized by a group of independent researchers and students and supported by EuroMoonMars in the Surtshellir-Stefanshellir cave system in the Hallmundarhraun lava flow. Students from the Wilson School of Design at Kwantlen Polytechnic University in Surrey, British Columbia, created a lightweight deployable habitat adapted to the geological characteristics of the lava tube.

Also in August, **ICON Technology Inc.** of Texas announced that it received a contract to 3D-print an analog habitat, dubbed **Mars Dune Alpha**, designed by the Bjarke Ingels Group, as part of the **Crew Health and Performance Exploration Analog, or CHAPEA**, at NASA's Johnson Space Center in Houston. The structure will be 158 square meters and include four private crew quarters, workstations, a medical station, an exercise station, a food-growth area and a shared living area. Research at CHAPEA will focus on crew health and performance studies, including tests of the viability of crop growth in long-duration missions with no resupply, simulation of communications delays, performance analysis with robotic simulators and surface spacewalks in virtual reality. The first trial is scheduled for 2022. ★

Contributors: *Antonia Sattler and Melodie Yasher*

Robotic milestones include first controlled powered flight on another planet

By Erik Komendera, Jian-Feng Shi and Gardell Gefke

The **Space Automation and Robotics Technical Committee** works to advance the development of automation and robotics technologies and their applications to space programs.

This year was eventful in terms of historic firsts in the domain of space automation and robotics. In February, **NASA's Perseverance rover** landed in the Jezero Crater on Mars. Its objectives emphasize collecting and studying rocks that may have been formed or altered in the presence of water. After identifying and drilling rock samples, Perseverance will preserve the samples in sealed tubes and leave them for future missions to return to Earth. In April, the **Mars Oxygen In-Situ Resource Utilization Experiment**, or MOXIE, **extracted 5 grams of oxygen** from atmospheric carbon dioxide, demonstrating a critical capability for future human and return missions. In September, Perseverance collected the first of its samples from the rock called "Rochette."

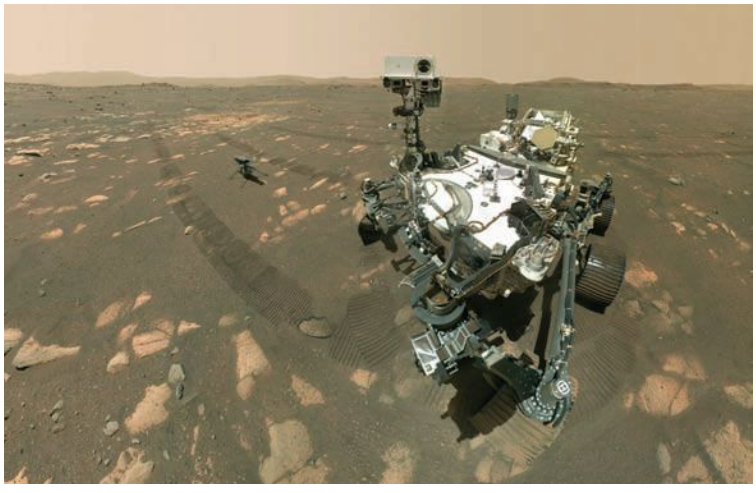
NASA's Ingenuity Mars Helicopter made the first powered flight on Mars in April. Its first flight of 39.1 seconds — and about 3 meters above Martian regolith — will stand as a "Wright brothers" moment for all future aircraft on Mars. Ushering in a new age in aerial exploration of the red planet, subsequent flights have pushed the boundaries of what was aerodynamically, energetically and operationally possible for a 1.8-kilogram co-axial rotorcraft. Ingenuity completed its technology demonstration phase after additional experimental flights and transitioned to an operations demonstration phase. Ingenuity has captured imagery for Perseverance engineers and scientists to study from a perspective never before possible on other planets. As of early November, Ingenuity had made **15 flights**, the longest of which was the ninth flight when it traveled 625 meters horizontally and achieved an altitude of 10 meters over 2 minutes and 46 seconds.

On the space automation front, **Blue Origin** flew its fully autonomous reusable rocket, **New Shepard**, with four passengers, reaching space above the Kármán line and back, in July. The flight was the first flight of a rocket with passengers. New Shepard is a testbed for automated guidance and control technologies that may be used for lunar applications.

NASA completed commissioning of the **Astrobee free-flying robots** on the **International Space Station**. During the year, Astrobee was used to conduct a variety of ISS tests, including acoustic monitoring, capture of space debris using gecko-inspired adhesion, radio-frequency identification-based inventory, spacecraft interior caretaking and robot programming. Among these tests, the **Spacecraft Robotics Laboratory at the U.S. Naval Postgraduate School** conducted the first two flight activities of the Astrobatics Project, working with the **Intelligent Robotics Group at NASA's Ames Research Center** in California, the **U.S. Space Test Program** and the **NPS Foundation**. A robotic hopping maneuver was for the first time tested in Earth orbit, by using an Astrobee vehicle as a model of a free-flyer space vehicle with a robotic manipulator. The first Astrobatics activity, performed in March, demonstrated using Astrobee's robotic arm to perform a series of "self-toss" maneuvers. The second flight activity, performed in July, included more "self-toss" robotic maneuvers and used Astrobee's propulsion system for motion stabilization. Such maneuvers could allow a free-flying spacecraft to maneuver around a larger space structure without expending propellant to perform activities such as inspection and robotic servicing.

In May, **MDA** (formerly MacDonald, Dettweiler and Associates), the **Canadian Space Agency** and **NASA** implemented and commissioned the autonomous capability software updates on the **ISS's Canadarm2**. The Mobile Servicing System Application Computer software — the first autonomous vision solution for pose measurement and manipulator motion command — underwent a series of operations, including some free space checkouts. ★

Contributors: *Stephen Kwok Choon, Terry Fong, Jennifer Hudson, David Spangler and Theodore Tzanetos*



▶ NASA's Perseverance rover generated a photo of itself and the Ingenuity Mars Helicopter this year with its Wide-Angle Topographic Sensor for Operations and Engineering, or WATSON, camera.

NASA

Gateway leads the era of deep space infrastructure development

BY HAO CHEN AND KOKI HO

The **Space Logistics Technical Committee** fosters development of integrated space logistics capabilities that enable safe, affordable and routine spacefaring operations.

As a critical component of NASA's Artemis program, the Gateway, an outpost orbiting the moon, will store cargo and have lodging for future human lunar surface activities. In February, NASA awarded a $332 million contract to SpaceX for the **Falcon Heavy** to launch fundamental components of the **Gateway**. This mission would deploy the **Habitation and Logistics Outpost** and the **Power and Propulsion Element** in 2024 to form the first usable lunar space station. In July, NASA awarded a $935 million contract to **Northrop Grumman** to develop the HALO module, short for habitation and logistics outpost, which will be a crew cabin for astronauts. Meanwhile, **Maxar Technologies** is developing the power and propulsion element, which passed the first ground test in March. The **Deep Space Logistics Project** office at **NASA's Kennedy Space Center** in Florida managed the awards for Gateway logistics. After the HALO and power and propulsion element are attached on Earth, SpaceX will launch them from Kennedy.

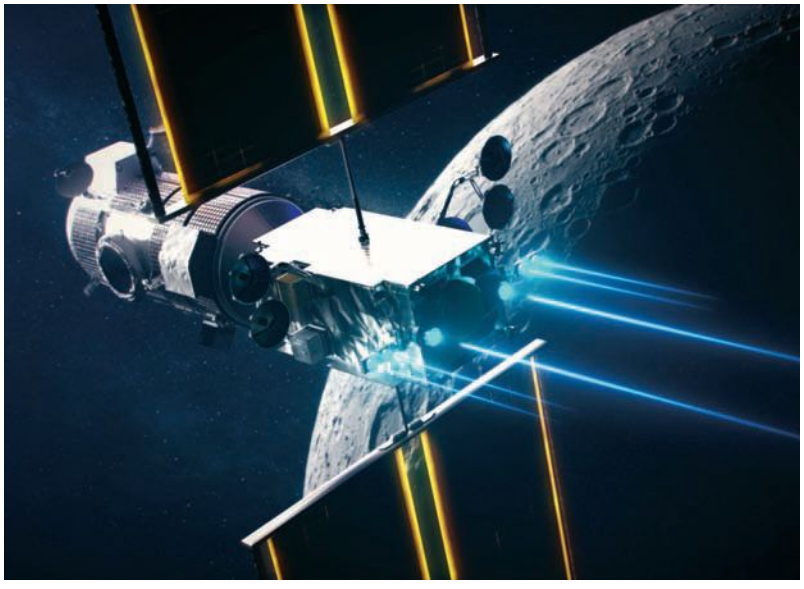
In April, NASA selected **SpaceX's Starship** as the **Artemis lunar lander** with a $2.94 billion contract. The competitors for this contract, Blue Origin and Dynetics, filed protests to the U.S. Government Accountability Office in the same month, citing "flawed acquisition." In July, the GAO denied the protest and affirmed the SpaceX award.

Beyond the cislunar plans, experiments on the red planet demonstrated the potential to build a sustainable crewed habitat on the Martian surface. **NASA's Perseverance rover** landed on Mars in February, and in April, it extracted the first oxygen from Martian's carbon dioxide-rich atmosphere. This experiment paved the way for science fiction to become a reality — generating and storing oxygen on another planet to support astronaut activities and help power rockets. At the same time, the **Ingenuity Mars Helicopter** completed the first powered, controlled flight on Mars, which was also the **first flight test on any planet beyond Earth**.

Earlier this year members of the **space logistics and supply chain management community** at NASA Headquarters, Kennedy Space Center, Ames Research Center and the Defense Contract Management Agency created an informal coalition. This group is embracing Digital Ledger Technology and Intelligent Analytics with existing supply chain modeling capabilities for the purpose of performing pre-procurement strategic sourcing evaluations and setting logistics requirements that will safeguard the health of the space industrial base. The capability of obtaining visibility into a program's industrial base, including the lower-tier suppliers has been achieved. Once the team has completed data sourcing and application programming interfaces by the end of fiscal 2022, simulations or "war games" will be performed to optimize system support, supplier viability, product quality, on-time delivery and obsolescence mitigation cost.

In academia, the **Space Systems Optimization Group at Georgia Tech** developed a dynamic network framework for on-orbit servicing, assembly and manufacturing. Funded by DARPA, the work enables holistic optimization on operations scheduling, logistics planning and infrastructure design for future satellite servicing missions. Also, the **Massachusetts Institute of Technology** and **Stevens Institute of Technology** developed an open-source, cloud-based platform named **SpaceNet Cloud** for multimission space campaign analysis and evaluation. This work aimed to establish a model-based engineering workflow in future space logistics campaign planning through application programming interfaces and modular, web-based services. ★

Contributors: *Goran Bencun, Craig Bennet, Vince Cappello, Michael C. Galluzzi and Parimal "PK" Kopardekar*



▶ An illustration of the Gateway's Habitation and Logistics Outpost and Power and Propulsion Element modules.

NASA

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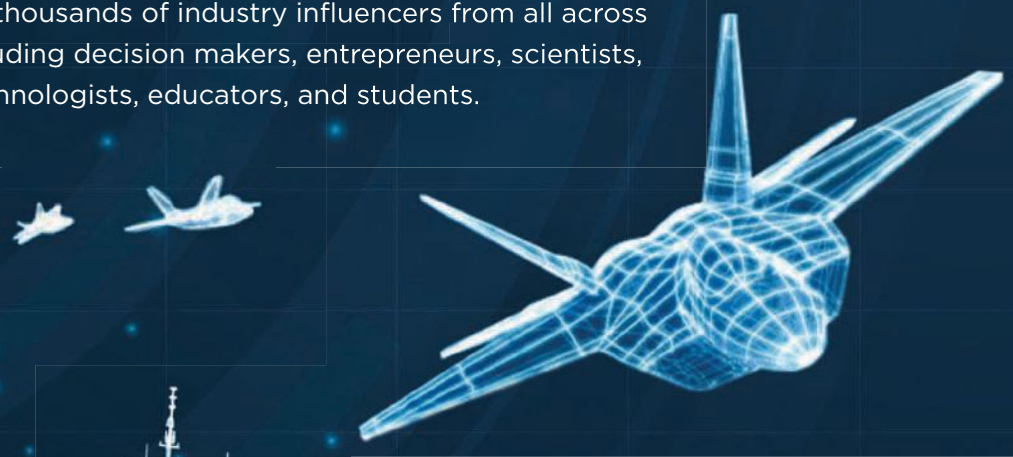

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SHAPING THE FUTURE OF AEROSPACE

A paradigm shift: First oxygen produced on Mars

BY LAURENT SIBILLE AND CHRISTOPHER B. DREYER

The **Space Resources Technical Committee** advocates affordable, sustainable human space exploration using nonterrestrial natural resources to supply propulsion, power, life-support consumables and manufacturing materials.

