Bharath
INSTITUTE OF HIGHER EDUCATION AND RESEARCH
(Declared as Deemed-to-be University under section 3 of UGC Act, 1956)
(Vide Notification No. F.9-5/2000 - U.3, Ministry of Human Resource Development, Govt. of India, dated 4th July 2002)
BHARATH INSTITUTE OF SCIENCE AND TECHNOLOGY
DEPARTMENT OF AERONAUTICAL ENGINEERING
Website : www.bharathuniv.ac.in

TECHNICAL MAGAZINE

Mach Book

2021-2022

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EDITORIAL COMMITTEE

STUDENT MEMBERS

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Mr.N.Kalaimani

B.Tech- Aeronautical &Aerospace Engineering

Vision of the Department

Department of Aeronautical Engineering will endeavor to accomplish worldwide recognition with a focal point of Excellence in the field of Aeronautics by providing quality Education through world class facilities, enabling graduates turning out to be Professional Experts with specific knowledge in Aeronautical & Aerospace engineering.

Mission of the Department

- To be the state of art Teaching and Learning center with excellent infrastructure and empowered Faculties in Aeronautical & Aerospace Engineering.
- To foster a culture of innovation among students in the field of Aeronautics and Aerospace with updated professional skills to enhance research potential for sponsored research and innovative projects.
- To Nurture young individuals to be knowledgeable, skilful, and ethical professionals in their pursuit of Aeronautical & Aerospace Engineering.

B.Tech- Aeronautical & Aerospace Engineering

Program Educational Objectives Statements (PEO)

PEO 1: Demonstrate a solid grasp of fundamental concepts in Mathematics, Science, and Engineering, essential for effectively addressing engineering challenges within the Aerospace industry.

PEO 2: Involve in process of designing, simulating, fabricating, testing, and evaluating in the field of Aerospace.

PEO 3: Obtain advanced skills to actively engage in research and development endeavors within emerging domains, while also pursuing further education opportunities.

PEO 4: Demonstrate efficient performance both as independent contributors and as valuable team members in diverse multidisciplinary projects.

PEO 5: Embrace lifelong learning and career advancement while adapting to the evolving social demands and needs.

Programme Outcomes (PO's)

PO1: Engineering knowledge: Apply the knowledge of mathematics, science, engineering fundamentals, and Engg. Specialization to the solution of complex engineering problems.

PO2: Problem analysis: Identify, formulate, research literature, and analyze engineering problems to arrive at substantiated conclusions using first principles of mathematics, natural, and engineering sciences.

PO3: Design/development of solutions: Design solutions for complex engineering problems and design system components, processes to meet the specifications with consideration for the public health and safety, and the cultural, societal, and environmental considerations.

PO4: Conduct investigations of complex problems: Use research-based knowledge including design of experiments, analysis and interpretation of data, and synthesis of the information to provide valid conclusions.

PO5: Modern tool usage: Create, select, and apply appropriate techniques, resources, and modern engineering and IT tools including prediction and modeling to complex engineering activities with an understanding of the limitations.

PO6: The engineer and society: Apply reasoning informed by the contextual knowledge to assess societal, health, safety, legal, and cultural issues and the consequent responsibilities relevant to the professional engineering practice.

PO7: Environment and sustainability: Understand the impact of the professional engineering solutions in societal and environmental contexts, and demonstrate the knowledge of, and need for sustainable development.

PO8: Ethics: Apply ethical principles and commit to professional ethics and responsibilities and norms of the engineering practice.

PO9: Individual and teamwork: Function effectively as an individual, and as a member or leader in teams, and in multidisciplinary settings.

PO10: Communication: Communicate effectively with the engineering community and with society at large. Be able to comprehend and write effective reports documentation. Make effective presentations and give and receive clear instructions.

PO11: Project management and finance: Demonstrate knowledge and understanding of engineering and management principles and apply these to one’s own work, as a member and leader in a team. Manage projects in multidisciplinary environments.

PO12: Life-long learning: Recognize the need for and have the preparation and ability to engage in independent and life-long learning in the broadest context of technological change.

Dean Message

Winged Words is particularly important as it encourages the students to share the knowledge they have acquired. Writing articles for the magazine also improves the communication skills of the budding engineers of the Aeronautical department. It is common knowledge that representation of an idea is as important as, if not more important, than the idea itself. Winged Words represents a cloud with a silver lining for the world of technology. It aims to inspire and nurture upcoming engineers to bring a revolution in this ever-evolving world of technology. The magazine captures the current technological advancements. To conclude I would like to congratulate the faculty and the students of the editorial team on bringing out the Second issue of Winged Words

HOD Message

Congratulations to the students and faculty associated to magazine committee for successfully publishing this issue of departmental technical magazine Winged Words is creating platform which provides an opportunity to the students and staff to express their original thoughts on technical topics.

The magazine plays an instrumental role in providing exposure to the students to develop written communication skills and command over the language. It is a step towards building professional and ethical attitude in them. The entire journey of creating Winged Words is an outcome of rigorous effort made by students and faculty. Students not only gain the knowledge about the latest technological developments and advancements through reading and writing articles but they also develop verbal and written communication skills.

This issue has expanded its scope by introducing articles by major stakeholders. Apart from students and faculty, inputs have been collected from alumni, parents and industry experts. On concluding note, I would like to thank all the stakeholders for their involvement and encouragement and wish all the best for their bright future

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

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.

Military research focuses on improving survivability in both air and space

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

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.

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

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

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 the German Aerospace Center, DLR, 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.

Researchers pursue design optimization in vehicle development technologies

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.

In May, Sandia researchers leveraged novel developments in uncertainty quantification to better enable statistical goal orientation within optimization under uncertainty. The researchers expanded the Dakftware 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.

Space tourism flights show off distinctly different designs approaches

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.

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

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.

Addressing future noise requirements in civil aviation

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.

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.

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

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.

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

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.

Enhancing capabilities to measure, analyze and control fluid flows

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.

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 discover 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.

Innovative imaging methods bring new diagnostic capabilities

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.

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

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

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.

Aircraft operations begin to recover from covid

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.

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 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.

Flight testing of commercial space vehicles and automation technology

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

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 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.

Demonstrating and testing artificial intelligence applications in aerospace

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.

Low-Earth orbit megaconstellations reach record capacity

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

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.

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

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.

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.

Refining challenge goals to make realistic progress

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.

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 1018 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.

Hypersonic flight systems: From research and testing to business analysis

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.

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New techniques and results enhance physical understanding

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.

Pace of reusable rocket launches picks up

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.

Missile defense and hypersonic tests characterize busy year

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

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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.

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.

Companies report a number of firsts for missile tests

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.

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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.”

Acknowledgement

At the end, we would like to extend our sincere gratitude to our management for their constant support. Also, we would like to thank Dr.S.Elangovan (Dean), Dr. M.Sundararaj (HOD) for the innovative ideas contributed to our magazine, Faculty Incharge Mr.R.Karthikeyan and the Student Editorial committee for shaping the Winged words. Lastly, we would like to thank all the faculty members, students and all stakeholders for their valuable inputs.