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The Chevron Nozzle: A Novel Approach to Reducing Jet Noise

Winglets: Striving for Wingtip Efficiency

Composite Fan Casings: Increasing Safety and Fuel Efficiency for Commercial Aircraft

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FACET: Helping Adapt National Airspace

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August 2011

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Preface

Every day, engineers and scientists at the National Aeronautics and Space Administration (NASA) are innovating new technologies that move our society forward. Their work has touched our everyday lives in countless ways. It has helped place the United States of America as the firm leader in aerospace technology and added deeply to the pride we feel as Americans.

Though NASA works on everything from biomedical science and space exploration to software simulation and satellites, it is from the field of aeronautics that NASA drew its humble origin. NASA's official beginning was October 1, 1958, when it took the place of its predecessor, the National Advisory Committee for Aeronautics (NACA). Today, with all the hype surrounding Space Shuttles and distant galaxies, it is easy for the public to overlook the still vital and thriving aeronautics branch of NASA.

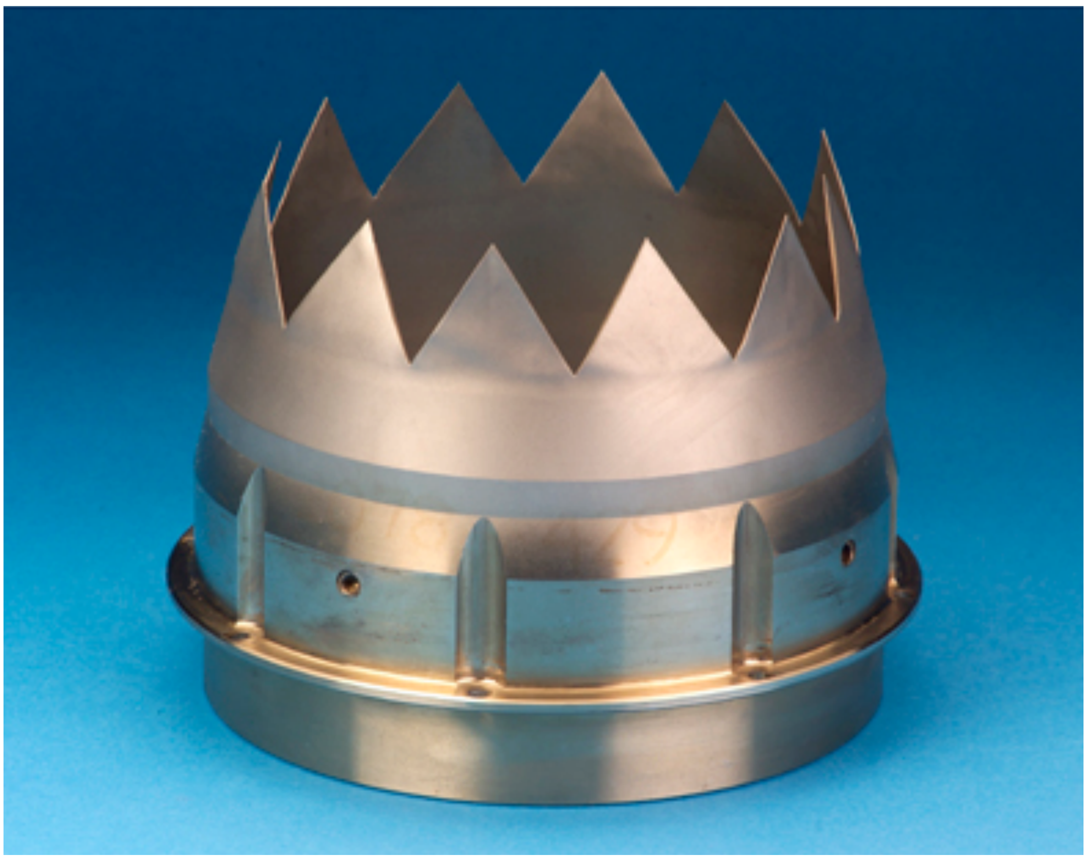
With some of the largest direct impacts on the lives of everyday citizens, advancements in aeronautics are the key to making flight more affordable and efficient. These advancements decrease pollutants and make flight faster, quieter, and safer for all. This industry gives our Nation strategic advantages over any global adversary, and it has also created a powerful network for sharing knowledge and improving international relationships. This industry has created many great opportunities for employment as well.

In the chapters that follow, we have taken a closer look at a handful of the top research accomplishments of NASA's Aeronautics Research Mission Directorate (ARMD). These technologies were chosen to demonstrate the diversity and profound impact NASA has had, and will forever have, on the aviation industry.

National Aeronautics and Space Administration

The Chevron Nozzle: A Novel Approach to Reducing Jet Noise

Malcolm Gibson
NASA Headquarters, Washington, DC



Introduction

Aircraft noise remains a significant concern for airports, nearby communities, and aircraft passengers. As the large volume of air traffic continues to increase, and jet engine technology continues to advance, the aeronautics industry is challenged with reducing the noise levels generated by modern jets.[1] Starting in the 1960s, significant attention was directed toward noise-reduction technologies for use on jet engines.[2] This is because jet noise has played a significant role in the history of aviation. The commercial airline industry has remained invested in the advancement of payload capacity for decades, and the industry is frequently moving toward greater means of propulsion. This requires constant technical investigation of means for increasing power and efficiency of existing turbojet and turbofan engines while significantly reducing engine acoustic levels. Engine noise has become a serious concern for many airports and surrounding communities. Without noise-reducing technologies, the Federal Government, airline companies, and nearby schools must spend millions of dollars on soundproofing installments to avoid the negative impacts of jet noise on schools and neighborhood communities around airports. In the early 1990s, about $63.1 million had been spent over a decade to soundproof schools near Chicago's O'Hare and Midway airports, 80 percent of which was paid for by the Federal Government and, ultimately, taxpayers.[3] The defense industry is also very concerned with reducing noise levels in order to develop advanced stealth technology for future military vehicles. Stealth research is strongly dependent on reduced noise and infrared signatures, and ongoing research in noise-reduction benefits both of these technologies. Over the course of the past few decades, the field of aeroacoustics has emerged to address many of these challenges and develop the enabling technologies needed to advance the next generation of aerospace vehicles.

Modern commercial aircraft employ high bypass ratio (HBPR) engines with separate flow, nonmixing, short-duct exhaust systems. These propulsion systems are known to generate significantly high noise levels due to the high-speed, high-temperature, and high-pressure nature of the exhaust jet, especially during high-thrust conditions such as those required for takeoff. The primary source of jet noise is the turbulent mixing of shear layers in the engine's exhaust.[4] These shear layers contain instabilities that lead to highly turbulent vortices that generate the pressure fluctuations responsible for sound.[5] In order to reduce the noise associated with jet flow, the aerospace industry has focused on developing various technologies to disrupt shear layer turbulence and reduce the overall noise produced. Through decades of innovative NASA research, the chevron nozzle has emerged to achieve exactly this. The novel design has allowed modern aircraft to employ engines with more acceptable noise levels. This noise-reduction research has been one of the key aspects of NASA's Fundamental Aeronautics (FA) program in recent decades, and it will continue to be so for many years to come.

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1. Noise regulations: The regulatory response to limiting aircraft noise is embodied in Federal Aviation Regulation (FAR) chapter 36 in the United States and in International Civil Aeronautics Organization (ICAO) Annex 16, which impose increasingly stringent limits on acceptable jet noise.

2. B.A. Janardan, G.E. Hoff, J.W. Barter, S. Martens, P.R. Gliebe, V. Mengle, and W.N. Dalton, "AST Critical Propulsion and Noise Reduction Technologies for Future Commercial Subsonic Engines" (NASA/CR-2000-210039).

3. J. Sjostrom, S. Vann, and T. Gregory, "Chicago Told To Pay for O'Hare Noise," *Chicago Tribune* (April 20, 1994).

4. O. Rask, S. Harrison, D. Munday, C. Harris, M. Mihaescu, and E. Gutmark, "Jet Aircraft Propulsion Noise Reduction Research at University of Cincinnati" (American Institute of Aeronautics and Astronautics [AIAA] 2007-5631).

5. M.J. Lighthill, "On Sound Generated Aerodynamically. II. Turbulence as a Source of Sound," *Proceedings of the Royal Society of London*, series A, vol. 222, issue 1148 (1954): 1–32; C.K.W. Tam, M. Golebiowski, and J.M. Seiner, "On the Two Components of Turbulent Mixing Noise from Supersonic Jets" (AIAA 96-1716, 1996).

Early Approaches

With the forecasted development of future high-thrust engine technology, NASA recognized the importance of investing in jet noise-reduction research starting in the 1960s. NASA initiated the U.S. Supersonic Transport (SST) program in 1965 to develop enabling technologies for future supersonic civil transport concepts and provided support to the Federal Aviation Administration (FAA) to run the program. The FAA subcontracted the Boeing Company to provide the various airframes and General Electric (GE) to provide the engines.[6] As the program progressed, jet noise became an increased concern, and noise goals were set forth for both takeoff and approach flight conditions. These noise goals represented some of the first attempts to regulate excessive jet noise from supersonic engines. Due to heightened interest in noise reduction and concerns with pollution, the SST program was canceled in 1971, and a new SST Noise Reduction Technology program was initiated. The program primarily focused on testing new ideas for jet noise suppression devices such as high-flow injectors, secondary injectors, and fluid injectors.[7] Also, in 1975, early flight-tests were conducted at NASA's Dryden Flight Research Center on five subsonic business jets, namely the Gulfstream 2, Jet Star, Hawker Siddeley 125-400, Sabreliner-60, and Learjet 24, in order to evaluate the effectiveness of new, quieter-approach methods on subsonic aircraft.[8] Shortly thereafter, the new SST program was integrated with NASA's Lewis Research Center's (now Glenn Research Center) Advanced Supersonic Technology program.[9] These studies found that devices such as hardwall ejectors and acoustic treatments led to decreased noise levels. This generated further interest in suppression devices and eventually evolved into the Supersonic Cruise Aircraft Research (SCAR) program, which brought on additional resources at NASA's Langley Research Center. With jet noise becoming an industry-wide interest, other companies pursued similar research efforts. In 1976, Pratt & Whitney (P&W) and GE initiated the Variable Stream Control Engine (VCE) Testbed program to study the sources of jet noise at various flight conditions.[10] The SCAR (later called SCR) and VCE programs reported an 8-percent decrease in jet noise, with a 5.5-percent reduction in thrust, as a result of suppression devices tested on a small turbojet (RR Viper 601) and on an HS-125 subsonic business jet. After reporting these results, the programs ended in 1981.[11]

NASA remained committed to the development of noise-reducing technologies throughout the decade. During the mid-1980s, ongoing research was beginning to focus on new engine designs in addition to suppressors. Contracted by NASA's High Speed Civil Transport (HSCT) program, the Boeing Company

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6. W.S. Aiken, Jr., "Supersonic Cruise Aircraft Research—Significant Progress," *Aeronautics and Astronautics* 14, no. 5 (May 1976): 24–25.

7. J.R. Stone, E.A. Krejsa, I. Halliwell, and B.J. Clark, "Noise Suppression Nozzles for a Supersonic Business Jet" (AIAA 2000-3194).

8. J.F. Brausch and V.L. Doyle, "Summary of the GE4/SST Acoustic Suppression Research," *Supersonic Transport Noise Reduction Technology Program, Phase 1* (General Electric Co., FAA-SS-72-43, December 1972).

9. W.S. Fisk et al., "Supersonic Transport Noise Reduction Technology Summary—Phase 1," in *Final Report* (General Electric Co., FAA-SS-72-43, December 1972).

10. J.R. Stone and O.A. Gutierrez, "Status of Noise Technology for Advanced Supersonic Cruise Aircraft," *Supersonic Cruise Research 1979*, part 2 (NASA CP-2108, November 13–16, 1979), pp. 493–518; P.R. Knott, J.F. Brausch, P.K. Bhutiani, R.K. Majjigi, and V.L. Doyle, "VCE Early Acoustic Test Results of General Electric's High-Radius-Ratio Coannular Plug Nozzle," *Supersonic Cruise Research 1979*, part 2 (NASA CP-2108, March 1980), pp. 417–452.

11. L.H. Fishback, L.E. Stitt, J.R. Sonte, and J.B. Whitlow, Jr., "NASA Research on Supersonic Propulsion—A Decade of Progress" (AIAA 82-1048, June 1982).

reported, in 1988, new high-speed engine technologies that could lead to decreased jet noise.[12] Newly designed mechanical suppressors were also among some of the promising technologies. In 1989, NASA issued a research announcement informing industry of the Agency's intention to further develop some of these new concepts. During this time, research efforts to investigate airflow past chevronlike structures were already underway at Ames Research Center due to beliefs that such structures might reduce engine acoustic levels.[13] Additionally, NASA had invested in research applicable to military stealth applications involving the reduction of jet infrared (IR) signatures. The reduction of IR signatures is attributed to the enhanced mixing of the engines' exhaust with cooler surrounding ambient air using mechanical tabs or slots similar to those employed in noise-reduction studies.[14] In 1990, NASA started the High Speed Research (HSR) program, which allocated approximately $75 million for jet noise research alone. Up until the early 1990s, most jet noise research was conducted on supersonic mixed-flow, low-bypass turbojet nozzle systems due to the fact that jet noise had not been the primary source of sound in subsonic HBPR engines of that time.[15] As the need for higher payload aircraft developed, these HBPR engines developed to a point where exploring options for reducing jet noise was increasingly important. In 1995, NASA's Advanced Subsonic Technology (AST) steering committee and technical working group decided to launch the Separate-Flow Nozzle (SFN) Jet Noise Reduction program with a goal of developing technologies that would achieve a minimum of a 3 Effective Perceived Noise Level (EPNLdB) reduction in jet noise while avoiding any significant loss in thrust.[16] This program was the first to seriously analyze a range of new mechanical suppression devices for HBPR engines, including young chevron designs, and would hold promising discoveries for the future of jet noise reduction.