▲ An illustration of NASA's Lunar Safe Haven concept in which structures would be made from lunar regolith.
NASA

Off-Earth resource extraction by human-made machines occurred for the first time in April when the **Mars Oxygen In-Situ Resource Utilization Experiment**, or MOXIE, **extracted 5.37 grams of oxygen** via electrolysis of carbon dioxide from the Martian atmosphere. The 17-kilogram, toaster-size payload nested inside **NASA's Perseverance rover** changed the paradigm about space exploration. As of the end of October, NASA had completed five of the production experiments planned during one Martian year to validate solid-oxide electrolysis and other technologies at a production rate of up to 10 grams of oxygen per hour. MOXIE achieved several primary objectives, including operation during day and night, during seasonal changes of a quarter of a Martian year and at varied operating temperatures.

In May, the **Polar Resources Ice Mining Experiment-1** completed an integrated interfaces critical design review with the lander team. NASA selected Intuitive Machines' Nova-C in October 2020 as the lunar lander to carry PRIME-1. PRIME-1 is NASA's first resource-prospecting payload and will go to the connecting ridge of south polar Shackleton crater with the Regolith and Ice Drill for Exploring New Terrains and Mass Spectrometer Observing Lunar Operations instruments.

In September, NASA selected the western ridge of Nobile Crater as the landing site for the **Volatiles Investigating Polar Exploration Rover**, or VIPER, which is scheduled to fly after PRIME-1 and will carry a copy of PRIME-1's TRIDENT drill and mass spectrometer along with the Near-Infrared Volatiles Spectrometer System, or NIRVSS and the Neutron Spectrometer System, to explore ice in the permanently shadowed region, or PSR of the moon.

NASA's Space Technology Mission Directorate awarded a record number of projects to NASA teams, academia and private companies for the development of technologies for space resources exploration and extraction guided by the **Lunar Surface Innovation Initiative** program. In August, NASA announced promising concepts from Florida-based **Redwire**, the **Colorado School of Mines** and Colorado-based **Austere Engineering** as the winners of **NASA's Break the Ice Lunar Challenge** Phase 1 among 31 teams representing the U.S., Canada, Australia and Sri Lanka. Ten runner-up teams also received awards. Phase 1 challenged teams to design a system architecture for excavating and transporting large amounts of icy regolith and water from a PSR near the moon's south pole..

In the field of construction technologies using in-situ resources, materials and concept testing has moved to a larger scale. In December 2020 and March, **NASA's Swamp Works** at Kennedy Space Center in Florida and California-based **Masten Space Systems** completed landing-launch pad materials exposure tests to a methane-oxygen rocket engine under conditions approximating that of large lunar landers. In January, NASA selected seven university teams to address dust mitigation technologies in the **2021 Big Idea challenge**, including a Colorado School of Mines team that completed landing-launch pad materials testing at Masten Space Systems in September.

Also in September, **NASA's Langley Research Center** in Virginia completed the multicenter **Lunar Safe Haven concept study** for creating a shelter using lunar regolith resources and autonomous robotics to protect crew members against radiation and meteoroids.

In March, **Michigan Technological University** inaugurated the **Planetary Surface Technology Development Lab** as one of the largest nongovernment versatile test facilities for space resources technology testing under lunar surface conditions, including dust, vacuum and temperatures. NASA announced in January that the laboratory won the 2020 NASA Big Idea challenge with its vehicle that can travel down 45-degree slopes while deploying a superconducting power and communication tether to explore resources in permanently shadowed craters. The lab tested the vehicle repeatedly early this year on 30-degree to 45-degree slopes in the lunar regolith test box while deploying the tether with only 1 newton of tension. ★

Contributors: *Michael Hecht, Julie Kleinhenz, Diane Linne, Robert Moses, Paul van Susante and Naveen Vetcha*

Human spaceflights and science missions lead dynamic year

BY PHILIP VENTURELLI

The **Space Systems Technical Committee** fosters the development, application and operation of space systems and addresses emerging issues in the area.

This year was ground-breaking for space systems accomplishments. The pace is only likely to accelerate, especially as NASA's ambitions to go back to the moon ramp up and the private space industry continues to rapidly grow.

In February, **NASA's Perseverance rover** landed on Mars. Perseverance traversed a significant amount of terrain on the red planet and began sampling Martian rock. The rover's mission is to seek evidence of ancient life and collect samples for a future return mission. Perseverance is about the size of a car and comparable in size to the Curiosity rover.

In April, NASA's **Ingenuity Mars Helicopter** took flight on Mars. It was the first powered flight on another planet. A **United Launch Alliance Atlas V** rocket launched both Ingenuity and Perseverance in July 2020 from the Florida Space Coast. Since its initial flight, the helicopter has zipped around Mars and taken pictures, demonstrating the value of scouting ahead by air. Its primary mission was as a flight technology demonstrator.

SpaceX launched the Crew-2 mission, which sent four astronauts to the International Space Station aboard the Crew Dragon Endeavour spacecraft in April. Endeavour traveled to the ISS in 2020 as part of the Demo-2 mission. Demo-2 was the first test flight of the SpaceX Crew Dragon capsule with humans on board.

In May**, SpaceX's SN15 Starship** spacecraft touched down safely after performing a **high-altitude test flight**. The spacecraft is intended to take astronauts to the moon in 2025 and subsequently to Mars. The Starship, fueled by methane, flew to an altitude of about 10 kilometers and then performed a "belly-flop" maneuver and returned to Earth, restarting its engines and landing.

In July, Richard Branson and Jeff Bezos flew to space aboard separate launch systems developed by their respective companies, **Virgin Galactic** and **Blue Origin**. The billionaires had been competing to become the first to send civilians into space as a kickoff for the new commercial space travel industry. To begin the era of space tourism, Virgin offered tickets for $450,000.

SpaceX launched its **Crew Dragon Resilience** spacecraft into low-Earth orbit in September. The **Inspiration4** mission to benefit St. Jude Children's Research Hospital carried four passengers. ★

Contributors: *John Carsten and Zack Krevor*

▶ The SpaceX Crew Dragon Endeavour carrying four astronauts pulled away from the International Space Station in November. The capsule splashed down hours later in the Gulf of Mexico.

NASA

Space tethers demonstrate deorbit capability

BY SVEN G. BILÉN

The **Space Tethers Technical Committee** focuses on the development and use of tether-based technology for space systems.

▲ In this illustration, a ribbon of Terminator Tape unfolds from the Alchemy satellite as part of the Dragracer mission. The Alchemy satellite deorbited this year, whereas its near twin, Augury, which does not have a tape module, will continue in orbit for as long as 10 years.

Millennium Space Systems

Tethers Unlimited Inc. of Washington and **Millennium Space Systems**, a Boeing company, announced in August that their **Dragracer** mission demonstrated rapid deorbit of a low-Earth-orbit satellite using a **Terminator Tape Deorbit Module**. TUI's module unfurls a long, thin-but-wide conductive tape to accelerate orbital decay of a satellite through passive electrodynamic and aerodynamic drag interactions with the space environment. Two identical nanosatellites built by MSS were launched in November 2020 into a 500-kilometer orbit. One satellite, called Alchemy, was equipped with the Terminator Tape, and the other, Augury, had no deorbit system. Subsequent tracking of the two satellites showed that Alchemy began deorbiting rapidly soon after launch, indicating deployment of the tether, whereas Augury's orbit decayed at a much slower rate. Alchemy reentered atmosphere in July, eight months after launch. Current estimates of Augury's decay predict it will deorbit within eight to 10 years, depending on solar conditions.

Also in August, Finland-based **Aurora Propulsion Technologies** announced plans to launch a satellite to **test space junk removal technologies** on **Rocket Lab's Electron launcher**. As part of a ride-share mission scheduled for late this year, after lifting off from Launch Complex 1 on New Zealand's Mahia Peninsula, Electron was to deploy **AuroraSat-1** into low-Earth orbit. The AuroraSat-1's mission is to demonstrate water-based resistojet propulsion devices and "plasma brakes" that can provide propulsion and deorbiting capabilities for small satellites. The plasma brakes have a deployable microtether that interacts with charged particles in ionospheric plasma to generate significant drag to deorbit the spacecraft safely at its end of life.

With respect to component technologies for tether deorbit systems, the **U.S. National Science Foundation** awarded a grant to the **University at Buffalo** in May to explore **how robotic tether systems could corral orbital debris using nets for later deorbit**.

In October, the European Commission-funded Electrodynamic Tether Technology for Passive Consumable-less Deorbit Kit, or E.T.PACK, finished manufacturing its **deorbit device prototype**. With a volume of 12 cubesat units and a mass of 24 kilograms, the prototype consists of a module with an electron emitter and a second module with a deployment mechanism that hosts a 500-meter-long tape tether. In May, **SENER Aeroespacial**, the **Universidad Carlos III de Madrid** and **Euroconsult** started working on the business model for the deorbit device with funding from the European Commission.

The **European Space Agency** selected **Universidad Carlos III de Madrid, University of Padova, Dresden University of Technology** and **SENER Aeroespacial** to investigate **consumable-less propulsion based on bare-photovoltaic tethers**. Combining a bare segment with thin-film photovoltaic cells, bare-photovoltaic tethers promise to provide increased power-generation capability for tether systems and are an enabling deorbit technology that is less dependent on ambient space conditions. ★

Missile defense and hypersonics tests characterize busy year

BY JAMES D. WALKER AND NICHOLAS J. MUESCHKE

The **Weapon System Effectiveness Technical Committee** advances the science and technology of predicting, measuring, evaluating and improving the lethality of weapon systems.

DARPA and the **U.S. Air Force** conducted a free flight test of the **Hypersonic Air-breathing Weapon Concept** in September. **Raytheon** built a HAWC prototype, and **Northrop Grumman** built the missile's scramjet engine. In the test, the HAWC prototype was carried under the wing of an aircraft and released. Seconds later, a solid rocket motor boosted the HAWC prototype to supersonic speed. The scramjet engine then ignited and accelerated the missile, enabling it to reach hypersonic speed, or greater than Mach 5. The air-breathing scramjet engine used hydrocarbon fuel. The test validated the HAWC prototype's airframe and propulsion system could reach and cruise at hypersonic speeds. The success built on pioneering scramjet projects, including the X-30 National Aero-Space Plane, the uncrewed flights of NASA's X-43 vehicles and the U.S. Air Force's X-51 Waverider.

▼ A false color schlieren image of a hypersonic conical test article in free flight at Mach 5.5. A digital overlay of the test article CAD on an experimental image is shown for clarity.

Southwest Research Institute

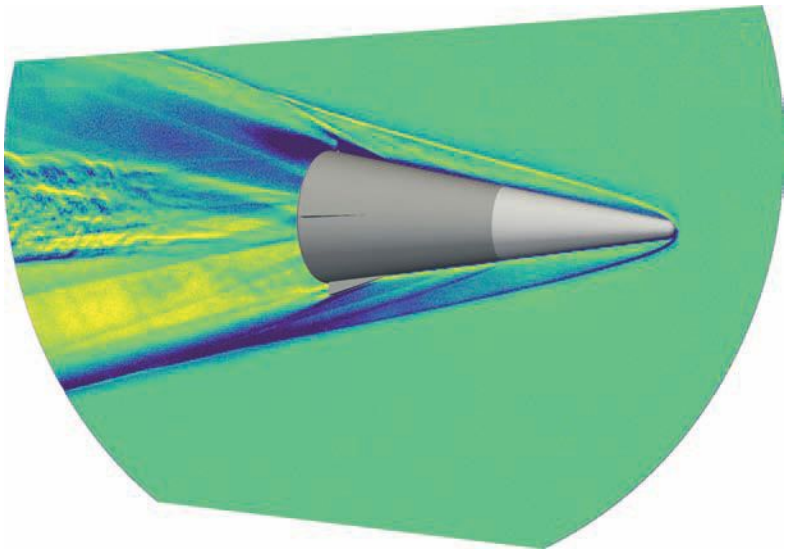
In other hypersonic air-breathing missile news, in March and August, the **U.S. Navy** put out a solicitation for a **Screaming Arrow prototype** program to develop an F/A-18E/F Hornet aircraft-compatible **air-launched hypersonic cruise missile** platform to complement the **Conventional Prompt Strike** boost glide system.

In conjunction with **Australia**, the U.S. began the **Southern Cross Integrated Flight Research Experiment** prototyping program to develop through a preliminary design review a solid rocket-boosted, air-breathing, hypersonic conventional cruise missile. The Air Force issued round-two contract options to **Boeing** and **Lockheed Martin** in September. It is a follow-on to the joint Hypersonic International Flight Research Experimentation Program between the U.S. and Australia that conducted flight tests of rocket-launched air-breathing vehicles in Australia.

The U.S. Air Force conducted arena testing of the **AGM-183A Air Launched Rapid Response Weapon** at **Eglin Air Force Base** in Florida. However, there were **two setbacks** during the ARRW's air launch tests over **Point Mugu Sea Range** in California. During the first scheduled booster flight test of the ARRW in April, the missile did not complete its launch sequence and remained attached to the B-52H Stratofortress aircraft that was carrying it. In July, the Air Force made a second attempt, and while the missile separated from the B-52, the rocket did not ignite.

The U.S. Army and Navy tested components of the **Long Range Hypersonic Weapon** as part of the Conventional Prompt Strike program in Utah. In May, the services tested the first-stage solid rocket motor, and in August, they tested the second-stage solid rocket motor. The solid rocket motors also demonstrated a thrust vector control system. The missile is a Navy-designed, Army-produced common hypersonic missile based on the Common Hypersonic Glide Body. The Army plans to field the initial LHRW battery by 2023. The Navy announced that, in addition to the initially planned submarine launch capability, the CPS system will also be outfitted on Zumwalt-class destroyers.

This year saw continued progress in missile defense. The **U.S. Missile Defense Agency**, in cooperation with the Navy, conducted flight tests of the **Aegis Weapon System** northwest of Hawaii in July. The objective was to intercept two short-range ballistic missile test targets using two Standard Missile-6 Dual II salvos (totaling four SM-6s). At least one target was intercepted. The SM-6 Dual II missile is designed for use in the terminal phase of a short- to medium-range ballistic missile trajectory. It followed a November 2020 developmental test of the SM-3 Block IIA intercepting an ICBM-class target. These tests open the discussion of the role of naval vessels in a layered homeland defense in support of the Ground-based Midcourse Defense and the terminal defense supplied by the Terminal High Altitude Area Defense interceptor system. ★



NASA, FAA open discussions on regulating urban air mobility and transiting space vehicle traffic

BY FRANK L. FRISBIE

The **Aerospace Traffic Management Integration Committee** monitors, evaluates and seeks to influence the direction of ATM technologies with a focus on efficiency, public safety and national security.

The momentum continued surrounding exploitation of the aerospace for unmanned aircraft systems, new point-to-point short and vertical takeoff and landing passenger vehicles, and transiting space vehicles. The U.S. military also made progress on aircraft development programs such as the Navy's Blue Water Maritime Logistics UAS and the Air Force's Agility Prime.

In January, NASA published its **Vision Concept of Operations for its Urban Air Mobility Maturity Level-4**. The document is a foundation for discussion about the development and integration of UAM. In June, the FAA published the **Conops V1 for UAM**, which states that with "traffic and commute times on the ground increasing, there will be an increasing demand and ... due to economic scaling, the volume of UAM operations may increase substantially. ... The increasing number of UAM operations may soon challenge the current capabilities of the ATM infrastructure and Air Traffic Control (ATC) workforce." The Government Accountability Office's January report on the FAA concept of a UAS traffic management ecosystem that it published in 2020 called that concept a "complex undertaking."

In July, the FAA announced a **prototype system to track space launch and reentry vehicles in near real time**. The **Space Data Integrator** improves situational awareness for controllers, which speeds the safe reopening of airspace after launches to reduce impacts on airspace users. While launch and reentry operators monitor their missions and vehicles in real time, the FAA relied heavily on manual processes to retrieve and communicate space data. SDI will provide some much-needed automation.

Further evidence of looming airspace congestion is found in the high investor interest in electric vertical takeoff and landing aircraft. Illustrative was the listing by **Joby Aviation** (a participant in the Agility Prime program) on the New York Stock Exchange in August. Joby plans to field an eVTOL aircraft as a fully certificated air taxi service in 2024. Investors, including **Toyota Motor Corp., Uber Technologies and JetBlue**, are collaborating to offer a door-to-door passenger service. According to the U.S. Air Force, there are now more than 200 companies that are developing cutting-edge vertical flight aircraft based on eVTOL technologies. The Agility Prime program is intended to speed the process of making these types of vehicles commercially viable.

Also carried over into this year was concern that Virginia-based **Ligado Networks**' deployment of 5G service on frequencies neighboring those used by GPS receivers would interfere with those who rely on GPS, including civil and military aviation. Three U.S. senators introduced legislation in June that would require Ligado to cover the cost of replacement or repair of any affected receivers.

In August, the **FAA opened a safety review of Boeing** to investigate complaints that the Organization Designation Authorization — the unit that is authorized to make safety decisions on behalf of the government — may not have had the required autonomy. Should the FAA find that these concerns are justified, it could have wide implications for certification of aircraft, including the requirement for more FAA personnel to perform the function directly.

In November, the **Russian Defense Ministry** fired a **direct-ascent anti-satellite missile** at the Soviet-era surveillance satellite COSMOS 1408, destroying the satellite and creating a cloud of at least 1,500 "trackable" pieces of new debris in low-Earth orbit, U.S. Space Command said. The fragments prompted astronauts and cosmonauts aboard the **International Space Station** to temporarily shelter in their docked Crew Dragon and Soyuz capsules. ★

Contributor: *Charles Keegan*

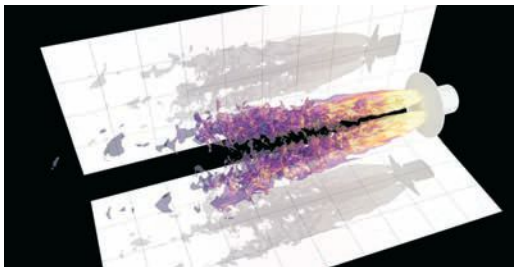
▶ Joby's S4 prototype aircraft flies above California. The company was listed on the New York Stock Exchange as investor interest in electric vertical takeoff and landing vehicles climbed.

Joby Aviation

Refining challenge goals to make realistic progress

BY REYNALDO J. GOMEZ III, ANDREW W. CARY AND ERIC NIELSEN

The **CFD Vision 2030 Integration Committee** advocates for, inspires and enables community activities recommended by the vision study for revolutionary advances in the state-of-the-art of computational technologies needed for analysis, design and certification of future aerospace systems.



This notional Mars lander entry flowfield at Mach 1.4 was computed in May by the NASA FUN3D flow solver. The plumes are an isosurface of the mass fraction of water colored with vorticity magnitude. This solution was computed on the U.S. Department of Energy's Summit supercomputer.

Patrick Moran/NASA

Three grand challenge problems crafted by the committee — low-speed, high-lift aerodynamics predictions; full engine turbofan unsteady simulations; and computational fluid dynamics-in-the-loop Monte Carlo simulation for space vehicle design — were reexamined this year and refined to focus on achieving the challenge goals, when possible, or determining where additional resources are required to achieve them. These challenges focus development work on complex real-world issues that exercise all elements of the original 2030 Vision Roadmap. A key goal of this effort is to **energize the aerospace computational aerodynamics communities** by collaborating across technology providers to accelerate the use of efficient and robust computational tools to ultimately create products with increased aerodynamic performance that are environmentally cleaner and more fuel efficient and ensure safe flight while reducing nonrecurring product development cost and risk.

Progress continued this year toward meeting the Roadmap milestones in high-performance computing, physical modeling and robust meshing of complex geometries. Researchers at **NASA's Langley Research Center** in Virginia ported the generic gas version of the **FUN3D flow solver** to run on graphics processing units, and in January they reported over a **10x reduction in time to solution**. FUN3D developers spent most of this year making improvements and applying them to supersonic retro propulsion problems and **Multi-Purpose Crew Vehicle abort simulations** and database development.

Physical modeling improvements in wall modeled large eddy simulation and demonstrations on complex configurations were reported by multiple groups. Researchers at **Stanford** and the **University of Pennsylvania** showed results in August indicating that wall modeled large eddy methods can be applied to flows to highly 3D boundary layers, but some errors are introduced if a simple 2D based wall model was used. **Hypersonics researchers** at the **University of Minnesota** and **Texas A&M** took on the challenge of applying wall modeled large eddy simulations to complex geometries and high-speed flows and used direct numerical simulation data to assess the accuracy of these models.

The year brought evolutionary progress and maturation of methods in mesh generation. Improvements in the **MIT** and **Syracuse University Engineering Sketch Pad software** and NASA's refine code have brought designers closer to the goal of "automatic generation of mesh on complex geometry on first attempt."

In August, Langley demonstrated automated meshing and solution of a supersonic **Space Launch System** configuration with support hardware in a detailed wind tunnel test section with only minor user intervention to repair the input geometry. A detailed review by the Roadmap subcommittee showed that while there was progress on key technology demonstrations, many of the original milestones were behind schedule. The Roadmap subcommittee recommended some minor updates including moving the HPC milestone "Demonstrate efficiently scaled CFD simulation capability on an exascale system" out one year, due to the current state of the art, and some of the multidisciplinary optimization milestones have been delayed by two years based on the state of the art.

Efforts continued throughout the year toward the CFD Vision 2030 and **2024 NASA Transformational Tools and Technologies** milestone to **demonstrate an exascale solution capability**, or throughput of approximately 10^{18} floating point operations per second. The end goal is to reduce analysis and design times by multiple orders of magnitude. For instance, an international team of 20 researchers continued applying the FUN3D CFD solver to **investigate aero-propulsive effects for human-scale Mars entry**. The researchers from NASA, Kord Technologies, the National Institute of Aerospace, NVIDIA in Berlin and Old Dominion University used computational time awarded in November 2020 by the **U.S. Department of Energy**. This year's award consisted of 770,000 node-hours of computational time on the **Summit computing facility**, the world's most powerful GPU-based supercomputer. The allocation is roughly equivalent to 1 billion central processing unit core-hours. The team extended its prior 2019 work by performing 10-species reacting-gas detached eddy simulations of oxygen and methane combustion along with the Martian CO_2 atmosphere using meshes of billions of elements, routinely running on 16,000 GPUs, or the equivalent of several million CPU cores. ★

NASA flies to Mars; Webb nears launch

BY LEENA SINGH AND SURENDRA P. SHARMA

The **Space Exploration Integration Committee** brings together experts on topics relevant to future human and robotic exploration missions.

The James Webb Space Telescope was unpacked at the Guiana Space Center in French Guiana in October after traveling by ship from California.

NASA

NASA's **Perseverance rover** touched down on the surface of Mars in February on a two-year mission to the Jezero Crater, a large impact basin north of Mars' equator. The rover will collect samples to characterize the region's geology, climate and astrobiology. Perseverance's entry sensors collected atmosphere data during transit while the Terrain Relative Navigation system autonomously guided the lander through its descent flight phase. Data from both are expected to help future human missions land on other worlds more safely and with larger payloads. Perseverance is armed with a multitude of scientific experiments in support of this and future missions, including the Mars Oxygen In-Situ Resource Utilization Experiment, or MOXIE, an instrument to produce oxygen from Mars' mostly carbon dioxide atmosphere. MOXIE had its first test run in April, when it extracted 5 grams of oxygen, or about 10 minutes of air for an astronaut. In September, the rover cored Martian rock for the first time in preparation for the sample's eventual return to Earth.

In April, the **Ingenuity Mars Helicopter** that arrived with Perseverance achieved an extraplanetary first — powered, controlled atmospheric flight, taking off and hovering at 3 meters for 30 seconds before a safe, controlled descent conducted by its autonomous guidance, navigation and control autopilot. Ingenuity had flown 15 flights by early November, scouting the Jezero neighborhood at 10-meter altitudes, augmenting overhead orbiter imagery with high-quality intel from nearer afield, in preparation for the rover's sample collection trips.

NASA continued progress toward a planned 2025 lunar landing under its **Artemis** program with the **Space Launch System rocket**. The core rocket stage was mated with twin solid rocket boosters and then joined to the launch stage adapter by June. The stage adapter connects the rocket's upper and lower launch stages and houses the engines that will insert the Orion spacecraft on lunar intercept course. NASA also conducted an eight-minute hot-fire of SLS' core stage gimbaled engines in March after a January test was cut short.