The Chevron Nozzle

Under the new SFN program, NASA awarded P&W contract NAS3-27727 (AST Task Order 14.2) to design, build, and test various separate flow exhaust nozzles in the higher bypass ratio range of 5 to 8. The nozzles selected were to utilize various suppression devices to study the effectiveness of emerging designs. P&W subcontracted the Boeing Company to help design the test configurations and perform phased array microphone setup and measurement. P&W also subcontracted United Technologies Research Center (UTRC) to perform computational fluid dynamics (CFD) analysis of the suppression mechanisms.[17] The nine configurations chosen by P&W for analysis consisted of flipper tabs, scarfed-fans, offset-centerline designs, existing lobed nozzles, and combinations of those aforementioned. In addition, NASA awarded a similar contract to GE to design and test 11 other nozzle devices, including vortex-generating doublets, tongue mixers (developed by Allison Engine Company), and chevron nozzles. Most of these designs are shown in figures 1a and 1b. Both companies selected Aero Systems Engineering (ASE) to manufacture the

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12. G.C. Nihart and J.J. Brown, "Supersonic Propulsion Systems and Community Noise Suppression Concepts" (AIAA-88-2986, July 1988).

13. J.F. Foss, J.K. Foss, and P.R. Spalart, "Numerical and Experimental Evaluations of the Flow Past Nested Chevrons," *AIAA Journal* 27, no. 6 (June 1989).

14. F.S. Alvi, A. Krothapalli, D. Washington, and C.J. King, "Aeroacoustic Properties of a Supersonic Diamond-Shaped Jet," *AIAA Journal* 34, no. 8 (August 1996).

15. J.K.C. Low, P.S. Schweiger, J.W. Premo, and T.J. Barber, "Advanced Subsonic Technology (AST) Separate-Flow High-Bypass Ratio Nozzle Noise Reduction Program Test Report" (NASA/CR-2000-210040, December 2000), p. 1.

16. Ibid.

17. Ibid.

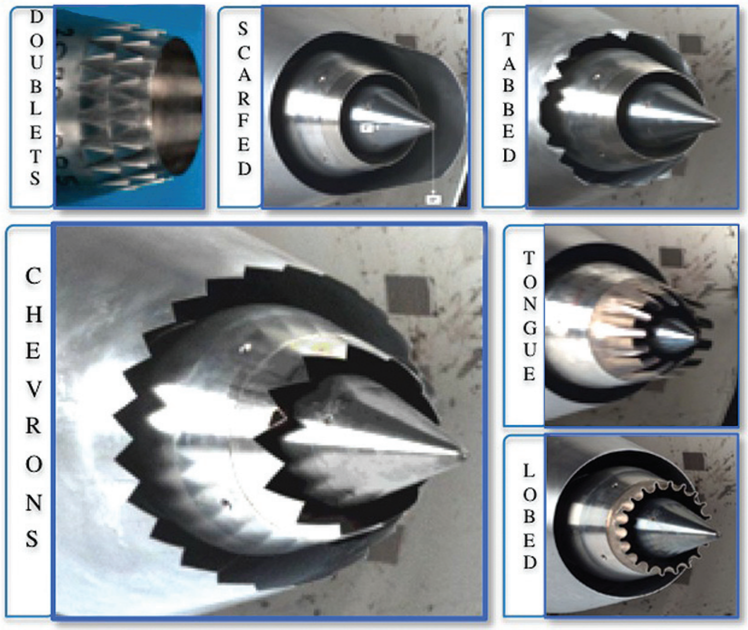

Figure 1a: Various nozzle designs from the SFN (AST) program tested at NASA's Langley Research Center in 1997 (NASA/CR-2000-210040).

nozzle components. NASA's Lewis Research Center was used to conduct noise tests using the Acoustic Test Rig (ATR) in the Aeroacoustic and Propulsion Laboratory (AAPL) from March 20 to June 18, 1997. Upon realizing the inherent losses in thrust caused by many of the noise suppression devices, NASA also contracted ASE to study the performance aspects of the new designs. To better assess the results of this large research effort, NASA requested separate reports from P&W, GE, and ASE.

The results from the noise studies conducted under the SFN program showed that only two of the investigated devices met the program goal of a 3 EPNLdB reduction with minimal losses in thrust. The test results showed that inward-facing chevrons on the core (primary) nozzle and flipper tabs on the core nozzle were sufficient in reducing the noise levels to those desired.[18] They also reported that additional chevrons on the fan (secondary) nozzle made additional contributions to overall noise reduction by shifting the noise further into the high-frequency range, making it more susceptible to atmospheric dampening. The phased-array microphone tests conducted by the Boeing Company confirmed that the approach was a successful means to provide qualitative images of the jet noise sources. They found that jet noise arises from two main sources in the jet engine, one near the nozzle exit plane (buzz saw noise) and the other further downstream of the jet plume (shockcell noise). This discovery would allow future researchers to implement different approaches that specifically target each source of jet noise. The program also determined the effective mechanisms behind the sound-reduction devices. Both chevron nozzles and flipper tabs were determined to decrease jet noise by inducing streamwise vorticity along the two shear-boundary layers in the jet flow.[19] The added vorticity causes smoother mixing of the core and fan flow and reduces the rapid pressure fluctuations responsible for jet noise. The success of this innovative research heightened interest in

18. Low, Schweiger, Premo, and Barber, "Advanced Subsonic Technology (AST)," p. 2.

19. W.H. Herkes, R.F. Olsen, and S. Uellenberg, "The Quiet Technology Demonstrator Program: Flight Validation of Airplane Noise-Reduction Concepts" (paper AIAA 2006-2720, 12th AIAA/CEAS Aeroacoustics Conference [27th AIAA Aeroacoustics Conference], Cambridge, MA, May 8–10, 2006).

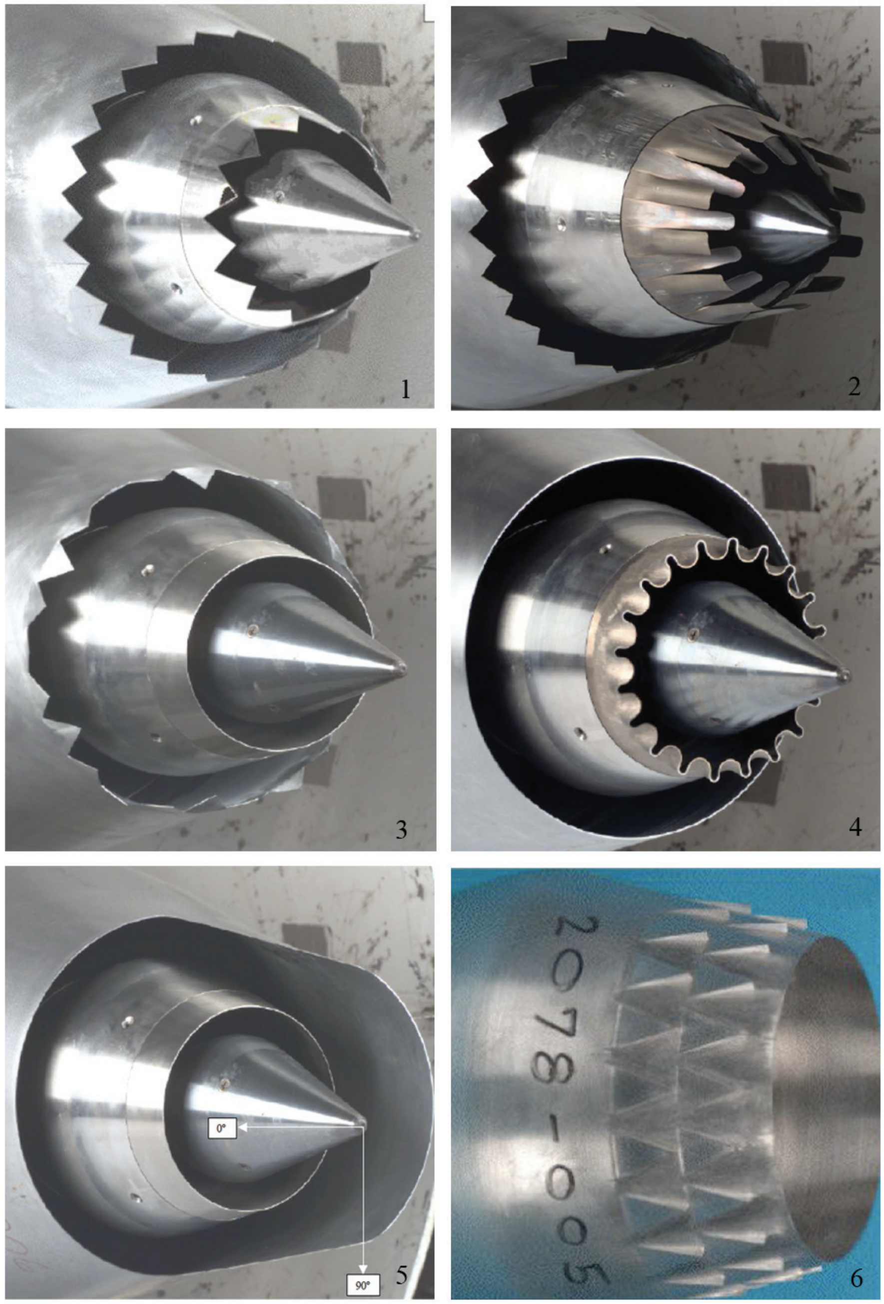

Figure 1b: The above six images show various types of noise-suppression devices from the AST program. From top to bottom, left to right are (1) fan and core chevron nozzles, (2) the core tongue nozzle, (3) the tabbed fan nozzle, (4) the core lobe nozzle, (5) the scarfed fan nozzle, and (6) the vortex doublet core nozzle (NASA/CR 2000-210040).

chevron development for use on future business-class and commercial jet engines. These new technologies were anticipated for flight-test validation in 1998 under funding from NASA's Engine Validation of Noise Reduction Concepts (EVNRC) programs, although such tests would not occur for a few years to come.

By the start of the new millennium, the aeronautics industry had discovered new approaches to reducing jet noise from modern high-payload commercial aircraft. Due to the efforts of NASA's SFN program, the chevron nozzle had become a promising new concept and would enter a period of continued interest and refinement over the next decade. In 2000, NASA's Glenn Research Center performed model scale tests using chevron nozzles on turbojet engines used by smaller business-class jets. The researchers determined a 2 EPNLdB reduction in noise was possible using the 6 and 12-chevron nozzles evaluated. In March 2001, these results were validated at full scale during flight tests conducted on a Learjet 25 at Estrella Sailport near Phoenix, AZ.[20] NASA continued to expand its research efforts by funding the new Quiet Technology Demonstrator (QTD) program, conceived by Rolls-Royce and the Boeing Company, in early 2000. The goal of this new program was to continue the development of noise-reducing technologies for the three main sources of jet noise, namely the engine fan, jet, and airframe.[21] Their approach to the reduction of jet noise was adapted from NASA's SFN program and employed similar chevron nozzles. The QTD program performed static model testing and in-flight validation of these technologies on higher bypass-ratio engines typically used by larger commercial aircraft. Around the same time, many other research investments were being made to refine chevron capabilities. In 2001, NASA initiated the Quiet Aircraft Technology (QAT) program and allocated $45 million for engine systems noise-reduction research. The QAT program sought to meet goals of reducing noise by 50 percent in 5 years and 75 percent in 20 years relative to best-in-fleet 1997 technology.[22] Another study, reported by the Boeing Company in 2003, compared traditional lobe mixers to new chevron mixers and concluded that, although the lobe mixers resulted in greater sound reduction, the coupled thrust lost was significantly higher, and chevrons were the more optimal choice.[23] One year later, in 2004, NASA's Langley Research Center (with the Boeing Company under contract number NASI-00086) took a closer look at exploiting the pylon (connection manifold to the wing) interaction with the exhaust jet and examined azimuthally varying chevrons. These chevrons vary the mixing around the nozzle periphery and gave rise to the T (top) and B (bottom) type chevrons shown in figures 2a and 2b.[24] The study concluded that T-fan chevrons could reduce the overall far-field jet noise of nozzles with pylon interaction better than the existing uniform chevrons. The combined results from each of these programs led to the development of a more refined and more efficient chevron nozzle for use on soon-to-be, modern-day commercial aircraft.

Chevron nozzles were becoming a well-known technology for the reduction of jet noise in turbojet and turbofan engines during the early 2000s, although there still remained downfalls that needed to be addressed. Industry's main concern was the thrust loss caused by chevron nozzles during cruise conditions where jet efficiency was essential. Decreased thrust meant decreased efficiency and higher fuel costs for airliners. In order to address this problem, the Boeing Company and NASA both invested in research to develop individual systems that would optimize chevron immersion into the jet flow based on the flight condition.[25] This would allow for full chevron immersion during high-thrust conditions where noise is a large concern (takeoff and

20. C. Brown and J. Bridges, "An Analysis of Model Scale Data Transformation to Full Scale Flight Using Chevron Nozzles" (NASA/TM 2003-212732).

21. P. Bartlett, N. Humphreys, and P. Phillipson, "The Joint Rolls-Royce/Boeing Quiet Technology Demonstrator Programme" (paper AIAA 2004-2869, 10th AIAA/CEAS Aeroacoustics Conference, Manchester, U.K., May 10–12, 2004).

22. D.L. Huff, "High-Speed Jet Noise Reduction NASA Perspective" (doc. ID 20020024448, Science and Technology Workshop for Reducing Naval Aircraft Noise, October 30–31, 2001).

23. V.G. Mengle, "Jet Noise Characteristics of Chevrons in Internally Mixed Nozzles" (paper AIAA 2005-2934, 11th AIAA/CEAS Aeroacoustics Conference, Monterey, CA, May 23–25, 2005).

24. V.G. Mengle, R. Elkoby, L. Brusniak, and R.H. Thomas, "Reducing Propulsion Airframe Aeroacoustic Interactions with Uniquely Tailored Chevrons: 1. Isolated Nozzles" (paper AIAA 2006-2467, 12th AIAA/CEAS Aeroacoustics Conference, Cambridge, MA, May 8–10, 2006).

25. F.T. Calkins, G.W. Butler, and J.H. Mabe, "Variable Geometry Chevrons for Jet Noise Reduction" (paper AIAA 2006-2546, 12th AIAA/CEAS Aeroacoustics Conference, Cambridge, MA, May 8–10, 2006).

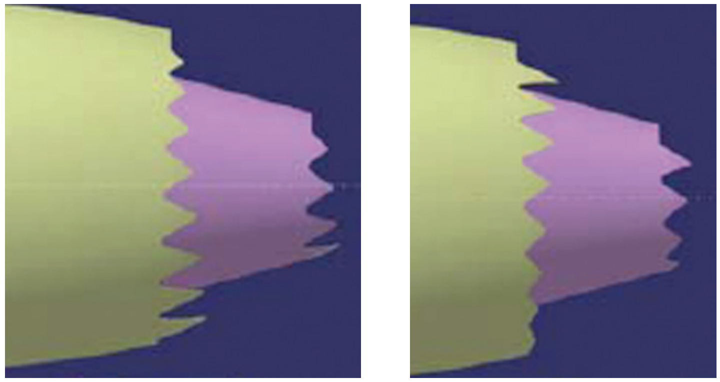

Figure 2a: The BB and TT types of chevrons (azimuthally varying) (AIAA 2006-2467).