In July, the **Parker Solar Probe** conducted a **flyby of Venus** in preparation for a close approach to the sun. Parker dipped into Venus' ionosphere, collecting measurements of its ambient atmospheric radio signals. The data confirmed Earth-based observations that Venus' ionosphere is much thinner during certain solar phases than in others, suggesting that Venus' atmosphere, once Earth-like, has become a hot, toxic gas cloud as its ionosphere leaks, potentially affecting its atmosphere.

Two **European Space Agency spacecraft** also performed **Venus gravity-assist flybys**, hours apart from each other in August. **Solar Orbiter**, a joint mission with NASA, is bound for the sun, and **BepiColombo**, a joint project with the Japan Aerospace Exploration Agency, is headed to Mercury orbit; both used Venus flybys to shape their orbital transfers to rendezvous with their host bodies. BepiColombo telemetered images from its closest approach at 552 kilometers above the surface, as well as measurements from its extremely sensitive Italian Spring Accelerometer. ISA registered the planet's strong gravitation, disturbance effects due to thermal shocks during day and night passages, and tidal forces. Both spacecraft also recorded the planet's magnetic field, capturing solar wind interference effects with the planetary atmosphere.

In August, the **James Webb Space Telescope** completed its final preflight tests in preparation for a December launch. These final operations tests were conducted at **Northrop Grumman**'s flight facility in California before Webb was shipped to Europe's spaceport in French Guiana for its launch to orbit on an Ariane 5 rocket. The telescope, a joint project of **NASA, ESA and the Canadian Space Agency**, has been decades in the making, involving participation from a dozen nations. Once operable, the telescope will be a generational leap beyond the Hubble Space Telescope's capability. Also this year, 266 general observation programs were selected from 1,000 science proposal submissions worldwide, booking the first cycle of observation times on Webb. ★

Low-boom technologies gain ground with improved measurement tools and more research

BY JULIET PAGE AND GÉRALD CARRIER

The **Supersonics Integration and Outreach Committee** promotes a community of practice engaged in the technical, business, environmental and societal issues associated with supersonic transports and the research needs of this emergent capability.

▲ This year workers joined the wing, tail assembly and fuselage of the Quiet SuperSonic Technology, or QueST, aircraft at Lockheed Martin Skunk Works in California.

Lockheed Martin

Several **low-boom technologies** were brought closer to readiness this year. Building on its Cart3D computational fluid dynamics solver, researchers at **NASA's Ames Research Center** in California demonstrated from January to April a fully integrated method for **adjoint-based sonic boom minimization** via trimmed control surface deflections that included geometry modeling, near-field aerodynamics, far-field propagation and ground-level loudness metrics.

From November 2020 to May, researchers at the **Japan Aerospace Exploration Agency** developed and validated a computationally efficient space marching method with molecular vibrational relaxation using a fast full-field simulation of sonic boom through a stratified atmosphere. These technology maturation advancements provide important tools enabling new and improved low-boom aircraft designs.

Researchers performed the **Exosonic low-speed tests** at the **Kirsten Wind Tunnel at the University of Washington** in May. These tests followed the November 2020 **Aerion high-speed tests** and the December 2020 EU project **RUMBLE sonic boom tests** in the **ONERA-S2MA wind tunnel in France**. These tests provided important technical information for use in model validation and design.

NASA continued construction of its **X-59 Quiet SuperSonic Technology** aircraft. In May, **Lockheed Martin** joined the X-59's wing, tail assembly and fuselage. The X-59 is designed to fly faster than Mach 1 while reducing the sonic boom to a quiet thump — a feat that may lead to commercial supersonic flight over land, reducing flight times dramatically. Acoustic validation flights for the X-59 will require chase aircraft flying at precise positions in the air relative to the X-59, capturing shock wave measurements. In April, NASA tested the **Airborne Location Integrating Geospatial Navigation System** visual navigation system to enhance precise aerial position between two aircraft in supersonic flight.

Regarding regulatory and certification aspects of supersonic flight, an International Civil Aviation Organization working group used simulated sonic boom measurement datasets that included turbulence to contribute to the development of **supersonic standards for en-route sonic booms that are over land**. These analyses demonstrated the viability of a potential certification scheme. In June, published findings suggested that a modest number of microphones spaced approximately 30 meters apart may be adequate for use in future certification protocols.

The **environmental impacts of supersonic transport** have also been the focus of several research efforts. Aerodynamic and acoustic modeling and testing of landing and takeoff noise and emissions have demonstrated and validated methodologies to evaluate and reduce the environmental impact of potential future supersonic transport. NASA sponsored computational modeling and 15% scale wind tunnel testing for a generic low-boom concept vehicle. Final processing, analysis and reporting of the measured aerodynamic and simulated aeroacoustic data used for validation of the predicted landing and takeoff flight regime results occurred from November 2020 to April. In Europe, the **H2020 project SENECA** was launched in January to address engine-related environmental aspects of supersonic transport aircraft, including emissions, contrails and landing and takeoff noise.

Regarding industry-led projects, despite **Aerion**'s abrupt shutdown in April, several other companies continued development of their aircraft concepts. **Boom Supersonic** began ground testing of its piloted **XB-1 scaled flight test demonstrator aircraft** (22 meters long) after rolling it out in October 2020. **Exosonic** is working toward a quiet supersonic airliner capable of overland supersonic flight with a low sonic boom. In May, the company completed low-speed testing of a 3.5% scale supersonic technology as part of its U.S. Air Force contract and used the aerodynamics data to help anchor its engineering tools. ★

Contributors: *Matthew Kamlet, David Lazzara and John Morgenstern*

Transformational flight business ramps up with mergers and purchase orders

BY KENNETH H. GOODRICH AND MICHAEL D. PATTERSON

The **Transformational Flight Integration Committee** serves as a focal point for a community of practice engaged in technical, business and societal issues associated with transformational approaches to on-demand air mobility enabled by the convergence of advanced technologies.

The year began with a realignment in the **urban air mobility** ecosystem as **Joby Aviation** of California completed its acquisition of **Uber's Elevate** initiative, consistent with an agreement announced in December 2020. The deal reshaped the UAM sector as Elevate transitioned from serving as a catalyst for many vehicle developers to being absorbed by one.

At the beginning of the year, multiple advanced air mobility aircraft developers announced plans to raise capital and become listed on public stock exchanges by merging with special purpose acquisition companies. Joby, U.K.-based **Vertical Aerospace**, Germany-based **Lilium** and California-based **Archer** announced mergers. Many of these deals were supported by aircraft purchase agreements from passenger and cargo airlines, as well as UAM operators. These agreements are typically conditional on type and production certification. As of September, Joby completed its merger and is listed on the New York Stock Exchange, having raised $1.6 billion.

In February, two companies conducted **demonstrations of autonomy stacks** they are developing for conventional and AAM aircraft with the goal of **certifying cargo aircraft that are remotely supervised from an operations center**. San Francisco-based **Xwing** completed a gate-to-gate demonstration of a modified Cessna Caravan autonomous cargo aircraft. Based in part on the flight, Xwing raised $40 million. At nearly the same time, **Reliable Robotics** of California completed a series of remotely supervised test flights, also using a modified Caravan. Reliable Robotics previously announced **a partnership with FedEx to develop and certify autonomous cargo aircraft** over several years.

The **regional air mobility market** gained prominence this year. In April, NASA released a white paper co-written by 21 researchers in government, industry and academia laying out a vision for RAM. In February, an acquisition of **Ampaire**, a California electric aircraft developer, by the subscription-based operator **Surf Air** was announced. Swedish startup **Heart Aerospace**, which is developing a 19-seat electric aircraft, received conditional orders for 100 aircraft from United Airlines, and Israeli company **Eviation** unveiled a new design for its nine-passenger Alice aircraft along with orders from DHL in July.

In May, "NOVA" on PBS premiered an episode titled **"Great Electric Airplane Race,"** documenting the motivations, challenges and progress toward developing practical electric aircraft, with an emphasis on AAM. This episode is evidence of the growing public interest and awareness of transformational flight activities.

In July, **Volocopter**, based in Germany, announced the purchase of composite sailplane manufacturer DG Flugzeugbau's manufacturing operation. The acquisition enhances Volocopter's ability to bring its multicopter to market by leveraging DG Flugzeugbau's production organization approval.

In July, Vermont-based **Beta Technologies** and **Joby Aviation** conducted long-distance test flights of their electric aircraft prototypes. Beta's **Alia aircraft** flew 330 kilometers in its conventional aircraft configuration with an onboard pilot. Although designed as an eVTOL aircraft, the flight was performed with the vertical lift system removed, resulting in weight and drag reductions. Joby's **prototype of its S4 aircraft** completed a flight of 247 km, including vertical takeoff and landing segments. While the production S4 is designed for an onboard pilot, the test flight was remotely piloted.

NASA's Advanced Air Mobility National Campaign series hosted its first eVTOL flights with the Joby S4 prototype aircraft, completing acoustic measurement scenarios in August and September. The flights resulted in the first known high-resolution acoustic measurements of an eVTOL aircraft in hover and low-speed flight and will be used to inform noise modeling and eVTOL certification requirements. ★

▼ Xwing's Cessna Caravan-based test platform is representative of aircraft that several companies are developing and testing, equipped with autonomy packages that enable remote supervisory operations for small cargo aircraft in the near term and passenger aircraft in the long term.

XWing

Recreational space travel and Martian exploration highlight year

BY KEVIN BURNS

The **History Committee** works to preserve the record of aerospace advances and recognize their impacts on modern society.

▲ Boom Supersonic says its Overture airliner will operate on sustainable aviation fuel, cut travel times by 50% and be ready to carry passengers by 2029.

Boom

In addition to the disruption caused by the pandemic, this year will likely be remembered for the first commercial passenger flights into space and the operations of NASA's Perseverance rover on Mars.

In commercial flights, Richard Branson's **Virgin Galactic VSS Unity** capsule was launched into orbit on July 11 with two pilots and four passengers, Jeff Bezos' **Blue Origin New Shepard** capsule was launched on July 20 with four passengers, and Elon Musk's **SpaceX Crew Dragon** was launched on Sept. 15 with four passengers. Some media outlets referred to these flights as the "Billionaire Space Race."

On Feb. 18, the **Perseverance rover landed on Mars** with the **Ingenuity Mars Helicopter**, which performed the first powered aircraft flight on another planet. Three national Mars exploration programs arrived at Mars in February. In addition to the United States landing Perseverance, which will search for past life on Mars and collect soil and rock samples, the **United Arab Emirates' orbiter Hope** arrived at Mars to study the planet's climate, and China landed its **Tianwen-1 orbiter** and Zhurong rover, which will look for pockets of water beneath the surface that may contain life.

China began construction of the **Tiangong space station** in a low-Earth orbit with the launch of the Tianhe core module in April, followed by robotic cargo deliveries in May and September. In June, China launched a 92-day crewed mission of three to begin building the space station.

In January, the FAA published the **Boeing 737 MAX investigation report**, and the U.S. Department of Justice announced Boeing had agreed to pay **$2.5 billion** to resolve a criminal charge related to the case.

In June, **United Airlines** announced it would order **15 Overture airliners from Boom Supersonic** with an option to buy 35 more, once the proposed Mach 1.7, 55-passenger aircraft meets safety, operating and sustainability requirements. Boom's XB-1, a **one-third scale tri-jet supersonic demonstrator**, rolled out of the factory in October 2020 and was expected to start flight testing in early 2022. Boom said that it has commitments for 70 aircraft and that those mark the return to supersonic passenger transport, which ended with the Concorde in 2003.