Figure 2b: Azimuthally varying chevrons used in QTD2 program (NASA).

landing), and it would allow for little immersion during cruise where thrust efficiency is of greater importance than noise. In 2005, the Boeing Company reported the success of newly developed variable chevrons (figure 3) that utilized shape memory alloy (SMA) actuators to control immersion. Since the nickel-titanium memory alloy selected by the Boeing Company is activated by heat, the variable chevrons could be used autonomously as well as fully controlled. In 2007, NASA also reported research conducted at Langley Research Center on the development of "active" chevrons that use embedded SMA actuators to control chevron immersion.[26] These innovative technologies brought chevron development to a new height, and the latest QTD2 program was ready to adapt the Boeing Company's variable-chevron technology on its upcoming test flights. Chevron nozzles had now transitioned from an emerging proof of concept to a refined technology with an undeniable future promise in aeronautics.

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26. T.L. Turner, R.H Cabell, R.J. Cano, and R.J. Silcox, "Testing of SMA-Enabled Active Chevron Prototypes Under Representative Flow Conditions" (paper 6928-36, LAR-17332, ASCE 11th Earth and Space Conference, San Diego, CA, March 9–13, 2008).

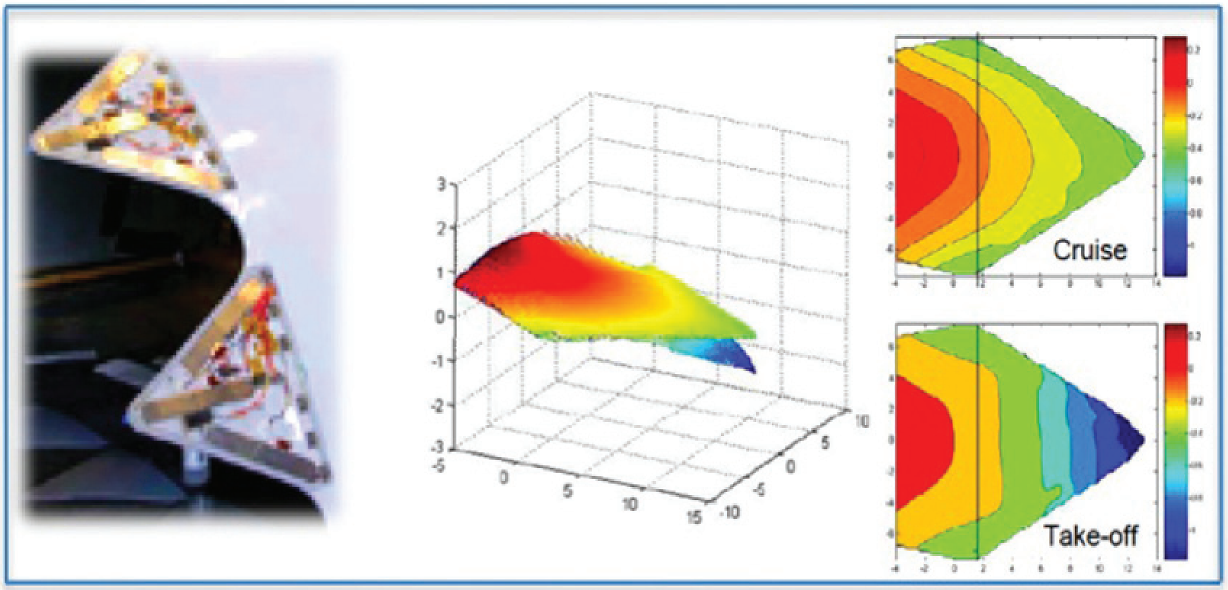

Figure 3. Variable geometry chevrons for immersion control (AIAA 2006-2546) (Boeing image).

Toward a Quieter Future

The NASA-funded QTD program, along with additional research efforts from industry partners, had led chevron technology to the brink of commercial application by 2005. With proven design concepts and technical readiness, flight-testing on modern commercial aircraft was the final step before such applications could be fully realized. In 2005, the Boeing Company, GE, Goodrich, NASA, and All Nippon Airlines (ANA) partnered to create the QTD2 program to perform flight-testing and static-testing of the noise-reduction technologies developed by QTD1 and subsequent programs. In August 2005, flights were conducted in Glasgow, MT, to test various combinations of noise-reduction devices. During these tests, uniform chevrons and variable geometry chevrons were tested and confirmed to reduce overall shockcell noise with little or no immersion into the jet flow.[27] The reductions achieved were close to 3 decibels while operating under normal power settings. The flight demonstration of this technology assured the success and reliability of chevron nozzles as a breakthrough noise-reducing technology.

Jet-noise research has continued to evolve, and more advanced chevron-based concepts have emerged in recent years. One new innovation focuses on the replacement of mechanical chevrons with fluidic jets that simulate the metal serrations that ultimately lead to noise reduction (figure 4). Recent studies have shown that this approach offers heightened flexibility and holds promise for even greater reductions in sound.[28] The ability to switch off the fluid injectors during cruise conditions, as well as the ability to avoid all thrust losses, makes this emerging concept very desirable. A recent study conducted by the University of Cincinnati showed that, currently, reductions of up to 4 decibels might be achievable using fluidic

27. E.J. Bultemeier, U. Ganz, J. Premo, and E. Nesbitt, “Effect of Uniform Chevrons on Cruise Shockcell Noise” (paper AIAA 2006-2440, 12th AIAA/CEAS Aeroacoustics Conference, Cambridge, MA, May 8–10, 2006).

28. S.F. Birch, P.A. Bukshtab, K.M. Khritov, D.A. Lyubimov, V.P. Maslov, A.N. Secundov, and K.Y. Yakubovsky, “The Use of Small Air Jets to Simulate Metal Chevrons” (paper AIAA 2009-3372, 15th AIAA/CEAS Aeroacoustics Conference, Miami, FL, May 11–13, 2009).

chevrons.[29] Alternative designs for variable chevrons (what NASA terms "active" chevrons) also continue to be of growing interest to industry. These are some of the future advancements to chevron technology that will define the next generation of noise-reducing technologies and contribute to the aeronautics industry for years to come.

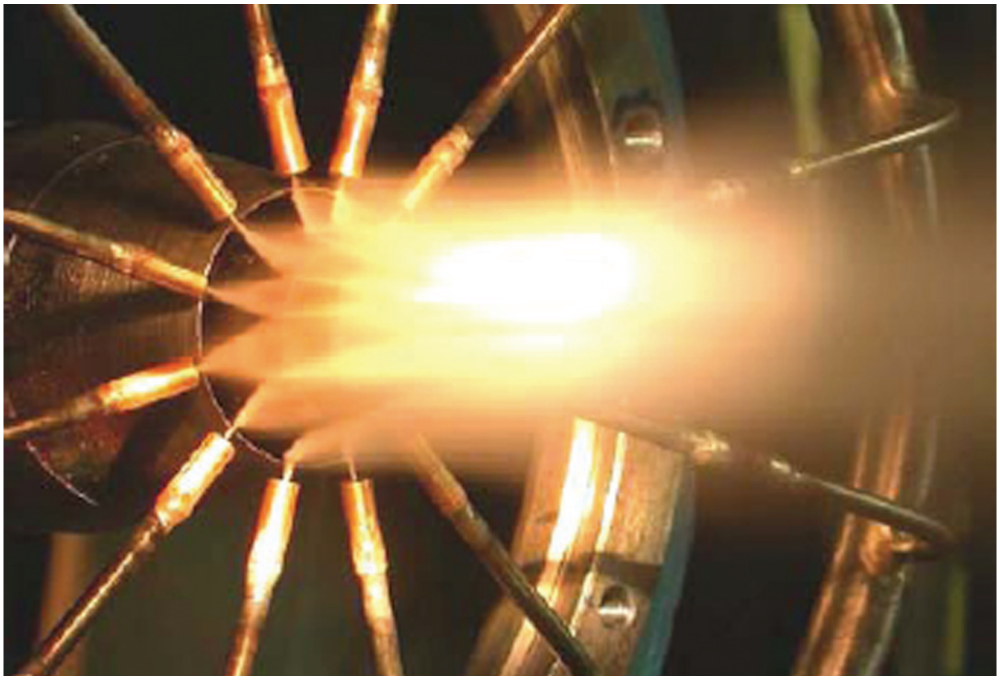

Figure 4: "Fluidic chevrons" or fluid jets used to simulate mechanical chevrons (AIAA 2009-3372) (Boeing image).

Today's commercial airlines have continued interest in increasing their payload capacity and engine efficiency, while complying with noise standards regulated by the FAA. In order to meet this growing demand, aircraft companies must consider new technologies to reduce the high noise levels produced by modern high-thrust aircraft engines. Thanks to decades of NASA research, effective noise-reduction technologies, such as the chevron nozzle, have emerged and earned their place in today's fleets.[30] Chevron nozzles are currently implemented on various Boeing, Embraer, and Bombardier commercial jets and will continue to be implemented on many future aircraft. In order to advance new technologies, critical research must continue to focus on many aspects of the problem, such as the specific sources of jet noise, the physical principles behind each source, and possible mechanisms that could be used to counteract this phenomenon, in order to ensure ongoing progress. As the aeronautics industry continues to face greater challenges in noise reduction, new solutions will have to be conceived to address the future need for greener, more efficient aircraft. Innovative concepts and ideas, along with new materials and resources, will play a major role in NASA's future contributions to noise-reduction research and the next generation of quieter air transportation.

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29. Rask, Harrison, Munday, Harris, Mihaescu, and Gutmark, "Jet Aircraft Propulsion Noise Reduction Research."

30. Chevron technology exists on today's Boeing 747-8, Boeing 787-3, Boeing 787-8, Boeing 787-9, Embraer 170, Embraer 175, Embraer 190, Embraer 195, and Bombardier Regional Jet CRJ700.

National Aeronautics and Space Administration

Winglets:
Striving for Wingtip Efficiency

Clayton Bargsten
NASA Headquarters

Introduction

Human flight is an impressive accomplishment of our society today. It affords us a freedom and speed of transportation never before observed in history. Every time we fly, we hope for the safest ride at the best possible price. We also hope that the flight is as environmentally friendly as possible. To make these goals a reality, the aeronautics industry must constantly innovate, bringing ever better products to market. The winglet is one of these innovations. It is one of NASA's most utilized developments, an idea that only truly came to fruition in the past few decades.

Winglets allow for drastic improvements in aircraft fuel efficiency, range, stability, and even control and handling. They are traditionally considered to be near-vertical, winglike surfaces that can extend both above and below the wingtip where they are placed. However, one may see them today as also being associated with any wingtip device intended to enhance wingtip performance.

How good can the performance enhancement really be? Well, some designs have seen astounding improvements, like 7-percent gains in the lift-to-drag ratio and a 20-percent reduction in drag due to lift at cruise conditions.[1] Wingtip technologies still hold great promise for aeronautics today and well into the future, with the potential to save hundreds of thousands of dollars in fuel costs per aircraft each year.

Wingtip Problems

Before we can understand how winglets work, we must first understand the problem they are intended to solve. Extremely hazardous and detrimental effects can be created at the tip of every wing. The severity depends on many factors, such as how much lift is being produced and how fast the wing is passing through the air. These effects usually take the form of a vortex trailing the tip of the wing.

A vortex is the rotational motion of a fluid medium, in this case air, generated as the high-pressure air from the bottom of the wing flows around the tip-side edge to the lower pressure region on top (figure 1). While vortices known as bound vortices are created along the entire length of the wingspan, it is the trailing vortices behind the wingtips that are much stronger due to the three-dimensional effect of a finite wingspan. Such a phenomenon can create significant stability and efficiency issues for the entire aircraft. For high-lift, low-speed conditions as seen on runways, or for high subsonic cruising speeds (figure 2), the drag induced from these vortices can account for up to half of all drag.[2]

To give an idea of how powerful the vortices behind a large jetliner may be, consider that a smaller aircraft can be flipped completely on end if it accidentally enters this trailing tip wake before the vortex has had time to dissipate. Techniques for preventing or quickly dissipating wingtip vortices have thus been a constant source of concern to the aeronautical industry. In order to prevent such disasters, as well as to address stability issues like flutter and buffeting (wing vibrations), and to increase fuel economy through better wing efficiency, winglets have arisen as a solution to the root vortex problem.

There is one possible benefit of tip vortices through the use of formation flight—think flocks of flying geese. Here, the upwash from the tip vortices of the aircraft in front provides additional lift to those behind it. Such flight techniques are being considered for airport capacity management and military applications. The accuracy required to ensure safe operation, however, has make formation flight a difficult task to implement to date. Also, as most operations throughout history and today do not involve formation flight, the

1. Joseph R. Chambers, *Concept to Reality: Contributions of the NASA Langley Research Center to U.S. Civil Aircraft of the 1990s* (Washington, DC: NASA SP-2003-4529, 2003), p. 39.