This year was the centennial for several aviation milestones. In February 1921, the **first day-and-night airmail flight** was made across the United States. Three months later, **Laura Bromwell set a women's aviation speed record** of 215 kph (135 mph); she died in an aviation accident in June of that year. Also in June 1921, Boeing won a $1.4 million contract to build 200 fighters for the U.S. Army, which allowed the company to abandon making furniture. **Bessie Coleman**, having attended flying school in France, got her pilot's license and became the **first black person to earn an international pilot's license**. In July 1921, **Donald Douglas founded the Douglas Aircraft Co.** at Clover Field (now Santa Monica Airport in California), and Billy Mitchell conducted bombing trials to show the power of aircraft to sink major warships, an exercise that remains controversial. In August, the U.S. Navy established the Bureau of Aeronautics. In September 1921, Navy Lt. John Macready set a world flight altitude record of 34,508 feet and received the Mackay Trophy for the flight. In December 1921, the USS Wright, AZ-1, was commissioned as the Navy's first and only balloon ship; it is the only Navy ship to bear the "AZ" designation for "lighter-than-air craft tender." ★

A year of space tourism flights, planetary exploration and limited air travel

BY AMIR S. GOHARDANI

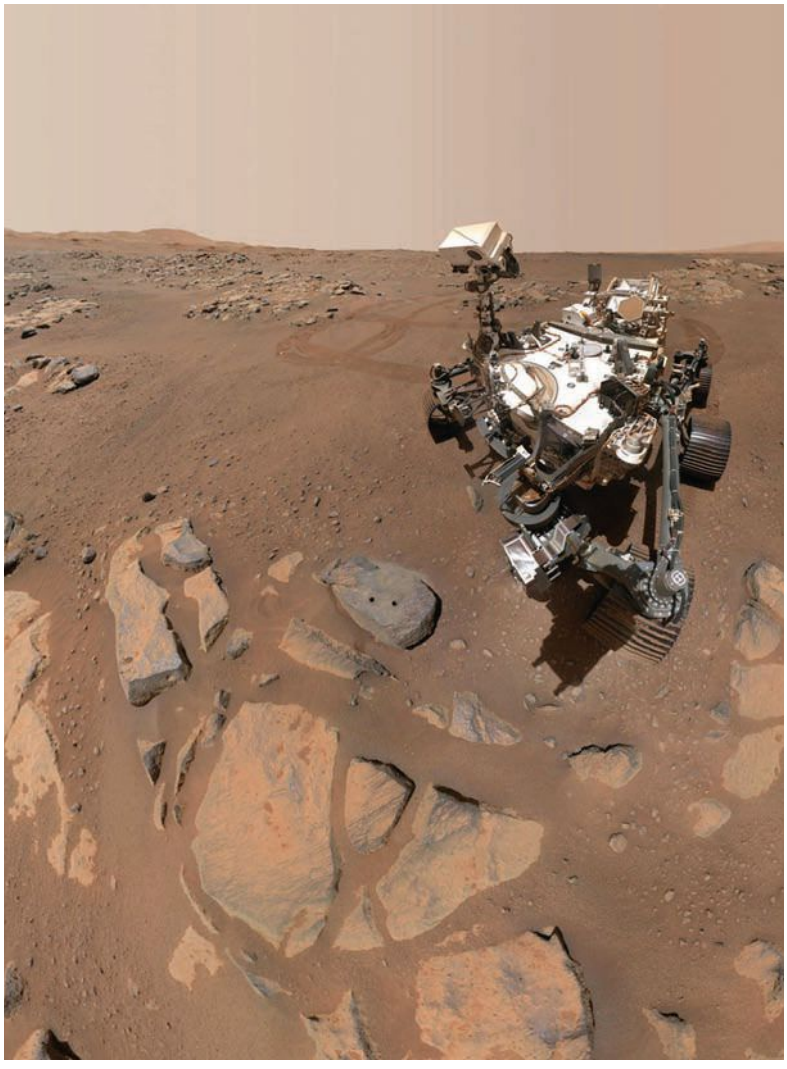
The **Society and Aerospace Technology Outreach Committee** promotes the transfer and use of aerospace technology for the benefit of society.

This year marked a notable era for space tourism and new planetary exploration.

In February, three nations arrived at the Martian atmosphere. The Chinese orbiter and rover **Tianwen-1 and Zhurong** arrived at Mars, making China the only nation other than the United States to land and operate a spacecraft on the red planet. With a mission objective of acquiring a complete picture of the Martian atmosphere, **United Arab Emirates' Hope orbiter** also initiated its studies. One of the space exploration highlights that engaged the public and drove trending media worldwide was **NASA's Perseverance rover**, whose mission is to search for past life and collect samples for eventual return to Earth. Then in April, NASA's 1.8-kilogram **Ingenuity Mars Helicopter** demonstrated the first powered flight on another planet, after hitching a ride on Perseverance and 118 years after the Wright brothers' historic flight on Earth. This technological feat was not only extraordinary because of the bold technology demonstration goal but equally marked a flight environment within a thin atmosphere, less than 1% as dense as Earth's.

Civil aviation continued to suffer the effects of the covid-19 pandemic. In a summary released in November, the **International Civil Aviation Organization** projected that **airlines would offer 61% fewer seats for international passenger flights** this year compared to 2019, resulting in an approximate $250 billion loss in gross operating revenue. A similar comparison for domestic passenger traffic revealed an overall reduction of 24% of seats, resulting in an approximate $72 billion loss. ICAO estimated there will be 1,300 million fewer international passengers this year compared to 2019 and about 860 million fewer domestic passengers.

Contrary to the unprecedented decline of world passenger traffic, commercial spaceflights began operating for the first time. In July, **Virgin Galactic**'s **Unity 22** reached apogee at 86 kilometers with two pilots and four passengers, including Richard Branson, the founder of the Virgin Group. Nine days later, **Blue Origin's NS-16** carried four space passengers, including founder Jeff Bezos, to 107 km above sea level in an approximately 10-minute flight. In September, **SpaceX's Crew Dragon Resilience** spacecraft carried four private citizens, including Shift4Payments CEO Jared Isaacman, to an altitude of 590 km. After three days orbiting the Earth, the spacecraft splashed down in the Atlantic Ocean. Isaacman contracted SpaceX for the Inspiration4 mission, which benefited St. Jude Children's Research Hospital in Tennessee. ★



▶ NASA's Perseverance rover generated this selfie on Mars in September over a rock nicknamed Rochette. The rover's robotic arm drilled two holes in the rock to extract core samples.

NASA

AIAA Bulletin

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We are frequently asked how to submit articles about section events, member awards, and other special interest items in the AIAA Bulletin. Please contact the staff liaison listed above with Section, Committee, Honors and Awards, Event, or Education information. They will review and forward the information to the AIAA Bulletin Editor.

Calendar

DATE	MEETING	LOCATION	ABSTRACT DEADLINE
2022			
3–7 Jan	AIAA SciTech Forum	San Diego, CA, & ONLINE	1 Jun 21
7 Jan	Combined 4th AIAA CFD High Lift Prediction Workshop and 3rd AIAA Geometry and Mesh Generation Workshop (HLPW-4/GMGW-3)	San Diego, CA	
8 Jan	Additive Manufacturing: Structural and Material Optimization Course	San Diego, CA	
8 Jan	Computational Aeroelasticity Course	San Diego, CA	
8 Jan	Hypersonics: Test and Evaluation Course	San Diego, CA	
8 Jan	Technical Writing Essentials for Engineers Course	San Diego, CA	
8–9 Jan	Agile Systems Engineering Course	San Diego, CA	
8–9 Jan	Aircraft and Rotorcraft System Identification Engineering Methods Course	San Diego, CA	
8–9 Jan	Design of Electrified Propulsion Aircraft Course	San Diego, CA	
8–9 Jan	Missile Guidance Course	San Diego, CA	
8–9 Jan	OpenFOAM CFD Foundations Course	San Diego, CA	
8–9 Jan	Spacecraft Design, Development, and Operations Course	San Diego, CA	
8–9 Jan	1st AIAA High Fidelity CFD Workshop	San Diego, CA	
18 Feb–8 Apr	Design of Experiments: Improved Experimental Methods in Aerospace Testing Course	ONLINE (learning.aiaa.org)	
23–25 Feb, 1–3 Mar	UAV Aircraft Design Course by Dan Raymer	ONLINE (learning.aiaa.org)	
28 Feb–11 Mar	Fundamentals of Python Programming with Libraries for Aerospace Engineers Course	ONLINE (learning.aiaa.org)	
3–4 Feb	Region I Mid-Atlantic Section Young Professionals, Students, and Educators (YPSE) Conference	ONLINE (www.aiaaypse.com)	
5–12 Mar*	2022 IEEE Aerospace Conference	Big Sky, MT (aeroconf.org)	
8, 9, 10 Mar	Understanding Space: An Introduction to Astronautics and Space Systems Engineering Course	ONLINE (learning.aiaa.org)	
8–17 Mar	Trusted Artificial Intelligence Course	ONLINE (learning.aiaa.org)	
14 Mar–6 Apr	Systems Thinking for Modern Aerospace Complexity Course	ONLINE (learning.aiaa.org)	
22–31 Mar	Fundamentals of Thermal Vacuum Testing Science Course	ONLINE (learning.aiaa.org)	
25–26 Mar	AIAA Region III Student Conference	West Lafayette, IN	27 Jan 22
25–27 Mar	AIAA Region I Student Conference	Blacksburg, VA	24 Jan 22

For more information on meetings listed below, visit our website at aiaa.org/events or call 800.639.AIAA or 703.264.7500 (outside U.S.).

DATE	MEETING	LOCATION	ABSTRACT DEADLINE
2022			
29 Mar–7 Apr	Technical Writing Essentials for Engineers Course	ONLINE (learning.aiaa.org)	
1–2 Apr	AIAA Region IV Student Conference	San Antonio, TX	31 Jan 22
1–3 Apr	AIAA Region VI Student Conference	Merced, CA	5 Feb 22
4–5 Apr	AIAA Region II Student Conference	Atlanta, GA	4 Feb 22
4–6 Apr*	3rd IAA Conference on Space Situational Awareness (ICSSA)	Madrid (http://reg.conferences.dce.ufl.edu/ICSSA)	
5, 6, 7, 8 Apr	Applied Model-Based Systems Engineering (MBSE) Course	ONLINE (learning.aiaa.org)	
5–14 Apr	Fundamentals of Data and Information Fusion for Aerospace Systems Course	ONLINE (learning.aiaa.org)	
8–9 Apr	AIAA Region V Student Conference	Colorado Springs, CO	13 Feb 22
11 Apr–18 May	Design of Space Launch Vehicles Course	ONLINE (learning.aiaa.org)	
19–21 Apr	AIAA DEFENSE Forum	Laurel, MD	19 Oct 21
21–24 Apr	AIAA Design/Build/Fly	Wichita, KS	
26 Apr	AIAA Fellows Induction Ceremony and Dinner	Arlington, VA	
27 Apr	AIAA Aerospace Spotlight Awards Gala	Washington, DC	
3–5 May*	6th CEAS Conference on Guidance, Navigation and Control (EuroGNC)	Berlin, Germany (eurognc2022.dglr.de)	31 Oct 21
16–19 May*	26th Aerodynamic Decelerator Systems Technology Conference and Seminar (ADSTCS)	Toulouse, France (https://earthlydynamics.com/adst-2022)	
30 May–1 Jun*	29th Saint Petersburg International Conference on Integrated Navigation Systems	Saint Petersburg, Russia	
14–17 Jun*	28th AIAA/CEAS Aeroacoustics Conference	Southampton, UK (aeroacoustics2022.org)	12 Jan 22
21–24 Jun*	ICNPAA 2021: Mathematical Problems in Engineering, Aerospace and Sciences	Prague, Czech Republic (icnpaa.com)	
27 Jun–1 Jul	AIAA AVIATION Forum	Chicago, IL	10 Nov 21
16–24 Jul*	44th Scientific Assembly of the Committee on Space Research and Associate Events (COSPAR)	Athens, Greece (cospar-assembly.org)	11 Feb 22
7–10 Aug*	AAS/AIAA Astrodynamics Specialist Conference	Charlotte, NC	1 Apr 22
4–9 Sep*	33rd Congress of the International Council of the Aeronautical Sciences (ICAS 2022)	Stockholm, Sweden (icas2022.com)	10 Feb 22
18–22 Sep*	73rd International Astronautical Congress	Paris, France (iac2022.org)	
24–26 Oct	ASCEND Powered by AIAA	Las Vegas, NV	

AIAA Continuing Education offerings

*Meetings cosponsored by AIAA. Cosponsorship forms can be found at aiaa.org/events-learning/exhibit-sponsorship/co-sponsorship-opportunities.

MAKING AN IMPACT

2021 AIAA Foundation Wrap-Up

For 25 years, the AIAA Foundation has been inspiring and supporting the next generation of aerospace professionals.

We are excited to share some highlights of the year with you:

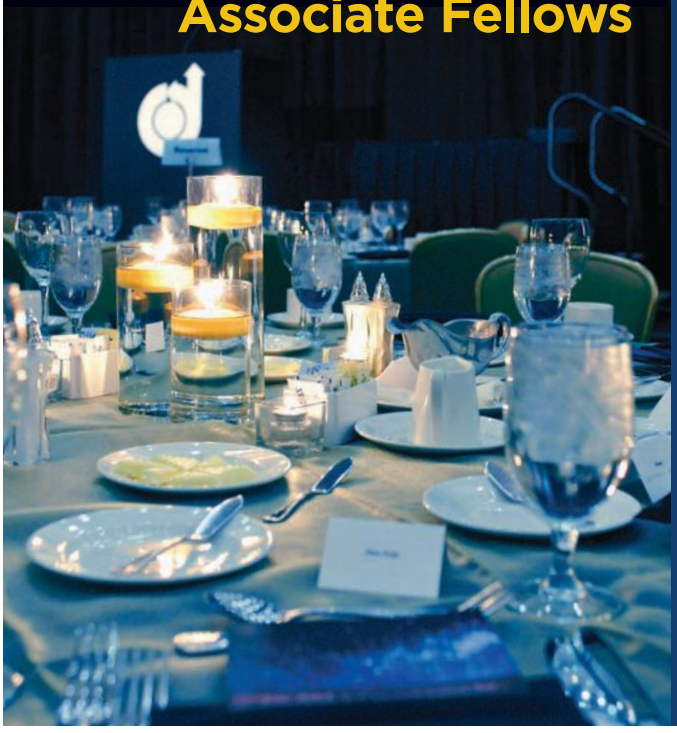
- Received a $1 million grant from Blue Origin's Club for the Future for future programming
- Presented over $100,000 in scholarships to deserving students, including 4 inaugural high school scholarships in honor of Roger Kahn
- Established a new AIAA Lockheed Martin Marillyn Hewson Scholarship for students in need
- Supported 45 diversity scholars at AIAA forums
- Awarded 83 educators across the world with classroom grants that will impact over 16,000 students
- Matched 100 students and mentors through our new Mentor Match program

In addition, we have set an ambitious goal of reaching a million students per year with meaningful aerospace engagement projects. We can only achieve this reach through partnerships, and we're grateful to our many existing partners as well as five new ones that were established this year! We are pleased to welcome these new partners to the AIAA Foundation family:

- Challenger Center: Partnering for a new Trailblazing STEM Educator Award
- AstroAccess: Launching people with disabilities into space
- Discovery Science Center and Planetarium: Implementing a new pilot museum program
- Galileo Program: Providing digital platform content for students and teachers
- National Science Teaching Association/Estes: Creating rocket curricula for teachers

PLEASE HELP US CELEBRATE OUR SILVER ANNIVERSARY WITH A SPECIAL GIFT, which would mean so much to the teachers, students, and future generations of aerospace professionals that we work with. To give, please visit www.aiaa.org/foundation to log in and donate or mail a check to AIAA Foundation, 12700 Sunrise Valley Drive, Suite 200, Reston, VA 20191.

CONGRATULATIONS
Class of 2022 AIAA Associate Fellows



AIAA Associate Fellows Induction Ceremony and Dinner

Monday, 3 January 2022

Manchester Grand Hyatt San Diego in San Diego, California

The Class of 2022 Associate Fellows will be officially recognized for their accomplishments in engineering or scientific work, outstanding merit, and contributions to the art, science, or technology of aeronautics or astronautics.

Join us in recognizing these exemplary professionals during the Associate Fellows Induction Ceremony and Dinner, to be held in conjunction with the 2022 AIAA SciTech Forum at the Manchester Grand Hyatt San Diego on Monday evening, 3 January.

Tickets to this celebrated event are available on a first-come, first-served basis and can be purchased at **aiaa.org/SciTech/registration** or onsite (based on availability).

For more information about the Class of 2022, please visit aiaa.org/news/news/2021/09/27/aiaa-announces-its-class-of-2022-associate-fellows

AIAA
SHAPING THE FUTURE OF AEROSPACE

The Sky is Falling! A Brief Primer on the Problem of Space Debris

By Michael Spencer, AIAA Sydney Section & Tjasa Boh-Whiteman, Co-Chair

On 7 October 2021, from his Missouri office, **Dr. William Schonberg** spoke to the AIAA Sydney Section about the issues and risks of space debris to the orbital space environment and to space missions. Dr. Schonberg is a Professor of Civil, Architectural & Environmental Engineering at Missouri University of Science and Technology (MST). Dr. Schonberg explained how the Earth orbital environment is cluttered with space debris, and understanding space debris, including its locations and collision risks, is essential to inform existing and future space programs and astronaut safety. Space surveillance and traffic management are critical elements to managing collision risks in space traffic management.

Since Sputnik was launched in 1957, the space race has exponentially increased the number of space launches and artificial objects in orbit. Satellites were being launched into two distinctly popular orbital regions—low Earth orbits and geosynchronous orbits. Over nearly 65 years, about 7,000 spacecraft have been launched into orbit, with approximately 3,500 spacecraft still resident in orbit. Today, only about 1,000 of those spacecraft are still functional.

Future predictions estimate that up to 65,000 new satellites will be launched in the next five to ten years. This is not necessarily all bad news since they will bring communications to places without internet access, and the increase in internet speed and reach will be good for business and disaster management. However, the exponential increase in orbiting space objects also will increase the probability of an on-orbit impact by a piece of space junk.

Space debris accumulates as satellites become defunct, as pieces of debris are jettisoned as a planned event in a space mission or have fallen off satellites after mechanical failures, or as a result of accidental on-orbit spacecraft collisions. Spacecraft materials deteriorate in space and near-empty fuel tanks explode in spent rocket boosters. Many legacy-designed spacecraft were launched in the early days when satellites had no regard for clearing the orbits or concerns for collision risks. Old spacecraft have expired and continue uncontrollably in orbit. Nobody back then foresaw what a mess space debris could make in the orbital environment. And currently, Dr. Schonberg said, "That's one of the interesting things about law in outer space—we're still kind of in the formative stages here. You're supposed to list dangerous ingredients in food and that's kind of like law in most countries. But no, you're not required by law to list if your satellite died. You don't have to tell anybody about it, which is kind of interesting."

Can we clean this up? If we do nothing, is this situation going to get better or worse? Better computational modelling is assisting with predictions of spacecraft breakups to help improve designs; satellites configured with propulsion systems keep a reserve of fuel to perform a de-orbiting maneuver at the end of their mission; popularly used small satellites that are too small to integrate propulsion system are confined to the lower orbital altitudes where aerodynamic drag can eventually remove them from orbit.

Professor William Schonberg (MST image).

Additionally, research efforts are being focused on technology and space missions that can remove debris from orbit. However, the contest between investment costs and returns of investments divides opinions on whether the priority should be on the small number of large-sized defunct satellites or the much larger number of much smaller sized space junk. All debris presents challenges for recovery planning to mitigate risks to current and future space missions and astronaut safety. Dr. Schonberg believes we need to educate the next generation, and referring to a children's book on the International Space Station, he noted "They were talking about space debris and Whipple shields. Wow. How cool is that? And I think ultimately that's what we have to do; we have to teach our children to help each other to be mindful about what it is that we do in outer space, and that space is a limited resource."

Dr. Schonberg, an AIAA Fellow and recipient of the 1995 Lawrence Sperry Award for his work on the design of spacecraft protection systems, completed resident research in Australia as the 2019 Fulbright Distinguished Chair in Advanced Science and Technology. He contributed a chapter to a collaborative book, "Project Asteria 2019: Space Debris, Space Traffic Management and Space Sustainability," on a joint project in space operations and space law between Australian, New Zealand, and U.S. researchers. The project is named Asteria after the Greek mythical goddess of shooting stars—a phenomenon that includes the bright and colourful re-entering space debris objects. The pdf version is freely available for downloading from **https://airpower.airforce.gov.au/publications/project-asteria-2019-space-debris-space-traffic-management-and-space-sustainability**.

The AIAA Sydney Section is grateful for the opportunity to host Professor Schonberg and share his experiences and insights into the nature and problems of orbital space debris. A video recording of this AIAA Sydney Section event is available for viewing on the AIAA Sydney Section's Facebook and YouTube channels at **https://youtu.be/hZggVfwz_6s**.

AIAA Greater Huntsville Section Ignites Interest in Rocket Science at STEAMfest 2021

BY Robin Osborne, Pre-College Outreach Director, AIAA Greater Huntsville Section

The AIAA Greater Huntsville Section (GHS) contributed to an exciting day of interactive science by hosting a large booth at STEAMfest 2021. According to Joe Iacuzzo, founder and director of the Huntsville Science Festival, over 4,500 people attended the festival on 30 October at the Von Braun Center in downtown Huntsville. Visitors to the AIAA GHS booth enjoyed activities such as launching small 3D-printed rockets, a "tour" of a scaled-down Saturn V rocket via Lego Saturn V models, an introduction to cryogenic materials through intriguing dry ice demonstrations, and aerospace-themed arts and crafts. Jeremy Fehrenbacher, AIAA GHS member and owner of the non-profit charity, Carve Out Tomorrow, brought a Bernoulli demonstrator, small tesla coil, thermal engines, and other fascinating items to share with booth visitors.

Future engineers and rocket scientists were excited to help assemble the 3D-printed rockets and watch them propel high into the air from the thrust generated by the chemical reaction inside the rockets' film-canister engines. Children and adults alike delighted in seeing 1:110-scale Lego models of the Saturn V rocket that took humans to the moon. In addition to sharing interesting facts about the Saturn V rocket, AIAA volunteers showed visitors the multiple rocket stages, the number and relative sizes of the different engines, the lunar lander and command modules, and other important features of the rocket.

Dry ice sublimating in the bottom of large, graduated cylinders in a mixture of water, dish soap, and food coloring formed lots of mesmerizing carbon dioxide bubbles that young festival goers were anxious to touch, examine, and observe. Many visitors noted how much faster the heavy CO^2-filled bubbles dropped in comparison to the light, air-filled bubbles that were also being generated at the booth. Guests could attempt to hold larger "ghost bubbles" in their hands that would pop and leave behind a fog of white vapor.

There were also plenty of arts and crafts, including aerospace-themed wooden ornaments for guests to decorate for AIAA GHS's Christmas tree that will be part of the 2021 Tinsel Trail in downtown Huntsville's Big Spring Park in December. Tinsel Trail is an annual event in which local businesses, organizations, and families participate to promote community.

AIAA GHS's participation in STEAMfest 2021 was made possible by the sponsorship of ERC, a company headquartered in Huntsville that was also a major contributor to STEAMfest 2021. ERC engineer and YouTube personality Destin Sandlin of "Smarter Every Day" fame served as the keynote speaker for the festival.

The AIAA GHS Council appreciates the assistance and support of Michele Armstrong, ERC's Charitable Giving and Community Outreach Coordinator, for working with AIAA GHS to make this year's booth both entertaining and educational.

AIAA San Diego Section Awards 2021 Fleet Scholarships

by Chris Root, Reuben H. Fleet Scholarship Coordinator, AIAA San Diego Section

Each year the AIAA San Diego Section awards a total of $10,000 in scholarships for up to ten students pursuing a career in aerospace. This annual scholarship is made possible by the donations from AIAA San Diego Section members and the San Diego Foundation's Reuben H. Fleet Fund.

Since 1983, the section has awarded 214 scholarships totaling $275,700 to deserving students inour region who are pursuing aerospace-related studies. This year's scholarship winners are:

Christopher Davami is a Senior at San Diego State University majoring in Aerospace Engineering with a minor in Mathematics. His older brother (a recent SDSU graduate) and his mother also are both Aerospace Engineers. In addition to being an AIAA member, he holds a leadership position in the Tau Beta Pi Engineering Honor Society and is also a member of the SDSU Rocket Project. This summer he will be doing an internship with NASA Langley Research Center.

Ian Jackson is a senior at San Diego State University, majoring in aerospace engineering with minors in oceanography and honors interdisciplinary studies. He has participated in SDSU Rocket Project and the AIAA SDSU Student Branch. Ian plans on attending graduate school and conducting research in spacecraft propulsion. He is also interested in biomimicry as it relates to transferring nature's solutions to technical applications in aviation.

CONTINUES ON 90

CONTINUED FROM 89

AIAA San Diego Section Awards 2021 Fleet Scholarships

David Markov just graduated from UC San Diego with a degree in Aerospace Engineering. He has completed summer internships in manufacturing in commercial aviation, configuration management and risk management, and marketing and communications within the defense industry. David participated in AIAA Design/Build/Fly, including serving as project manager for the past two years. He was also part of UC San Diego's AIAA Student Branch leadership board.