2. Ibid., p. 35.

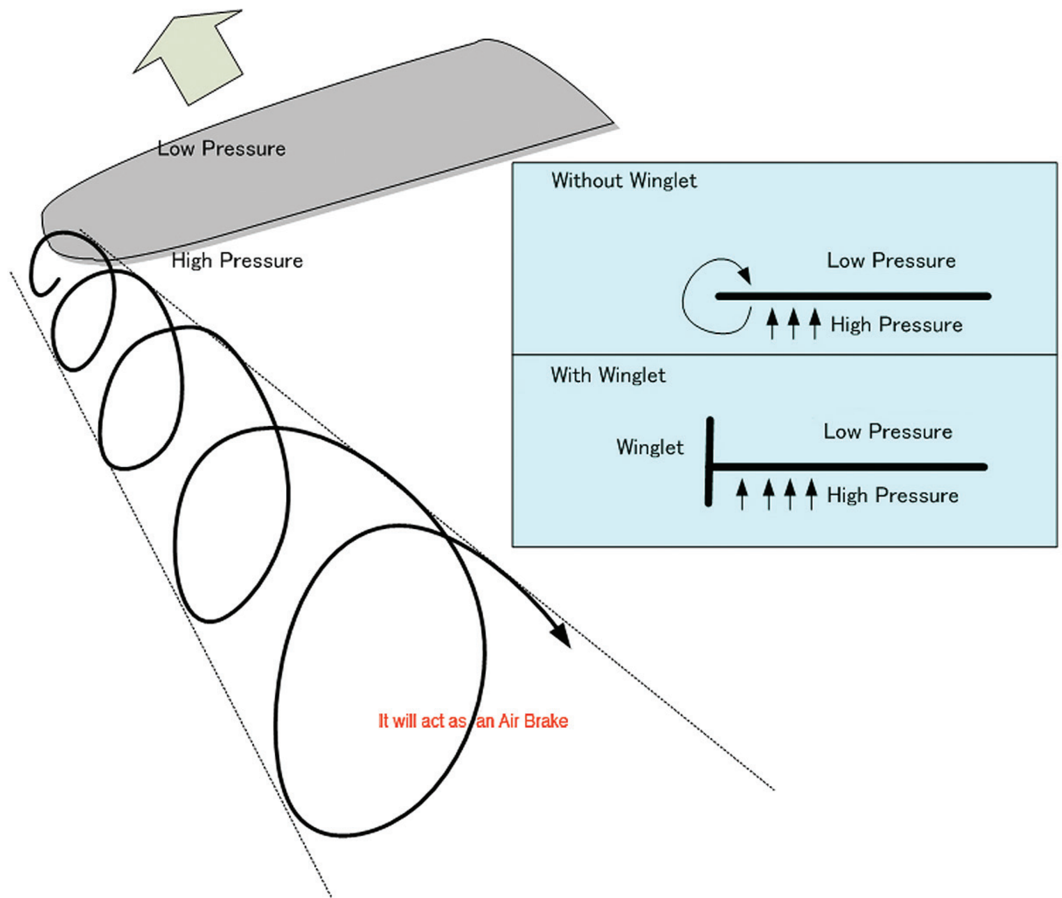

Figure 1: A vortex is created as air from high-pressure regions on the bottom of the wing curls around the tip to low-pressure regions on the top of the wing. Winglets help prevent vortex creation (Takeshi Asahara/Partnership RC-Sailplane.com).

Figure 2: The vortices created by high-lift, low-speed conditions seen on runways (left) and at high subsonic cruising speeds (right) (NASA).

focus has primarily been on methods to reduce the effects of these detrimental wingtip vortices during solo aircraft flight through the use of winglets. Though winglets have a rather long and checkered history, NASA has been one of the chief innovators in their research and development.

Early Background

The history of winglets begins with that of human flight, dating back to the late 1800s. In fact, the first studies on wingtip devices were conducted in 1897 by English engineer Frederick W. Lanchester. He and fellow engineers of the time noted how strongly the shape of an aircraft's wing influenced multiple facets of its aerodynamic efficiency.

Lanchester's theoretical studies and experimental investigations of this phenomenon indicated that placing a vertical surface at the wingtip could strongly reduce the wingtip drag under high-lift conditions. He designed and patented such surfaces, calling them "endplates." However, at cruise conditions his design created large flow separations, generating too large an increase in profile drag to justify its use.[3]

Unfortunately, further development would then be very slow for around the next 70 years. The Wright brothers placed what they called "side curtains" or "blinkers" on a few example models of their Wright Model B aircraft. This was, however, a biplane where the side curtains were placed between the wings for stability. The stability factor would become another key consideration for winglets from this time on.

The next small progression in the history of winglets would come in 1922 from Elliott Reid, working at Langley. He was studying the effects of shielding airfoil tips. His work showed that in comparison to an unaltered airfoil, all modified tip forms were slightly inferior at small lift coefficients yet provided for a considerable reduction of induced drag at high-lift coefficients.[4] Paul Hemke would build on this knowledge in 1927, when he developed some of the rudimentary formulas used to calculate the induced drag of endplates for mono- and biplanes. His calculations showed decent agreement with experimental results and that the shape and section of endplates were very important.[5]

After World War II, a German aeronautical engineer, Dr. Sighard Hoerner, came to the United States to work at the U.S. Wright-Patterson Air Force Base in Ohio. While there, he completed development on his drooped wingtips in 1952; they are often referred to as "Hoerner Tips" in classrooms today. They were used on gliders for years; and though not overly effective, they did direct the vortex away from the wing's top and increase the wing's overall lift-to-drag ratio.[6] A bit of additional research was done by the British Aeronautical Research Committee in 1956 to investigate "nonplanar" (nonhorizontal) lifting systems. Its members saw theoretical potential for aerodynamic improvements at the wingtips, but experiments again confirmed that current designs produced too much additional profile drag to justify their use.[7]

The Beginning of Success—Wind Tunnel Test

The Organization of the Petroleum Exporting Countries (OPEC) oil embargo and resulting energy crisis, beginning in 1973, vigorously renewed interest in energy-saving techniques and research. In response,

3. Richard Hallion, *NASA's Contributions to Aeronautics: Aerodynamics, Structures, Propulsion, and Controls*, vol. 1 (Washington, DC: NASA SP-2010-570-Vol 1, 2010), p. 118.

4. Elliott G. Reid, *The Effects of Shielding the Tips of Airfoils* (Rep. No. 201, Langley Memorial Aeronautical Laboratory, 1922), p. 347.

5. Paul E. Hemke, *Drag of Wings with End Plates* (Rep. No. 267, Langley Memorial Aeronautical Laboratory, 1927), p. 253.

6. Sighard Hoerner, *Aerodynamic Shape of Wing Tips* (Technical Report [TR] 5752, 1952), p. ii.

7. Hallion, *NASA's Contributions to Aeronautics*, vol. 1, pp. 116–117.

NASA created the Aircraft Energy Efficiency (ACEE) program. At the time, Richard T. Whitcomb was an American aeronautical engineer working for NASA's Langley Research Center, primarily with the 8-foot Transonic Pressure Tunnel. His innovations had greatly contributed to the previous development of the supercritical airfoil.

With the new ACEE program, he switched focus to the wingtip-induced drag phenomenon. He was reportedly inspired by an article in Science detailing the use of tip feathers by soaring birds to control flight characteristics. What set Whitcomb apart from the other scientists studying the bird's tip feathers was his deeply intuitive and methodical approach in emulating them for aircraft

Whitcomb began experimenting with wingtips in 1974. His analysis led him to hypothesize that a near-vertical, winglike surface at the wingtip could indeed reduce the strength of trailing vortices, if properly designed. He envisioned that they would extend above and, in certain cases, below each wingtip. A proper design would require a balance between cant, the winglet's angle off vertical, and toe, the angle the winglet deviates from airflow.[8]

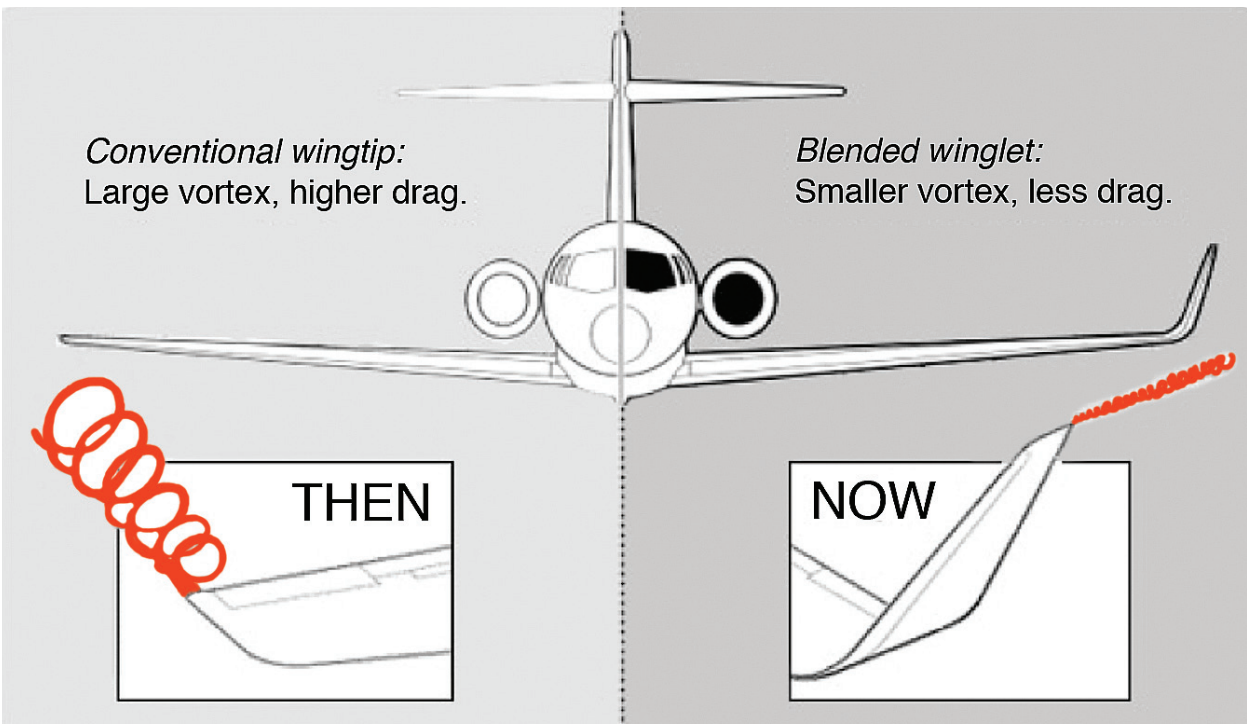

Figure 3: This example shows how large an impact winglets can make on the diffusion of vortices (Aviation Partners, Inc.).

In Whitcomb's own report, published in 1976, he found that previous experimenters had primarily observed the fact that winglets would create greater moments on the wings, requiring heavier wing-support structures to accommodate. This was thought to render simple wingtip extensions more effective. Thus, the pursuit of winglets was minimal or disregarded other than for certain sweptback and delta-wing configurations where the vertical surfaces did provide greater directional stability. What his predecessors had overlooked, however, was that in order for winglets to be used successfully, they must produce significant side forces to

8. Hallion, NASA's Contributions to Aeronautics, vol. 1, pp. 116–117.

decrease lift-induced inflow above the wingtip and outflow below the tip. In this sense, they could be called "vortex diffusers" (figure 3).[9] One had to be careful that flow separation did not occur at any critical speeds, either on the winglet surface or at the winglet-wing junction.[10] To do this, careful consideration must be taken in their design, and strictly vertical surfaces are not optimal for most flight conditions.

If angled correctly, winglets could actually create a lift force from the vortices and thrust when angled forward.[11] Yet they maintained the same or lower bending moment and a smaller wingspan with greater flight stability than tip extensions in most cases. To stress the fact that the design of these surfaces requires considerable care and attention to airfoil aerodynamic characteristics, similar in effort and sophistication to those required for wing design, Whitcomb called them "winglets."[12]

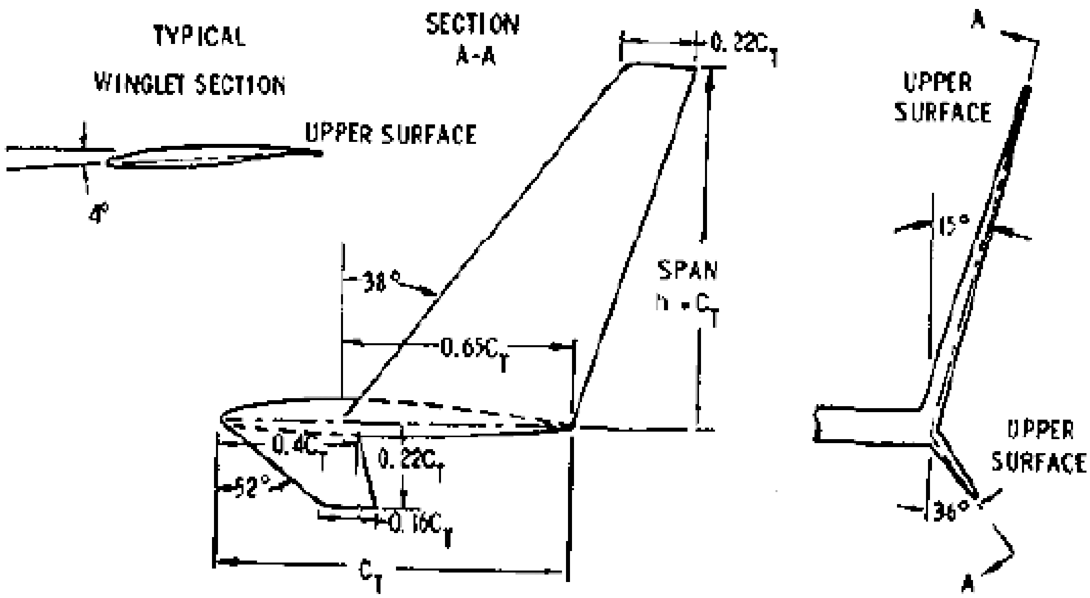

Figure 4: The original design for a set of winglets carefully designed by Whitcomb and his team at Langley (Richard Whitcomb, NASA Langley Research Center).

Whitcomb's design was specifically intended for lifting and subsonic mach numbers, with primary surfaces located rearward above the tips and smaller secondary surfaces placed forward below the tips (figure 4). They were designed with first-generation, narrow-body jet transports in mind. His team's wind tunnel tests at Langley showed an amazing reduction in induced drag of almost 20 percent and an increase in wing lift-drag (L/D) ratio of roughly 9 percent. This was twice the performance enhancement given by simple tip extensions.[13]

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9. Richard T. Whitcomb, *A Design Approach and Selected Wind-Tunnel Results at High Subsonic Speeds for Wing-Tip Mounted Winglets* (Washington, DC: NASA TN D-8260, 1976), p. 2.

10. Chambers, *Concept to Reality*, p. 38.

11. Hallion, *NASA's Contributions to Aeronautics*, vol. 1, p. 117.

12. Chambers, Concept to Reality, p. 36.

13. Whitcomb, *A Design Approach*, p. 1.

Historical Developments—Industry and Full-Scale Use

Before the full findings of Whitcomb's winglet work at NASA were developed and flight-tested, Burt Rutan flew his famous home-built Vari-Eze. Rutan was an American aerospace engineer who specialized in light, strong, and energy-efficient aircraft. His Vari-Eze was the first plane to officially be designed, built, and flown using NASA-inspired winglets. His maiden flight was in 1974. Though he carefully designed the winglets on the Vari-Eze for efficiency, his primary focus was to use them for stability on a front canard to prove its viability as a safe and efficient alternative to conventional wing designs. The Vari-Eze set many flight-distance records of the time in the under-500-kilogram class. Rutan's later Voyager design was to be the first aircraft to fly around the world without stopping or refueling in 1986, although its winglets got ripped off in flight.[14]

In 1978, subsequent lab research for low-speed general aviation aircraft found that designing for this class of aircraft was easier and stood to gain substantially as well. The wing taper was shown to be a critical consideration, and wing L/D could show improvements of up to 15 percent.[15] In early 1978, Langley also organized a meeting with the airliner, business jet, and personal aircraft industries. It was to focus on advanced technologies developed by NASA for conventional takeoff and landing (CTOL) aircraft. A primary goal of the convention was to officially share Langley's discoveries regarding winglets. Many of the major aircraft producers such as Lockheed and the Boeing Company acknowledged the increased efficiency NASA's winglets had to offer. Upon completing their own studies, however, they determined that the cost of retrofitting their fleets with winglets was not worth the cost of fabrication.

On the other hand, the business jet community was quickly fond of winglets. Learjet created the Model 28 as a test bed for its new high-aspect-ratio wings, adding NASA's winglets in 1977 (figure 5). The winglets improved directional stability and added 6.5 percent to the flight range. The Model 28 performed so remarkably and was so popular at conventions that the model entered production in 1979. Winglets were included on subsequent Learjet models as well. Learjet competitors were not far behind either. Gulfstream included winglets on their Gulfstream III, IV, and V models. The Gulfstream V even received the 1997 Collier Trophy, set 70 other national and world flight records, and allowed for unprecedented nonstop New York-to-Tokyo business trips.

McDonnell Douglas was also very impressed with NASA's findings on winglets. The company immediately began research and development as an alternative to increased wingspan for their DC-10.[16] Increased wingspan is a critical issue for planes that are already so large as to take up all available space at airport runways and loading bays. In their own flight-test on a modified DC-10, McDonnell Douglas researchers took detailed data on flutter, buffet boundaries, stability and control characteristics, stall speed impacts, drag reduction, and varying load and flight conditions. They ultimately determined that winglets significantly improved most of these flight characteristics, with an overall 3-percent reduction in fuel burn and 5-percent reduction in takeoff distance at the maximum takeoff weight.[17] Unfortunately, the high costs of the Federal Aviation Administration (FAA) recertification process made adding winglets to the current DC-10 fleets unfavorable. Nonetheless, all was not lost, and the experience gained was instead applied to

14. J. Chambers, *Concept to Reality*, p. 41.

15. J.F. Marchman III, H.F. Faery, Jr., and D. Manor, "Whitcomb Winglet Applications to General Aviation Aircraft" (*Proceedings of AIAA Aircraft Systems and Technology Conference*, 78-1478, Los Angeles, CA, 1978), p. 6.

16. Hallion, *NASA's Contributions to Aeronautics*, vol. 1, pp. 120–122.

17. J.R. Agar and the staff of Douglas Aircraft Company, *DC-10 Winglet Flight Evaluation* (Washington, DC: NASA CR-3704, 1983), p. v.

Figure 5: The Learjet Model 28 with its newly designed winglets (NASA Langley Research Center, UID: SPD-NIX-EL-1997-00215).

the new, advanced, derivative design called the MD-11. This would expand Pacific air routes, as it could carry 300 passengers over 8,200 miles and entered service in 1990.[18]

For NASA, full-scale flight evaluations would begin in 1979 at Dryden Flight Research Center in cooperative operation with the Air Force. Evaluations were to be conducted using a Boeing KC-135 Stratotanker. It was chosen for two main reasons. First, the Air Force wanted to explore the possibilities of retrofitting its aging fleet of tankers to make them more efficient. Second, the KC-135 exemplified traditional early jet transports that featured elliptical-type span loading and relatively high loads on the outer wing panels. Flight evaluations confirmed lab work and showed a 7-percent gain in the L/D ratio and a 20-percent reduction in induced drag at cruise conditions. Though this was a huge success, it was instead decided to retrofit the fleet with new, more efficient engines that were also necessary at the time.[19]

Back in the world of general aviation, the Boeing Company, which had initially been reluctant to add NASA-developed winglets, finally decided it was cost effective to incorporate them on its aircraft in 1985. The Boeing 747-400 was the first large U.S. commercial transport to do so. Winglets increased the range of the 747-400 by over 3 percent and helped to limit the wingspan, which already took up nearly all space at

18. Hallion, *NASA's Contributions to Aeronautics*, vol. 1, p. 123.

19. Chambers, *Concept to Reality*, pp. 38–39.

airport loading bays.[20] Even so, the Boeing Company did decide to leave off the smaller winglet below the wingtip in accommodation of ground-handling equipment.

On the European front of aircraft manufacturers, Airbus developed a variant of the Whitcomb winglets. Airbus called its wingtip solutions “wingtip fences.” The fence surfaces extended both above and below the wingtips, looking more like a “V” at the end of the wing rather than the tip that molded out of the wingtip naturally, as developed at NASA. This design was developed by British aerodynamicists at Hatfield and Hertfordshire, U.K., and it was more suited to the Airbus wing style. They were first installed in 1985 on the A310-300 with a savings of almost 5 percent in fuel costs.[21] It is also important to note that in 1988, the Ilyushin Il-96 was the first Russian jet to feature winglets. Much of their research, however, is not readily available.

Winglets Today—Around the World

Today, research has shown that the most effective shape for winglets is indeed carefully engineered, near-vertical surfaces attached to the tips of a wing. Because circulation strength is a factor of the lift loads near the wingtip and the wing planform, winglets have traditionally been most effective on aircraft requiring high lift, such as high-altitude executive jets and heavy commercial transports. Stated otherwise, winglets are not as good for high-aspect-ratio wings with supercritical sections. Accordingly, winglets are of greatest benefit to long-ranged aircraft, fitted by and large to second-generation airliners and business jets.[22]

Drastic increases in fuel prices have driven the retrofitting of over 2,500 Boeing jets with blended winglets by 2003. While winglets were included on the 747-400, the Boeing Company partnered with a smaller Seattle-based company, Aviation Partners, Inc., to provide blended winglets as retrofits for customers of its 737 series. This specialty manufacturer has introduced them for other companies, such as Gulfstream, as well.

Blended winglets are merely designed to arise (or blend) naturally out of the wing in a smooth fashion in order to reduce interference drag at the wing-winglet junction. They are estimated to cost around $600,000 for an 8-foot set, and the savings in efficiency are mostly used to save fuel rather than to fly faster.[23] While it may seem hard to justify spending upward of $600,000 for a pair of winglets that might only save a couple of percent in fuel savings, perspective must be put on the situation. A 1-percent fuel savings at cruise conditions can mean up to 12 gallons of fuel saved per hour. This represents tens of thousands of gallons of saved fuel and hundreds of thousands of saved dollars over the course of a single year.[24]

The U.S. Air Force is retesting and again trying to retrofit winglets on the KC-135 Stratotanker to reduce fuel consumption. It is also considering new concepts such as raked wingtips. This is another idea that has arisen from carefully understanding how wingtips work and from an association between the Boeing Company and NASA for development and testing. Raked wingtips give the tip of the wing a higher degree of sweep than the rest of the wing. They are another wingtip technology to increase efficiency, to improve climb performance, and to shorten takeoff distance, all by increasing the effective aspect ratio of the wing by disrupting the detrimental wingtip vortices. Such technologies and retrofits promise between

20. Maurice Allward, “Wingtip Technology,” *Putnam Aeronautical Review* no. 1 (May 1989): 41.

21. Hallion, *NASA's Contributions to Aeronautics*, vol. 1, p. 124.

22. Allward, “Wingtip Technology”: 40.

23. Hallion, *NASA's Contributions to Aeronautics*, vol. 1, pp. 124.

24. Allward, “Wingtip Technology”: 42.

Figure 6: Various wingtip devices in use today are shown here, including the (1) "traditional" winglet, (2) blended winglet, (3) wingtip fence, and (4) raked wingtips ([1] NASA Dryden Flight Research Center, UID: SPD-NIX-EC79-11481; [2] Aviation Partners, Inc.; [3] Bruce Leibowitz, Northwest Airbus A319, N353NB, Sept. 2003; [4] The Boeing Company, DVD-1147-1, copyright 2005).

6- and 12-percent increases in range.[25] Ever-rising fuel costs are making retrofits for aircraft like the KC-135 a viable and attractive option, in many cases for the first time. To get an idea of what all these wingtip solutions and winglet variations look like, see figure 6.

The new Boeing 747-8 due out at the end of 2010 will incorporate raked wingtips, while Boeing's new 787 will have options for either winglets or raked wingtips, depending on the chosen model in the series. The Airbus A319, 320, 330, and 340 models all have implemented winglet solutions as well. These offer a total 5-percent savings in fuel costs. As fuel prices continue to rise, it is becoming appropriate for more and more fleets of all types to be retrofitted with fuel-saving technologies such as winglets. Even gliders are starting to benefit.

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25. Joel F. Halpert, Daniel H. Prescott, Thomas R. Yechout, and Michael Arndt, "Aerodynamic Optimization and Evaluation of KC-135R Winglets, Raked Wingtips, and a Wingspan Extension" (paper AIAA 2010-57, 48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition, Orlando, FL), p. 1.

Novel Uses

An interesting side note is the strong interest the yacht community saw for NASA's winglet creations in hydrodynamics. Australian entrepreneur Alan Bond embraced winglets by designing a racing yacht with a winglet tacked craftily onto the bottom of the keel. His yacht won the America's Cup race in 1983, breaking a 132-year American winning streak.[26] Today, a variety of winglike structures are used on keels to reduce drag, providing additional side forces and allowing the boat to sail upwind more efficiently. It also provides a downward force slightly benefiting the boat's stability.

Much research has also gone into the investigation of winglets on rotating blades. They can be used on propellers, helicopter rotors, and wind turbine blades to reduce drag, diameter, and noise. The reduction of blade-tip vortices stands to reduce detrimental interaction with each other and with the ground surface during taxiing, takeoff, and hover. This would consequently reduce damage from dirt and small objects picked up in these vortices. Winglets are even being investigated for wind turbine generators to increase efficiency and productivity.[27]

Future Research and Development (R&D) Possibilities

The future of wingtip technology is perhaps the most important topic of discussion. While winglets have provided for significant improvements in efficiency in the past, is their future potential enough to warrant further research and development? Should funding be allocated to retrofit existing fleets or simply to design new ones? Does the greatest potential lie in efficiency, stability, or control and handling, and for what types of aircraft? What about nonaeronautics applications? What are the most appropriate and economical policies to adopt in approaching these issues?

To give a glimpse of what the future could hold for wingtip technologies, consider these ideas for application evolving through the research of today. Split wingtips are under study as a "morphing" technology for morphing aircraft. They would be independently actuated and mounted on a baseline flying wing to adapt to and to optimize for the present flight conditions. They also show potential as alternatives to conventional elevons and drag rudders.[28]

Another idea is that by controlling the trailing tip vortices, we would be able to gain control over the dispersal of insecticides and fertilizers behind agricultural aircraft. This control would also allow for more flexible ground maneuvering. Smaller vortices would dissipate more quickly, reducing the space and time required between airliners on the runways. That would greatly increase airport safety and productivity, especially for runways handling large planes. Ideas to control these vortices include placing cylindrical airfoils at each wingtip, mounting engines at wingtips, or even placing "small windmills" at each tip, all to dissipate or capture the vortices' energy.[29]

Current approaches to wingtip issues include both new designs for future aircraft and retrofits for current aircraft when economical. For example, the Boeing 727 and 737 configurations mentioned earlier have both been retrofitted with winglets. The FAA has many constraints in the retrofitting process that can

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26. Hallion, *NASA's Contributions to Aeronautics*, vol. 1, pp. 124–125.

27. Jeppe Johansen and Niels N. Sørensen, Aerodynamic Investigation of Winglets on Wind Turbine Blades Using CFD (Roskilde, Denmark: Risø-R-1543(EN), Risø National Laboratory, 2006), p. 1.

28. P. Bourdin, A. Gatto, and M. I. Friswell, *Potential of Articulated Split Wingtips for Morphing-Based Control of a Flying Wing* (paper AIAA 2007-4443, 25th AIAA Applied Aerodynamics Conference, Miami, FL, June 2007), p. 1.

29. Allward, "Wingtip Technology": 44.

make it slow and costly. Continued development for both retrofits and new designs makes economic and environmental sense, however, especially considering the costs and types of fuels available today. With further research, wingtip technologies will continue to drastically increase aircraft performance.

Applications for winglets have spread far beyond commercial and military aviation and well into the personal aircraft market. All together, these applications make winglets stand as what might very well be NASA's most widespread concept in use, on both domestic and international levels.[30] They have highly visible benefits today and even greater prospects through continued research for the future.

30. Chambers, *Concept to Reality*, p. 44.

National Aeronautics and Space Administration

Composite Fan Casings:
Increasing Safety and Fuel Efficiency for Commercial Aircraft

Malcolm Gibson
NASA Headquarters

Introduction

Today's commercial aircraft employ large turbofan engines due to their high efficiency, high thrust at low speeds, low fuel consumption, and reasonable noise levels. Turbofan engines use a large fan to draw air into the engine. A large portion of this air is accelerated around the outside of the jet engine, while the lesser portion is compressed, mixed with fuel, and ignited to generate additional thrust and provide power to the fan. The fan is enclosed in a large structure known as the fan casing (figure 1). In the case of a malfunction or unexpected obstruction, fan blades can break off at very high speeds and create a serious threat to the engine and airframe. This situation is known as a blade-out and can occur at any stage of flight. In order to secure the damaged blade, the fan casing must be built robust enough to avoid penetration of the engine nacelle.[1] The fan casing must also endure an additional, secondary load that occurs due to rotor imbalance while the engine is shutting down.

Figure 1: The fan casing of a modern turbofan jet engine (*http://www.sti.nasa.gov/tto/Spinoff2006/T_1.html*).

Today's commercial aircraft makers most often address these challenges by manufacturing fan casings using strong metal alloys. These materials are strong enough to deflect broken blades and contain them within the engine compartment. Unfortunately, these materials are also very heavy and contribute to a significant portion of the engine's total weight. Increased weight translates to poor fuel efficiency, shorter transits, and decreased cargo capacity. In order to advance the next generation of commercial aircraft, new solutions need to be conceived to decrease weight while also retaining adequate levels of safety.