Reiley Weekes is an aerospace engineering Ph.D. student at UC San Diego researching fluid mechanics and combustion. He previously earned his bachelor's from UC San Diego in mechanical engineering, and following a year in industry at Northrop Grumman, he returned to UC San Diego and earned his master's in aerospace engineering. Reiley interned with the propulsion group at ABL Space Systems in summer 2021.

MORE INFORMATION ON 2022 FLEET SCHOLARSHIP DATES AND DEADLINES CAN BE FOUND AT aiaa-sd.org/reuben-h-fleet-scholarship.

Obituaries

AIAA Associate Fellow Greatrix Died in June

David R. Greatrix of Penticton, B.C., age 62, died on 30 June 2021.

Mr. Greatrix received his Ph.D. in Aerospace Engineering from the University of Toronto in 1987. He was a Professor of Aerospace Engineering at Ryerson University for 25 years, and his research on rocket propulsion is internationally recognized.

He was the author of *Powered Flight – The Engineering of Aerospace Propulsion*, a popular internationally well-received engineering textbook, as well as numerous technical papers. Mr. Greatrix was a frequent attendee at the AIAA Propulsion and Energy Forum and the Joint Propulsion Conference. He was a member of the AIAA Solid Rockets Technical Committee for several years.

AIAA Senior Member Baker Died in September

Mary Baker, chairman and senior technical director at ATA Engineering, died on 7 September 2021 at age 77.

In 1966 Baker was the first B.S. graduate of the new Engineering Mechanics Department at the University of Wisconsin-Madison. In 1972 she received her Ph.D. in Applied Mechanics at Caltech, where she was the only woman Ph.D. student in engineering. Afterward, she briefly worked for IBM in New York and for Rohr Industries and Systems Science & Software in California.

In 1977 Baker joined the newly established San Diego office of Structural Dynamics Research Corporation. SDRC did pioneering work in mechanical computer-aided design and had developed several novel technologies, most notably the use of 3D solid modeling, and she adapted these technologies to the aerospace industry.

Baker led a NASA project during the early stages of the space station design that used the solid modeling capability to define and communicate the current design configuration to the participating NASA centers and contractors working in various disciplines. The resulting software, called IDEAS^2, ensured that consistent models were used through each design iteration.

Baker also led a multidisciplinary team in the design, analysis, and testing of the Space Shuttle and its components. The team performed modal tests on many components that revealed damage that had previously been missed upon inspection. Because of this, NASA used the SDRC-developed tests to inspect the shuttle for damage between flights. After the *Challenger* accident, the team developed and implemented novel computer methods for modeling solid rocket boosters with enough detail to reproduce the opening of the O-ring joint that was the cause of the accident. Modeling this failure was not possible with previous methods.

While at SDRC, Baker began a long-term relationship with Pratt & Whitney on liquid rocket engines. She was the SDRC principal investigator supporting Pratt & Whitney's development of the RL10B-2 engine, which powers the upper stage of the Delta IV launch vehicle. She was responsible for determining dynamic loads for the deployable nozzle that allowed the RL10 engine to increase its performance significantly but still fit within the payload fairing of the first-stage booster. Baker eventually worked on rocket engines from all major suppliers in the United States.

As vice president of the aerospace division of SDRC, Baker negotiated a friendly spinoff of that division in 2000 to form a new company called ATA Engineering with her as chairman and, later, president. ATA has since grown from 28 employees to nearly 200.

Baker promoted and practiced a visionary leadership philosophy that was refreshingly different from the prevailing one in industry. She insisted that ATA be 100% employee owned from the outset because she saw that it eliminated conflicts between employees and owners. Baker also wanted ATA to focus on continually developing and applying novel engineering methods to challenging problems rather than maximizing revenue and profit. She recognized that ATA's competitive edge was having an outstanding technical staff who could develop new methods. Rather than keep those methods proprietary, she thought it was better to openly share them with customers because that was in their best interest.

Baker structured ATA to allow senior management to be heavily involved in technical work. As ATA's senior technical director, she oversaw ATA's involvement in the testing, analysis, and design of two generations of Mars rovers developed by NASA Jet Propulsion Laboratory. ATA's efforts helped ensure the successful Mars landings of the Curiosity rover in 2012 and the Perseverance rover in 2021.

Baker received many awards but always said that they were only possible because of the talented staff that she recruited. She was elected to the National Academy of Engineering and received Distinguished Alumni Awards from both Caltech and the UW-Madison College of Engineering. She was a regular participant at the AIAA SciTech Forums and a Senior Member of AIAA.

AIAA Senior Member Mattingly Died in September

Jack D. Mattingly died on 26 September 2021 at the age of 77.

Mattingly earned a Ph.D. in Aeronautical and Astronautical Engineering from the University of Washington, and a B.S. and M.S. in Mechanical Engineering from the University of Notre Dame.

He served for 20 years in the United States Air Force as an officer, initially in the civil engineering field, but ultimately — under the tutelage of Professor Gordon C. Oates — was completely drawn into the propulsion field in 1982 when he received his Ph.D. "Uncle Jack," as he was best known, loved to teach and did so for the past 50 years with a passion for masterfully challenging his students to think at a systems level by applying fundamental principles from a practical perspective. He taught at the Air Force Institute of Technology (AFIT), USAF Academy, Seattle University, and numerous professional development continuous education short courses that he developed. He won teaching excellence awards at Seattle University and AFIT. Mattingly was the architect of the Aircraft Engine Design system (AEDsys) suite of gas turbine engine cycle and component analysis and design software used in university classrooms and short courses. Many users say they have become better engineers because of the big-picture knowledge and insights they obtained from using this software.

Mattingly was very involved with AIAA from 1983 until his passing. He was one of the pioneers of the AIAA Education Series books as lead author of *Aircraft Engine Design*, published in 1987. He published a total of seven textbooks as the sole or primary author and was a major contributing author on an eighth book, *Aircraft Engine Controls – Design, System Analysis, and Health Monitoring*. He was two-time recipient of the Summerfield Book Award for best book recently published by AIAA in 2019, for *Elements of Propulsion – Gas Turbines and Rockets, Second Edition*, and in 2005, for *Aircraft Engine Design, Second Edition*.

As a member of the AIAA Air Breathing Propulsion Technical Committee, Mattingly headed up the first undergraduate air breathing propulsion design competition in 1987. Also, as a member of the Publications Committee, he was chairman of the Ways and Means Subcommittee responsible for the annual publication budget (1992–1996), and chairman of the Ethics Subcommittee (1997–2004).

Mattingly learned from and worked with many of the legends — Gordon Oates, William Heiser, Frank Gillette just to name a few — in the relatively short history of jet-powered flight. From 1986 to 1989 while in Dayton, OH, he frequently got together with the co-inventor of the jet engine, Hans von Ohain for fellowship over lunch or dinner. Their friendship led to the remarkable 38-page historical foreword by von Ohain that is provided in both editions of *Elements of Propulsion – Gas Turbines and Rockets*. From 2012 until his death, he was affiliated with Practical Aeronautics, Inc., providing short courses to engineers in the Department of Defense, NASA, and industry. He was recognized as an expert in the field and often was called upon to provide expert witness testimony and consulting in gas turbine propulsion. The extraordinarily large reach of his positive influence surely extends into the tens of thousands and his legacy will live on through these courses, his textbooks, software, and mentorship of many of us.

AIAA Associate Fellow Powell Died in October

Dr. E. Stan Powell died on 5 October 2021, after a long illness. He was 72 years old.

Powell was known to many in AIAA and the aerospace community as a skilled expert in flight and test-facility-related thermodynamics and fluid dynamics. He held a Ph.D. from Iowa State University (1980, Dissertation: "The Influence of Turbulence on Open Premixed Propane-Air Combustion") and undergraduate degrees in Mechanical and Aerospace Engineering from the University of Missouri - Columbia.

After completing a Master of Science at the University of Missouri, Powell worked for about a year at the Heavy Truck Division, Ford Motor Company. He was a long-time employee of various contractors at the Air Force's Arnold Engineering Development Complex (AEDC) in Tennessee, where he retired in 2014 after 36 years. During his career at AEDC, he contributed extensively to the test mission in many high-speed facilities, including the von Karman Gas Dynamics Facility (VKF), the arc-heated High Enthalpy Ablation Test Facility (HEAT), the combustion-heated Aerodynamic and Propulsion Test Unit (APTU), and the transonic and supersonic Propulsion Wind Tunnels (PWT).

Powell is remembered for his contributions in many ground-test-related areas, including hot-wire anemometry, vitiated air heaters, sabot wear in a gas gun facility, test medium contamination effects, thermodynamics modeling, and heat-transfer modeling. One of his last efforts was the development of a new equation of state for equilibrium air, which included a computer code (Mollier-2008) now implemented in several operational CFD codes.

Powell received several significant honors and awards during his career, including the 2009 AIAA Ground Testing Award and the 2014 General H. H. Arnold Award from the Tennessee Section for his development of the Mollier-2008 equation of state and computer code. He was inducted as an AEDC Fellow in 2010.

He was very involved in STEM K-12 outreach at the AIAA section and national level. Powell regularly participated in many student conferences and the Design/Build/Fly competition. He participated in middle school STEM activities such as MathCounts and FIRST® LEGO® League, and the Hands-On Science Center in Tullahoma. In 2006 he was recognized with the Harry Staubs STEM K-12 Outreach Award, and he also received a Sustained Service Award (2004) for his work with AIAA.

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CAREER OPPORTUNITIES

CONTINUED FROM PAGE 96

reality, the system is geared toward young people, not those who are older and possibly looking for a career change. As Master Yoda said to then "young" Skywalker, "too old to begin the training." That is sometimes the spoken or unspoken mindset. I call BS on this by welcoming veterans and older people. I began undergraduate school at 23 years old, after all, following four years as an enlistee in the U.S. Air Force and some soul searching at home. Arriving at Embry-Riddle in Arizona, my academic adviser advised me against aerospace engineering. It was made clear to me that if I tried this, I'd almost certainly fail. I'm not sure if Yoda actually meant to inspire Skywalker, but I don't think my adviser meant to inspire me. Regardless, I stepped up to the challenge.

Looming over everything for some students is the question of which career goal they should pursue. Many students, understandably, have not decided that. They sometimes ask me how I knew what I wanted to do so early. I let them know that in fact I did not know early, and that I eventually had to apply abductive reasoning to the problem. Instead of picking a career somewhat arbitrarily, I listed all the possibilities and then used evidence and my experience to remove the things I knew I did not want to do. Astrodynamics and research are what survived, so going to grad school had to be my path.

The question was how to set myself up to do that, given that I was not an academic star. Graduate school at a first-tier research university is all about, well, research. To be attractive to one of them, one must show evidence, inter alia, of being excellent at research. So, as an undergrad, I got into the NASA Space Grant program and got my research accepted at a major professional conference. It's there that I impressed my future doctoral adviser, the late George Born, who directed the Colorado Center for Astrodynamics Research at the University of Colorado Boulder.

This led to my dream job at NASA's Jet Propulsion Lab, where I became a spacecraft navigator in the Inner Planet Navigation Group, working on a handful of Mars missions, and built my career on sifting through data to infer models describing the movements of space objects for improved trajectory prediction. This foundation led to my work in space situational awareness and space traffic management, and now space environmentalism.

So, I was perhaps the last person one would have expected to become an academic at a top-tier university. I am proof that students can become what they want and do a great many things that both create knowledge and create solutions to humanity's problems. It takes work and dedication to get there, no doubt, but it does not take perfection. ★

LOOKING BACK

COMPILED BY FRANK H. WINTER and ROBERT VAN DER LINDEN

1921

Dec. 1 The C-7, the first non-rigid U.S. Navy dirigible to use nonflammable helium, makes its first voyage from Hampton Roads, Virginia, to Washington, D.C. E.M. Emme, ed., **Aeronautics and Astronautics, 1915-60**, p. 14.

Dec. 4 Western Australia Airways opens the first regularly scheduled airline service in Australia when it begins flight operations with six Bristol F.2B fighters modified to carry two passengers each. David Baker, **Flight and Flying: A Chronology**, p. 141.

Dec. 15 Glenn Curtiss is judged the inventor of the flying boat by a decision of a federal appeals court. This is part of ongoing litigation between Curtiss and the Wright and Wright-Martin interests. David Baker, **Flight and Flying: A Chronology**, p. 141.