In the past, aircraft manufacturers have investigated two approaches to building a lighter fan casing. The first approach is referred to as the "hard-wall" approach and minimizes weight by selecting light-weight metals like high-grade aluminum alloys as opposed to stronger, heavier metals like steel. The thick

1. A nacelle is the streamlined, outermost enclosure used to house the engine under an aircraft wing.

aluminum walls serve to deflect stray blades and keep them within the engine. The second approach, referred to as the "soft-wall" approach, involves wrapping a thick, high-strength fabric around a thinner aluminum fan casing. This approach aims at stopping the stray blade as it enters the fabric layer, where it would remain until later extraction. This approach was first used on a General Electric (GE) CF-34 turbofan engine during the early 1990s.[2] These approaches represent early success in the development of damage-tolerant fan casings and have been implemented on the majority of today's commercial airliners.

As the commercial aviation industry continues to evolve, so does the need for greater means of improving fuel efficiency. NASA has recognized that the large turbofan engines employed by commercial aircraft make considerable contributions to the overall weight of the airplane. By targeting the largest component in these engines, namely the fan casing, NASA believes further weight reductions can be made.

NASA's Glenn Research Center (GRC) in Cleveland, OH, has been investigating the use of advanced composite materials for use in the manufacturing of lighter weight fan casings over the past decade. Advanced composites are of interest due to their high strength, low weight, and ongoing availability to the aerospace industry. The use of high-strength composites in new engine fan casings represents the potential for great reductions in weight, increased safety, and other cost-saving benefits. In order to fully realize this technology, comprehensive research must be done in advanced composite manufacturing along with ballistic impact testing for concept validation. NASA has invested in overcoming these challenges and bringing the commercial aviation industry one step closer to improved fuel efficiency, increased payload, and greater aircraft range.

Composites Research

Engineering composites are usually composed of two constituent materials with significantly different chemical and physical properties. The two constituents, referred to as the matrix and reinforcement, work together to create a synergism of material properties different from their own. In aerospace engineering, high-strength fibers are often combined with durable epoxy resins to create a durable structural material that can be used as a lightweight alternative to heavy metals.

In the past, advanced composites research was expensive because of the materials used and the manufacturing processes involved. Fortunately, fiber costs are projected to decrease substantially, allowing for new, rapid developments in the area of low-cost manufacturing of large composite structures.[3] Composites have a high specific stiffness and low density, which make them very advantageous to aircraft structures. However, impact resistance can sometimes be a problem. In order to use composites in large engine structures like fan casings, comprehensive development must be done in manufacturing and impact testing in order to ensure efficiency and safety.

In 2003, after 4 years of research, GRC had developed TEEK, a low-density, lightweight, flame-resistant polyimide foam that provides excellent thermal and acoustic insulation, and high-performance structural support.[4] In conjunction with this research, GRC developed the first advanced composite jet engine fan-blade containment system concept and began looking into new ways of manufacturing composite fan casings. They also developed new tools, including simulation software that could be used to study the dynamics of blade-out occurrences without the use of real engines.

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2. G.D. Roberts, J.M. Pereira, M.S. Braley, and W.A. Arnold, *Design and Testing of Braided Composite Fan Case Materials and Components* (Washington, DC: NASA TM-2009-215811).

3. G.D. Roberts, D.M. Revilock, W.K. Binienda, W.Z. Nie, S.B. Mackenzie, and K.B. Todd, *Impact Testing of Composites for Aircraft Engine Fan Cases* (Reston, VA: AIAA-2001-1633).

4. 2004 NASA Technical Excellence, "New Material Improves Rotor Safety," available at *http://www.aeronautics.nasa.gov/te04_rotor_safety.htm.*

As a continuation of previous research, NASA's Aviation Safety Program funded a team of GRC scientists to develop composite fan casings for use on turbofan engines. In order to bring in additional talent from industry, GRC issued a small business innovation research (SBIR) grant to A&P Technology, Inc., one of the leading manufacturers of braided composites. A&P Technology is also partnered with two leading engine companies, namely Williams International and Honeywell International, making them an appropriate choice.[5] Under this agreement, A&P Technology developed a new generation of carbon fiber-reinforced polymer (CFRP) that could be used in advanced lightweight fan casings. One of the novelties of this material was its triaxial braided fiber construction (figure 2), which greatly reinforced its structural integrity and resistance to crack propagation. The new material was composed of T-700 12K carbon fiber and EPON 862 bisphenol F-based epoxy resin, both of which provided increased strength and durability.[6]

Figure 2: Triaxial braided carbon fiber (*http://www.sti.nasa.gov/tto/Spinoff2006/T_1.html*).

One of the greatest challenges for A&P Technology and GRC researchers was automating the manufacturing process in order to make the technology efficient, reliable, and affordable. Composite manufacturing involves two main processes. First, manufacturers must lay out a pre-form of dry fibers, and second, they must impregnate the fibers with resin using methods like resin transfer molding (RTM) or vacuum-assisted RTM. The process of laying out dry fibers can be quite difficult, especially when the structure is a large, complex cylinder incorporating flanges at both ends. Since NASA desired a system that was adaptable to different engine designs, A&P Technology needed to design a robust system that could braid the fiber directly around a capstan that incorporated the profile of the particular containment case without any warping. This led to the novel invention of the A&P Megabraider, the largest 800-carrier braider machine in the world.[7]

5. In addition to being partnered with Williams International and Honeywell International, extra sponsorship funding was provided to A&P Technology by GE Aviation in order to conduct this research.

6. B. Griffiths, "Composite Fan Blade Containment Case," *Composites World* (May 2005).

7. NASA, "Damage-Tolerant Fan Casings for Jet Engines," *Spinoff* (Washington, DC: GPO, 2006), available at *http://www.sti.nasa.gov/tto/Spinoff2006/T_1.html.*

With this innovative technology, A&P Technology has been able to successfully create dry fiber layups of various fan casing designs. After the construction of the dry fiber layup, a series of RTM processes draw the resin into the dry fiber mold and complete the major manufacturing process of the composite structure. One of the composite fan casings developed through this process is shown in figure 3.

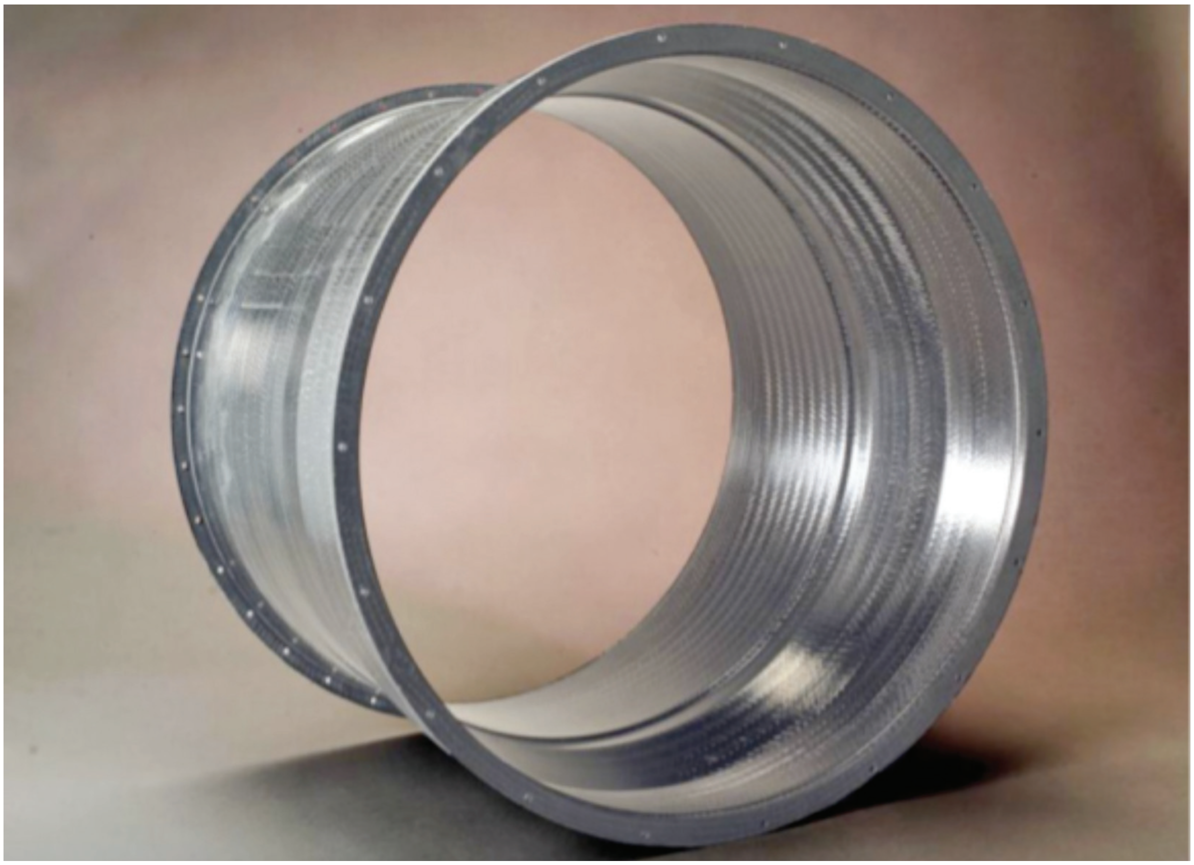

Figure 3: Composite fan casing developed through the A&P Technology manufacturing process (*http://www.sti.nasa.gov/tto/Spinoff2006/T_1.html*).

Ballistics Research

In order to ensure that composite fan casings perform as well as, or better than, existing metallic fan casings, comprehensive ballistics research must be performed. This research involves ballistic impact testing as well as cyclic testing to evaluate the structural integrity of the composite case and ensure its improved safety in the case of a blade-out occurrence.

Early ballistics research dates back to 1994, when NASA's Enabling Propulsion Materials (EPM) program investigated the use of composite casings for fan blade containment. Damage testing was originally undertaken using flat material panels to evaluate the performance of emerging composite materials compared to aluminum under conditions representative of a blade-out event. Projectiles were fired at the panels, and the resulting penetration holes were analyzed and compared (figure 4). Initial results showed that new composite materials generated lower stress levels and could be a promising replacement for the heavy aluminum fan casings in existence at the time. These early results encouraged NASA to investigate more accurate and affordable methods to simulate the use of composites in containment of stray fan blades.

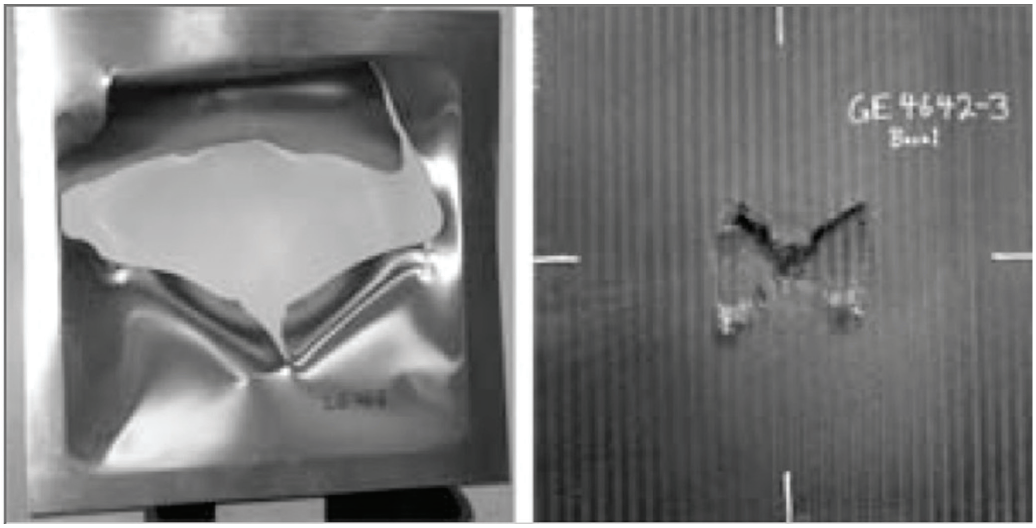

Figure 4: Impact damage endured by an aluminum and composite panel (Glenn Research Center).

In order to avoid the high costs of ballistics testing, new research work included a closer analysis of the dynamics of blade-out scenarios where the mass, speed, orientation, and angular acceleration all play important roles. Using these better-understood dynamics, researchers were able to program computers to simulate blade-out scenarios with different materials. NASA undertook this work in collaboration with the University of Akron, using LS-DYNA, a unique analytical code developed by Livermore Software Technology Corporation. This simulation software gave researchers new insight while maintaining significantly lower costs than previous impact testing. As computer-based testing continued, composites research was advancing to the point where material testing could not keep up. Therefore, simulations were limited by inadequate material property data and lack of validated material models.[8]

In order to progress this research to the next level, NASA began impact testing of new tribraided composites using small flat panels and, eventually, full-scale fan-case models. This research allowed scientists to confirm the success of new A&P composite materials in resisting fan-blade impacts. Impact tests showed improved performance of composites when compared to traditional metal alloy fan casings.

In addition to resisting fan-blade impacts, composite fan casings must also endure secondary loads during the spool down stage of the engine directly following the blade-out malfunction. During this time, secondary damage is caused by impact debris and out-of-balance motion of the engine rotor and may lead to crack propagation and severely compromised safety. Research showed that composites are very resistant to crack propagation due to the tribraided fiber construction. These results, in combination with impact testing results, gave researchers the confidence to begin full-scale testing.

Implementation

Certification of new composite fan casings begins with a full-scale engine blade-out test to confirm that the new case safely contains the stray blade and retains its structural stability during the large dynamic loads imparted during the spool down stages of the engine. With successful results, the fan casing can be used on emerging aircraft designs that employ lighter weight turbofan engines.

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8. G.D. Roberts, R.K. Goldberg, W.K. Binienda, W.A. Arnold, J.D. Littell, and L.W. Kohlman, *Characterization of Triaxial Braided Composite Material Properties for Impact Simulation* (Washington, DC: NASA TM-2009-215660).

The modern aviation industry is focused on improving fuel efficiency in order to save money while providing continued service. Composite fan casings present an opportunity to reduce engine weight by up to 40 percent,[9] which directly translates into longer flight distances, greater cargo, and improved fuel burn. Thanks to nearly a decade of NASA investment and industry collaboration, this technology allows for increased safety and weight reduction on new commercial aircraft.

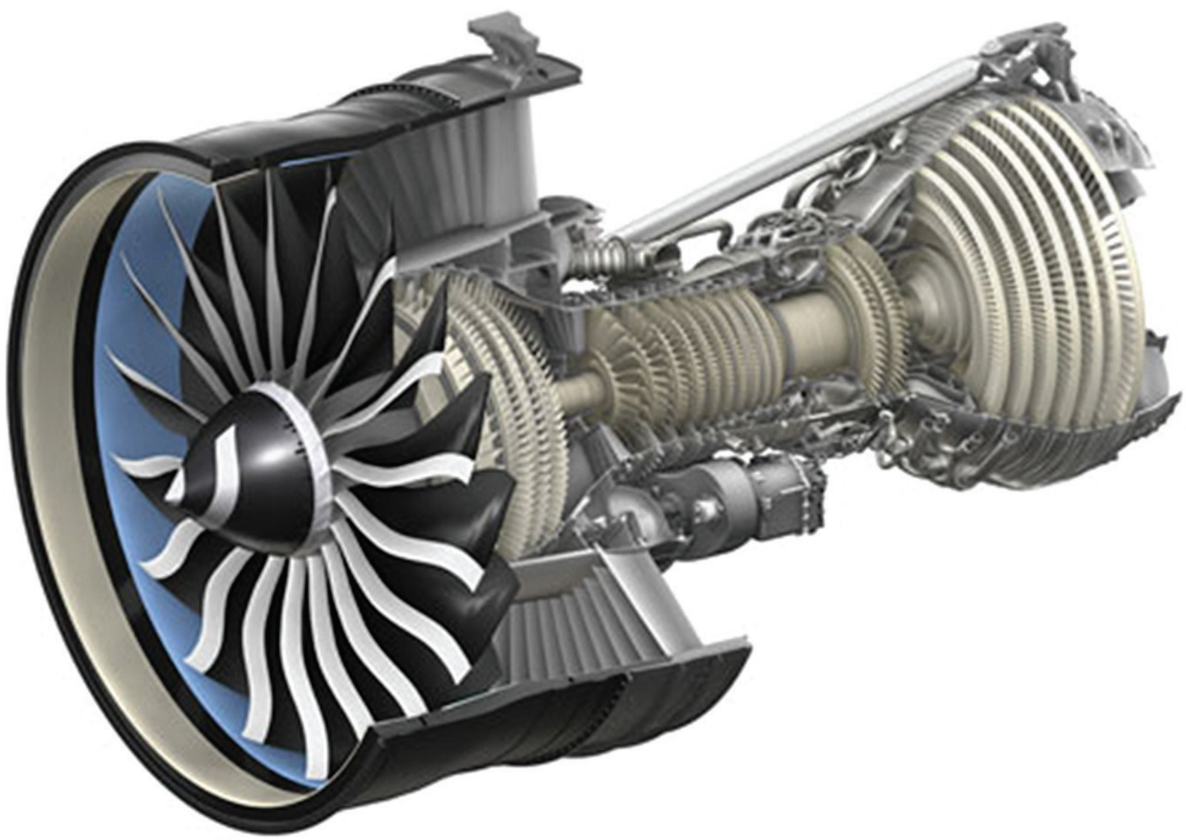

Figure 5: The GE Aviation GEnx turbofan engine (General Electric Aviation).

GE Aviation has recognized the benefits of composite fan casings and has chosen to employ them on their new GEnx high-bypass turbofan engine (figure 5). The company selected GKN Aerospace to develop and manufacture the front fan containment case. The GEnx engine represents the first to have both a fully composite fan case and fan blades.[10] The composite fan casing alone allows for up to an 800-pound weight reduction for a two-engine aircraft.[11] Final testing of the GEnx engine took place in 2006 with certification by 2007, and companies such as Boeing and Airbus have implemented these new engines on the new 787 Dreamliner and A350 aircraft. It is easy to see why top commercial aircraft companies would employ this safer, new lightweight engine technology.

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9. Griffiths, "Composite Fan Blade Containment Case."

10. "Press Release: New GEnx Engine Advancing Unprecedented Use of Composites in Jet Engines," GE Aviation press release (December 2004), available at *http://www.geae.com/aboutgeae/presscenter/genx/genx_20041214.html.*

11. The Minerals, Metals, and Materials Society (TMS), "General Electric Tests Composite Jet Engine," *JOM* (February 2005).

Conclusion

The development of alternative materials for use in reducing the weight of an aircraft has been of great significance since the dawn of flight. In today's commercial aviation industry, jet engines comprise a significant portion of the weight, and new alternatives are of interest to aircraft companies. In the early 2000s, the rising usability of advanced composite materials, along with the development of more effective ballistics testing methods, has stemmed new growth in composites manufacturing for large aerospace structures.

NASA has recognized the benefit of transitioning existing metal fan casings into safer, more effective composite fan casings in order to significantly reduce the weight of commercial aircraft engines. This technology benefits passengers and airline companies alike by improving safety, reducing fuel burn, increasing aircraft range, and expanding cargo capabilities. Through an SBIR with A&P Technology, NASA has worked with industry to develop the materials and manufacturing techniques to make this technology a reality for commercial aviation.

NASA and A&P Technology have been recognized for their novel work in the development of composite fan casings. The Ohio Department of Development awarded A&P Technology the Emerging Technology Award for their novel work during the SBIR with NASA. In addition, NASA's containment concepts and blade-out simulation team received the NASA Turning Goals Into Reality Award for its dedicated research work. The innovation and research genius put forth during the development of composite fan casings will benefit modern aviation for many years to come.

National Aeronautics and Space Administration

ADS-B and Airspace Awareness

Clayton Bargsten
NASA Headquarters

Introduction

Have you ever been on a flight, reached the destination airport, and had to watch in agony as your plane circled the airport rather than landing immediately? Perhaps you have pondered the location of other aircraft in the sky around you as you fly, or how a pilot can fly in weather with little to no visibility. NASA and the Federal Aviation Administration (FAA), along with many other companies and organizations, have been dealing with these exact issues for decades.

While there have been many different programs and technologies developed to help aircraft take off and land efficiently, avoid midair collisions, and fly in the dark, most are dated and incapable of handling the drastic increases in air traffic anticipated over the coming years. Such systems to track and guide aircraft have traditionally been based on radar. It is, however, expensive to install and maintain, as well as limited in scope, accuracy, and speed. Providing radar coverage for many regions of the United States, including mountainous areas, large swaths of Alaska, and the gulf coast, has never been economical.

This is why extensive research and development are being done on the Next Generation Air Transportation System (NextGen) in order to overhaul and upgrade the National Airspace System (NAS). A key component of NextGen is the Automatic Dependent Surveillance-Broadcast (ADS-B) technology. It will help ensure future airspace safety and efficiency in an economical manner that can provide a level of coverage over the entire United States, even those regions previously excluded from radar. It derives its information from satellites, and it will thus also help to end national reliance on ground radar systems as the primary means of tracking aircraft.[1] The work on ADS-B has been so successful and promising that a team consisting of over 26 private and public groups was given the prestigious Collier Trophy in 2007. NASA was a key member of that team, along with the FAA, United Parcel Service (UPS), Garmin, Lockheed Martin, the Air Line Pilots Association, and others.[2]

Advantages of ADS-B

To understand the advantages of the ADS-B system, let us first begin by understanding the conventional radar system ADS-B is intended to replace. Radar works by bouncing radio waves off of targets from fixed terrestrial antennas and obtains required information by processing reflected signals from the radar. Getting a readable and accurate reflection signal requires a large energy output from the antennas. Reflected waves are far from perfect and require powerful computational centers to process and interpret the returned data. This all creates a slow and expensive system with limited range and accuracy

So how is the new ADS-B technology able to provide such amazing situational awareness over the entire NAS without the use of radar? In short, it is powered by a Global Navigation Satellite System (GNSS) akin to the more commonly known Global Positioning System (GPS). Information derived from the satellites is then broadcast by each aircraft outfitted with proper equipment to other equally equipped aircraft and ground stations. In this way, aircraft are visible not only to Air Traffic Controllers (ATC) on the ground, but also to each other while they fly. This is a huge advantage, as it allows pilots to make better decisions during flight. By giving pilots more authority in the air, the NAS also moves closer to enabling free flight, where aircraft operators have the freedom to select their path and speed in real time.

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1. Richard Hallion, *NASA's Contributions to Aeronautics: Aerodynamics, Structures, Propulsion, and Controls*, vol. 2 (Washington, DC: NASA SP-2010-570-Vol 2, 2010), p. 156.

2. Maria S. Lee, "ADS-B: An Evolution in Air Traffic Control," *MITRE Digest* (August 2008), available at *http://www.mitre.org/news/digest/aviation/08_08/av_adsb.html.*

Furthermore, while radar will continue to be used as a backup and verification system, ADS-B messages contain far more information than radar has ever offered. Messages can include such information as aircraft type, location, altitude, speed, heading, climb or descent rates, flight ID, intent, navigational uncertainties, and more.[3] Because the messages are in digital format, they maintain integrity over a greater distance. Their content is not skewed by weather conditions introducing timing anomalies into the return signal from which radar derives its information.

Two other systems are used to augment the accuracy of the GNSS signal used in ADS-B. They are the Wide Area Augmentation System (WAAS) and Differential GPS (DGPS). Both use a network of ground-based reference stations to measure small variations in GPS satellite signals and thus correct for any anomalies caused by the upper atmosphere in determining GPS information. Thus, ADS-B has far greater positional accuracy and integrity than any predecessor, and ADS-B is a strong candidate to augment or replace current midair collision prevention systems like the Traffic Collision Avoidance System (TCAS). While TCAS has a range of less than 40 miles, ADS-B is viable for up to 200 miles depending on interference conditions.[4]

ADS-B also has a much higher information update cycle, typically one to five updates per second, than radar. While it still requires ground stations for full operating capabilities, the ground stations are mostly intended to translate between different types of ADS-B transmissions and to communicate with ground control. Ground station transceivers are also small with minimal power requirements, effectively making them fewer in number and far less expensive to install and operate. Surveillance of remote or inhospitable areas lacking radar coverage becomes possible because the aircraft derive their own state information and communicate amongst themselves. This process also reduces voice communication and dependency on the ATC for flight following. To get a visual feel for how ADS-B works, see figure 1.

With such precise information, reduced search and rescue periods are possible in areas of ground station coverage (without the ground station, only other aircraft might know of the troubled plane's condition, as it is not being received by ground controllers).[5] Real-time traffic from ADS-B, weather data, and further aeronautical information delivered directly to the cockpit in combination with other NextGen technologies like Synthetic Vision will drastically increase the safety of pilots flying in low visibility, bad weather, or rough terrain. Pilots will effectively be able to "see" the terrain and other aircraft in the NAS, despite poor visibility, as it will be built synthetically around their precisely determined location. They will then be able to avoid both midair collisions and collisions with any rough terrain as is often found in mountainous regions. It will also allow for improved airline ability to manage traffic and aircraft fleets, as well as reduced separation during takeoff and landing, and provide for better predictability in departure and arrival times at airports. Reducing congestion both in the air and on the ground around major airport hubs is vital to airline profitability.

As you may have already deduced, ADS-B really is described by its name. It is ***A**utomatic* in the sense that it periodically transmits vital information without pilot or operator input. It is ***D**ependent* because that information is derived from the GNSS. ***S**urveillance* is a method of determining the occupants and conditions of your surroundings, and ***B**roadcast* sends this information to anyone with the appropriate receiving equipment.

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3. Fairuz Romli, J.D. King, and J.P. Clarke, *Impact of Automatic Dependent Surveillance—Broadcast (ADS-B) on Traffic Alert and Collision Avoidance System (TCAS) Performance* (Reston, VA: American Institute of Aeronautics and Astronautics [AIAA] 6971, 2008), pp. 3–5.

4. Bryan Barmore, Research Scientist, Langley Research Center, telephone interview, July 27, 2010.

5. Robert Strain, Matthew DeGarmo, and J. Moody, *A Lightweight, Low-Cost ADS-B System for UAS Applications* (Reston, VA: AIAA 2750, 2007), p. 4.

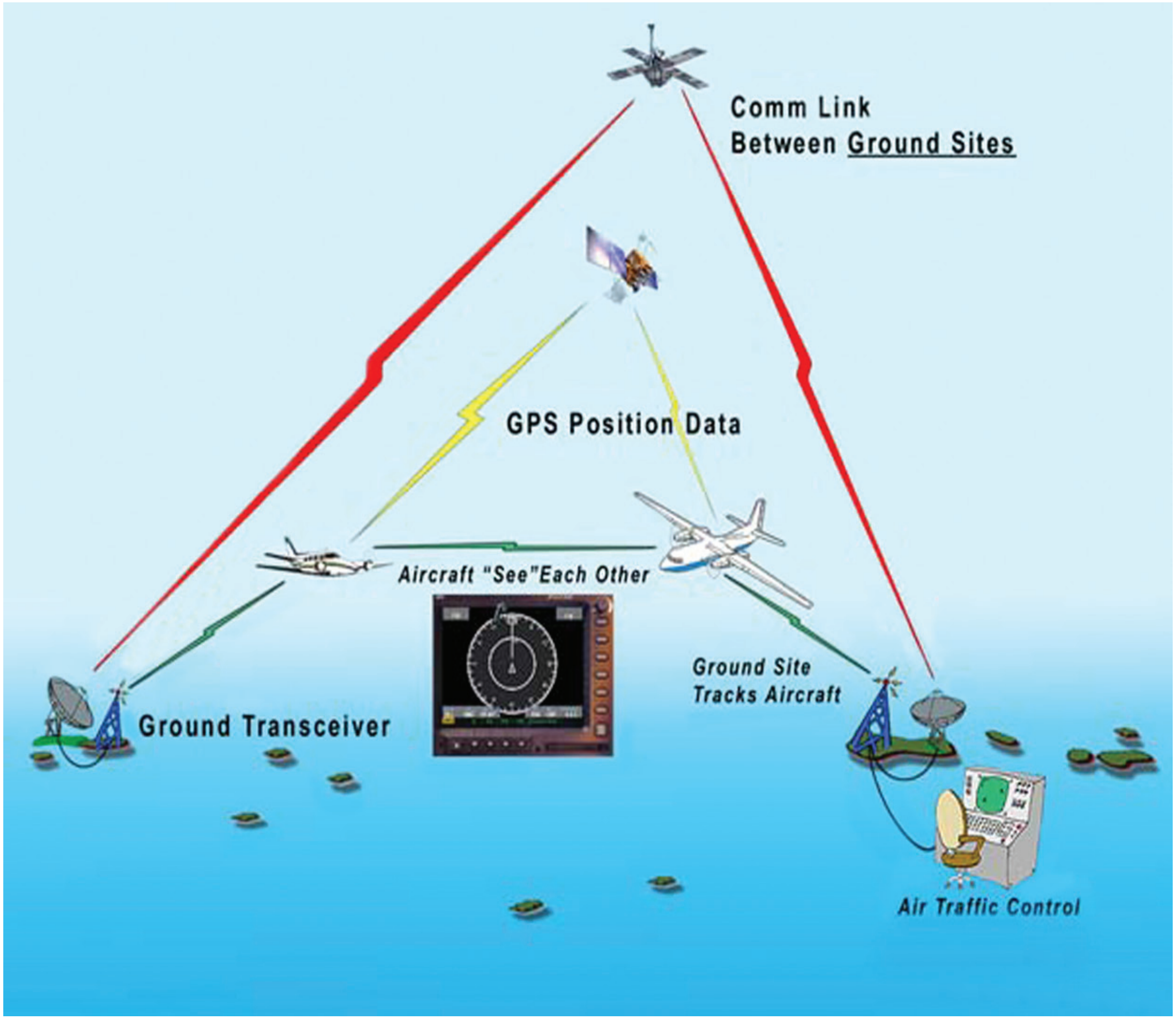

Figure 1: A representation of how ADS-B works (ADS-B Technologies).