Dec. 29 A new flight endurance record of 26 hours, 18 minutes, 35 seconds, is established by Edward Stinson and Lloyd Bertaud in a Junkers-Larsen JL-6 BMW IIIa aircraft flying over Roosevelt Field, New York. E.M. Emme, ed., **Aeronautics and Astronautics, 1915-60**, p. 14.

1946

Dec. 2 Hilda Lyon, a leading British aerodynamicist, dies. Lyon contributed to stress calculations for the British R.101 airship in 1925, and in 1930 became the first woman to be awarded a prize by the Royal Aeronautical Society. She undertook research work at MIT and later at Gottingen University under Ludwig Prandtl. She also examined the flutter of wings and elastic blades and worked on the aerodynamic staff of the Royal Aircraft Establishment, first working with wind tunnels and then becoming an authority on aircraft stability. **The Aeroplane**, Dec. 27, 1946, p. 767; **Flight**, Jan. 9, 1947, p. 38.

Dec. 8 A Bell XS-1, powered by a Reaction Motors rocket engine, achieves its first powered flight, piloted by Chalmers Goodlin. The first U.S. plane designed for supersonic flight, it reaches 800 kph and is flown from Muroc, California. E.M. Emme, ed., **Aeronautics and Astronautics, 1915-60**, p. 55.

2 **Dec. 11** American Overseas Airlines inaugurates the first regular trans-Atlantic freight service when a Douglas DC-4, carrying 4,000 kilograms of fountain pens for Paris, arrives at London's Heathrow Airport. The plane also carries 1,300 kilograms of relief supplies for Belgrade, Yugoslavia. **The Aeroplane**, Dec. 20, 1946, p. 756.

Dec. 17 A space biological research program is begun at Holloman Air Force Base, New Mexico, by the U.S. National Institutes of Health. Later it is to feature rocket sleds in which both animal and human subjects are subjected to controlled high-speed runs of many G-forces simulating rocket liftoffs and other phenomena of space and high-speed flight so that their physiological reactions can be monitored. E.M. Emme, ed., **Aeronautics and Astronautics, 1915-60**, p. 55.

Dec. 17 A captured German V-2 rocket is flown at White Sands Proving Ground, New Mexico, and sets velocity and altitude records for a single-stage rocket of 3,600 mph (5,700 kph) and 116-mile altitude. Small metal slugs were to be ejected from the nose of the rocket at 40 miles to provide enough speed to continue into space, but this experiment did not work. E.M. Emme, ed., **Aeronautics and Astronautics, 1915-60**, p. 55; **Flight**, Jan. 2, 1947, p. 19.

1971

3 **Dec. 2** The Soviet Union's Mars 3 probe, which had been launched on May 29, reaches the vicinity of Mars and its lander becomes the first space probe to soft land on the planet. However, the capsule transmits only one gray picture for about 20 seconds and then goes silent, although the orbiter continues to transmit images back to Earth for another eight months. NASA, **Aeronautics and Astronautics, 1971**, pp. 337-338.

Dec. 2 The Soviet Union launches two satellites from Kaputsin-Yar, the Intercosmos-5 and Cosmos 461. The Intercosmos-5 is a joint project of the Soviet Union and Czechoslovakia that is designed to continue the scientific investigation of radiation levels in near-Earth space in connection to solar activity and the nature of low-frequency electromagnetic oscillations of the natural plasma. The satellite descends on Cosmos 641 to investigate micrometeoroids and gamma ray astronomy. NASA, **Aeronautics and Astronautics, 1971**, p. 337.

Dec. 3 The first trans-Atlantic telephone call is made between the U.S. and Sweden via the Intelsat-IV F-2 satellite in geosynchronous orbit over the Atlantic. The one-hour transmission is part of ceremonies held in Sweden and at CmSat Coporation's headquarters in Washington, D.C., that formally inaugurate the new Nordic Earth station at Tanum, Sweden, that is jointly owned by Denmark, Finland, Norway and Sweden. NASA, **Aeronautics and Astronautics, 1971**, p. 341.

Dec. 4 The newspaper Pravda reports that during its approach to Mars, the Mars 3 planetary probe had detected possible evidence of Earth's magnetic tail farther out than previously reported. This area is situated 19 million kilometers from Earth. **New York Times**, Dec. 5, 1971, p. 9.

Dec. 6 France's 90-kilogram Polaire scientific satellite is launched on a Diamant-B booster from the Kouro Space Center in French Guiana but fails to go into orbit when the second stage malfunctions. NASA, **Aeronautics and Astronautics, 1971**, p. 342.

Dec. 8 A Spartan anti-ballistic missile intercepts one of several reentry vehicles in a test of Spartan's ability to distinguish a real nuclear warhead from a flock of dummies. The test is conducted above the atmosphere over the Pacific. **Chicago Tribune**, Dec. 10, 1971, p. 12.

Dec. 11 The United Kingdom's 99.6-kilogram Ariel 4 satellite is launched by NASA on an all-solid-propellant Scout booster. The primary objective of the satellite is to investigate interactions between electromagnetic waves, plasmas and energetic particles in the upper atmosphere. **NASA Release 71-277**.

Dec. 13 The first photos of a solar flare spouting from the far side of the sun are taken by the Oso 7 satellite that had been launched on Sept. 29. The photos also show for the first time the effects of massive eruption of the sun traveling through its outer corona. According to Capt. Earle W. Sapp, director of the U.S. Naval Research Lab, Oso satellites are increasingly helpful in forecasting the sun's weather and its effects on navigation and communication equipment. **New York Times**, Jan. 11, 1972, p. 26.

4 **Dec. 13** The Soviet Union launches its largest and most advanced tracking ship, the Cosmonaut Yuri Gagarin in the Odessa Harbor. The ship is equipped with 100 antennas, including four large parabolic antennas for deep space communications and can operate at sea for up to one year. **New York Times**, Dec. 14, 1971, p. 11.

5 **Dec. 15** The U.S. Air Force's X-24A Lifting Body is airlifted from the Flight Research Center at Edwards Air Force Base, California, to Martin Marietta Corp.'s Denver plant where it is to be modified and redesignated the X-24B. The X-24B

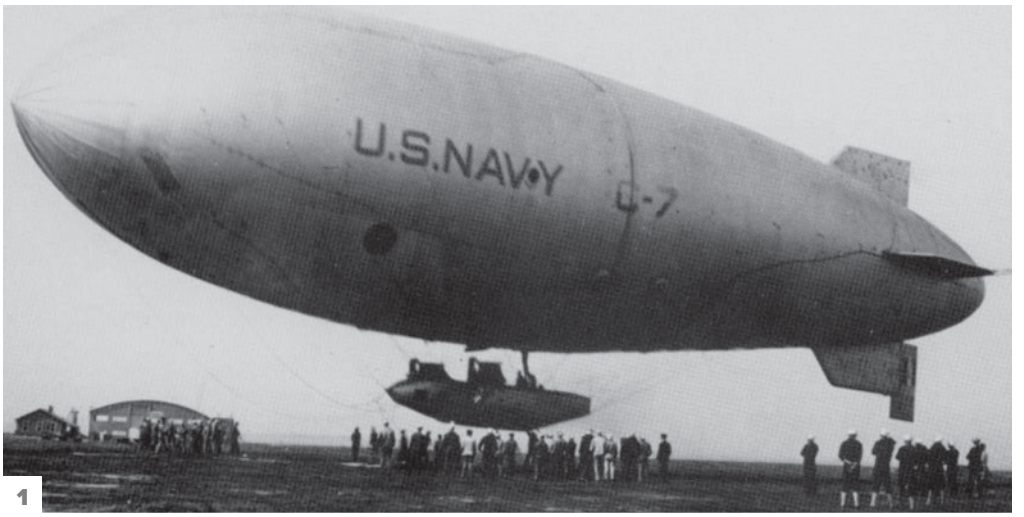
model is to be of a new shape with improved hypersonic lift-to-drag ratio and then sent back to the Flight Research Center. The X-24A had flown 28 flights, reaching up to 1,676 kph and 21,600 meters altitude. Data from the test flights will be used in the design of the space shuttle. NASA, **Aeronautics and Astronautics, 1971**, p. 351.

1996

Dec. 2 Scientists using data collected by radar from the Clementine spacecraft announce the discovery of ice at the bottom of an extremely deep crater on the moon. NASA, **Astronautics and Aeronautics: A Chronology, 1996-2000**, pp. 45-46.

6 **Dec. 4** The Mars Pathfinder spacecraft is launched on a Delta 2 rocket to Mars and carries the United States' first lander and rover vehicle. The rover, called Sojourner, is an automatic, six-wheeled vehicle with cameras controlled from Earth. **Aviation Week**, Dec. 9, 1996, pp. 25-26.

Dec. 15 Boeing announces that it will merge with McDonnell Douglas to form the world's largest aerospace company. Supporters hope $13.3 billion deal will strengthen Boeing in its competition with Airbus in the commercial airliner market and increase its presence in the military market. McDonnell Douglas is the manufacturer of the F-15 and F/A-18 fighters for the U.S. Air Force and Navy. NASA, **Astronautics and Aeronautics: A Chronology, 1996-2000**, pp. 48-49.



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Advice for disheartened students

BY MORIBA JAH | moriba@utexas.edu

When students come to my office or meet virtually with me seeking advice and mentorship about their academic and professional careers, they sometimes have misperceptions about what it takes to succeed. With that can come a sense of paralysis that, thankfully, they can move through if they use the discomfort in a way that leads to action.

As their first test scores and grades roll in, some students express fear that they are not smart enough for a first-tier university and a career in aerospace engineering. Their math skills might indeed be lacking compared to other students here at UT Austin, so they question whether or not they belong. I share with them that for high school I attended the Captain Pedro Maria Ochoa Morales military boarding school in Los Teques, Venezuela. Although my curriculum was science-focused, I never saw calculus. The most advanced math I saw was trigonometry and algebra. Despite that, I was able to navigate through an undergraduate aerospace engineering degree program by staying up late at night doing problems, no doubt missing the finer details but managing to get through it.

Other students express remorse that their GPAs are less than perfect, say in the 3.0 range. They're wondering if their paths to graduate school are all but over. I tend to hear this and chuckle, because to their surprise, I was a "B" student at best. My lack of self-confidence was my biggest enemy and, of course, back then it became a self-fulfilling prophecy. In many respects, I continue to struggle with self-confidence to this day. As an undergrad student, I had bought into the narrative that I didn't look, walk, sound, or think like an engineer, whatever that meant. I counsel students to have confidence. My own undergraduate GPA was a 3.2, and if I were judged solely on GPA, I would not have been seen as graduate school material.

Digging a little deeper with students, I've discovered that many of them are as smart as their 4.0 GPA counterparts. It's just that they are oversubscribed with service activities like being in a gazillion clubs and groups, and volunteering many hours a week. Moreover, many underrepresented minorities have to hold jobs while going to school and this also exerts a toll on their academic achievements. While being involved in the community and clubs is moving and commendable, it works against their purpose, because academia weighs academic excellence — defined by grades and so-called scholarly work — over such activities. Once I can get these students to drop 18 of their 20 clubs — an exaggeration but not by much — they unsurprisingly tend to do much better.

Of course, neither I nor anyone can guarantee success for all students. My strategy as a role model is to inspire students to find out for themselves what they want to do and whether they want to do what is required to get there.

Then there are the military veterans and older people who are considering attending college as a STEM major. While we like to think of our American education system as focused on STEM regardless of age, in

CONTINUED ON PAGE 93

Moriba Jah is an astrodynamicist, space environmentalist and associate professor of aerospace engineering and engineering mechanics at the University of Texas at Austin. He holds the Mrs. Pearlie Dashiell Henderson Centennial Fellowship in Engineering and is an AIAA fellow. He also hosts the monthly webcast "Moriba's Vox Populi" on SpaceWatch.global.

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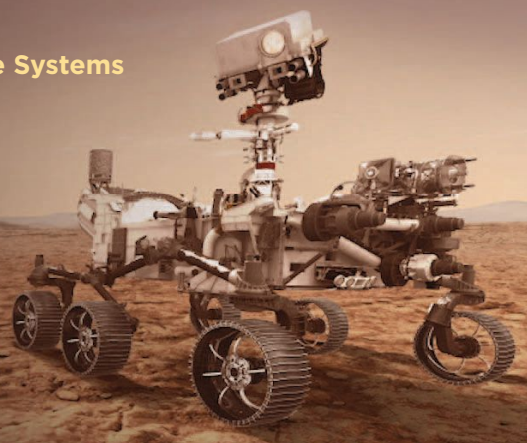

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