Historical Developments

There were many challenges to overcome in getting ADS-B to the point where it is now such an integral part of NextGen. It is important to understand these challenges from the beginning. In a manner of speaking, ADS-B has its origins in the late 1950s. Horrible midair collisions, like the one over the Grand Canyon in 1956, brought a stark reality to the need for collision avoidance and guidance safety systems. As mentioned previously, TCAS was one of the first programs implemented to help avoid these midair collisions. Due to the limited scope and range of TCAS, there has been a constant search for better options.

It was realized early on that the desire for free flight and airborne precision spacing, in addition to vital safety concerns like collision prevention, could all be addressed by the powerful offerings of GPS. It took until the early 1990s, however, for GPS technology to reach a level of maturity and coverage capable of working for the aviation industries. Honeywell Aeronautics, MITRE, the FAA, and NASA, all previously heavily involved with the development of TCAS, would again be primary developers for the ADS-B technology.

In a fashion, ADS-B grew out of TCAS. In fact, one of the primary frequencies proposed for use with the new ADS-B technology was the same frequency system in use for TCAS. That frequency is the 1090MHz Extended Squitter (1090ES). The reason for proposing adding ADS-B operations to 1090ES is simple. All major aircraft have already been required to install 1090ES antennas to accommodate the TCAS program. With the antennas already installed, equipage costs could be low, because only upgrades would be required rather than entire retrofits.

Despite this attractive low-cost equipping advantage for the airlines, there are many other problems to consider. The question of which frequency to use has been one of the greatest sources of debate in determining ADS-B standards. Because 1090ES will then be used by both TCAS and ADS-B, there becomes a strong possibility of detrimental signal interference accompanied by a decrease in effective range. Ensuring adequate bandwidth on the 1090ES channel to carry all vital information has also been a strong source of concern.

There are a total of three hardware options available for ADS-B, each enabling a different frequency for use. In the United States, the FAA has chosen to initially allow two of the three options with mandated equipage by 2020 for most aircraft. The two U.S. options are the 1090ES for carrier and commercial airline operators and the 978MHz Universal Access Transceiver (UAT) for general aviation users (though they may use 1090ES, if they so choose). UAT offers many advantages, as it was designed specifically for ADS-B use. It operates on an unused frequency, so it has plenty of open bandwidth that is interference-free. Ground transceivers for UAT are also less expensive and can provide more traffic information. Communication between these two systems has also been a challenge of its own.

In Europe and other parts of the world, another, less likely option is the VDL4 (very high frequency [VHF] data link) operating in the VHF domain.[6] The hope is to one day standardize all ADS-B systems to a single physical layer. As under the guidance of the FAA, groups like the Radio Technical Commission for Aeronautics (RTCA) have already developed minimum operational performance standards for 1090ES and UAT.[7]

Even as these physical layers were being chosen, testing the viability of ADS-B under real-world conditions had begun. Field tests of early prototypes first took place in Chicago, IL, under NASA supervision. Prototypes were examined both for their basic operational capabilities and for their abilities to enable vital NextGen concepts. Also under study at the time was the concept of efficiently merging multiple streams of air traffic into one for approaching an airport runway.[8]

With the successful demonstration of ADS-B as a viable technology, full-scale testing was then to begin. The first major test bed was the Alaska capstone project. Primarily funded by the FAA, but with heavy support from NASA, MITRE, and a host of other Alaskan organizations, the project began in 1999. Alaska was chosen for the great number of small aircraft accidents resulting from its mountainous terrain and poor weather. Large portions of the state were also reachable almost exclusively by air travel with little to no radar coverage. ADS-B was installed on over 100 small aircraft, a process involving cockpit upgrades from traditional analog instruments to digital avionics. An ADS-B-fitted cockpit can be seen in figure 2. This is also one of the most expensive parts of the upgrade process for aircraft owners. ADS-B ground stations were installed in the geographical areas under observation; they were far better suited than radar

6. Barmore telephone interview, July 27, 2010.

7. "Minimum Operational Performance Standards for 1090 Extended Squitter Automatic Dependent Surveillance," broadcast (ADS-B) (Washington, DC: RTCA SC-186, 2006), change 1.

8. "Automatic Dependent Surveillance," *The Leading Edge*, NASA TV Education Channel (September 3, 2009), available at *http://www.aeronautics.nasa.gov/leading_edge_ads_b.htm.*

Figure 2: A cockpit fitted with new ADS-B technology (ADS-B Technologies).

for use in remote areas. From 2000 through the end of 2004, the FAA reported accident rates for Capstone-equipped aircraft in Alaska decreased by an amazing 47 percent.[9]

At roughly the same time as Capstone was getting underway, Langley and Honeywell were also developing a concept using ADS-B called Airborne Information for Lateral Spacing (AILS). Many major airport hubs have multiple runways in parallel with each other. This can greatly complicate the landing process, especially if the runways are situated close together. The study examined normal approaches and potential collision scenarios for closely spaced runways. While the minimum parallel runway separation for

9. Wallops Flight Facility, Goddard Space Flight Center, "Transforming Airspace One Plane at a Time," *Inside Wallops*, vol. XX-08, no. 35 (October 2008).

independent instrument approach was 4,300 feet, it was shown that using the speed and accuracy of ADS-B, optimization could allow for such approaches to parallel runways as close as 2,500 feet.[10]

The next major tests of ADS-B took place in collaboration between Langley, Rockwell Collins, and the Dallas-Ft. Worth International Airport (DFW) starting in October 2000. The focus here was on using ADS-B to improve the safety of airport surface operations. This took the form of the Runway Incursion Prevention System (RIPS). Runway incursions are extremely dangerous situations in which anything becomes detrimental to runway safety. One of the most serious runway incursions involves aircraft collisions on the ground. Often due to poor visibility or situational awareness, runway incursions like the Tenerife airport disaster of 1977 have led to some of the deadliest and most expensive accidents in aviation history.

RIPS tests using ADS-B found the systems able to provide both pilots and controllers with enhanced situational awareness. It gave supplemental guidance cues, a real-time display of traffic information, and advance warning of runway incursions.[11] A smaller set of tests over airports in mountainous regions of Colorado was to follow. The effectiveness of ADS-B for both runway incursions and midair collision was again tested, with positive results, over the rough terrain, weather, and areas of spotty radar coverage.

Such successful test results of a potentially powerful new technology did not go unnoticed. Express shipping companies, for which speed, safety, and reliability translate directly into money, immediately saw the value ADS-B could bring to the air traffic system. UPS, with its own international fleet of aircraft, volunteered in 2002 and 2004 to collaborate with NASA, the FAA, and MITRE Corporation to begin testing ADS-B on a large scale. It had been shown that ADS-B could significantly improve safety in the air and on the ground, but now they hoped to increase airspace efficiency.

Under consideration were the Airborne Precision Spacing and Continuous Descent Arrival (CDA) approach alternatives. The goal was to use the speed and accuracy of ADS-B to start scheduling aircraft for landing a couple of hundred miles out for precision spacing when they reach the airport (see figure 3). That way each aircraft would only need to make minor speed and heading adjustments to arrive on time and to land immediately, rather than waste precious time and fuel circling the airport before it could land. The tests revealed an amazing 30-percent reduction in noise (up to 6 decibels), a 34-percent reduction in nitrous oxides emissions below 3,000 feet, and 250 to 465 fewer pounds of fuel burned per flight, all a direct result of less time spent in flight.[12]

In 2006, the team was to take the work a step further at the UPS world hub in Louisville, KY. The operational concept was now under consideration for airline operations centers (AOC) and termed Airline Based En route Sequencing and Spacing (ABESS). The use of ADS-B to shape arrival streams into advanced spacing and flight procedures such as CDA and Flight Deck-Based Merging and Spacing (FDMS) was to be a crucial component of a new Self Managed Arrival Re-sequencing Tool (SMART) or Air Traffic Management Automation (ATMA). Tests provided the necessary information to make software, accuracy, and procedural requirements feasible for implementation. UPS has since been given operational installation certification for its fleet to be completely equipped with a second-generation ADS-B system.[13]

10. Dawn Elliott and Brad Perry, *NASA Research for Instrument Approaches to Closely Spaced Parallel Runways* (Reston, VA: AIAA 4358, 2000), pp. 1, 7.

11. J. Timmerman, *Runway Incursion Prevention System ADS-B and DGPS Data Link Analysis Dallas-Ft. Worth International Airport* (Washington, DC: NASA CR-211242, 2001), pp. i, 20.

12. "Automatic Dependent Surveillance," *The Leading Edge*, available at *http://www.aeronautics.nasa.gov/leading_edge_ads_b.htm*.

13. Peter Moertl, Emily Beaton, and Paul Lee, "An Operational Concept and Evaluation of Airline Based En Route Sequencing and Spacing" (paper AIAA 2007-6552, Guidance, Navigation, and Control Conference and Exhibit, Hilton Head, SC, August 20–23, 2007), p. 1.

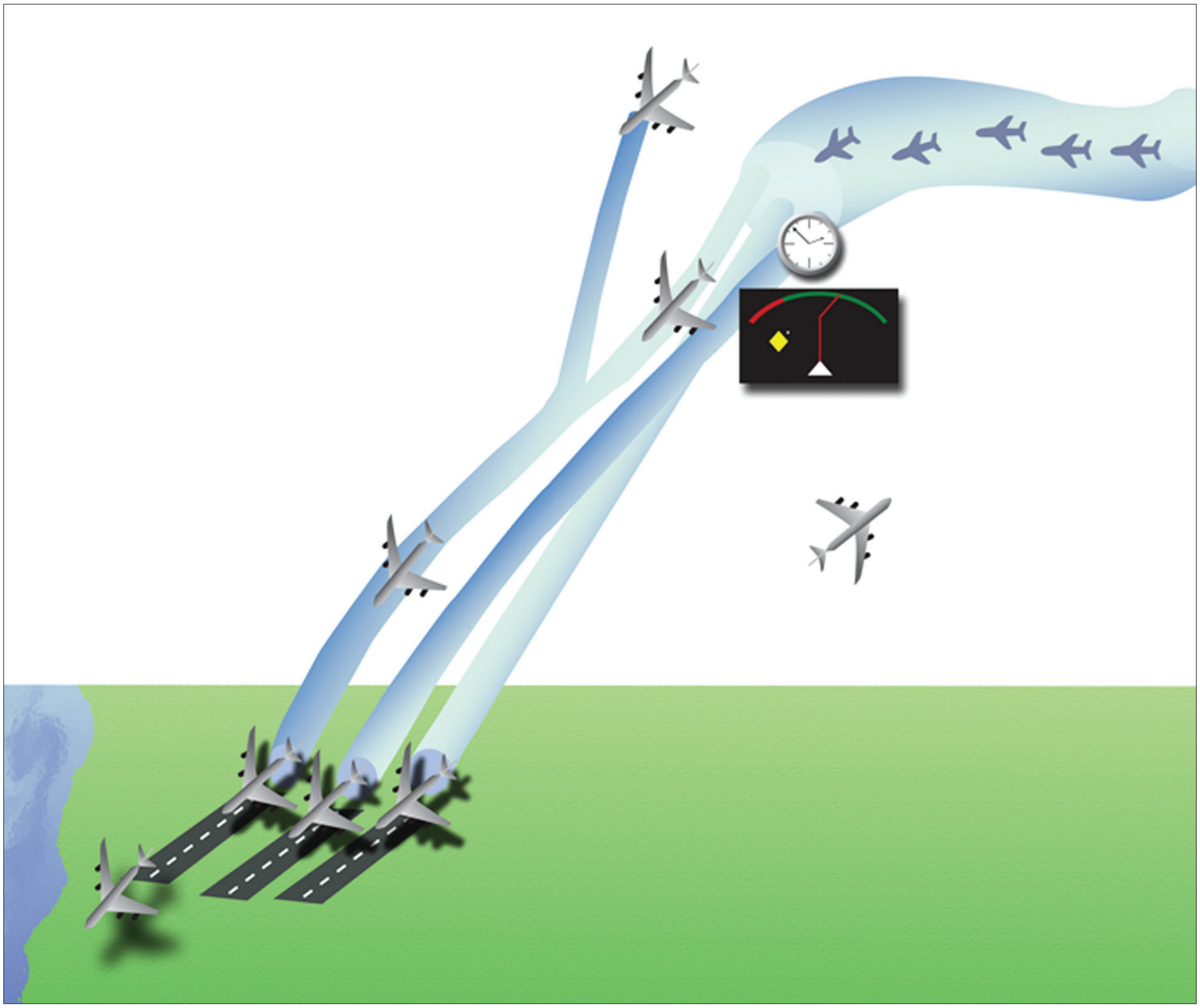

Figure 3: An example of ADS-B merging and precision spacing (Federal Aviation Administration).

Current Research and Implementation

Australia was the first country to achieve full ADS-B coverage. The United States, Taiwan, New Zealand, Austria, and more are quickly following suit. In 2005, the FAA decided that ADS-B technology had proven itself to be at a mature enough level to enter operation over the entire U.S. airspace. All ground stations, roughly 800 for the contiguous United States, are to be fully installed by the end of 2013. Many coastal regions have already instigated ground capabilities.

There are still many challenges to face, however, with ongoing research to address remaining issues and to develop even better ways to put ADS-B to work. Most noticeable of the issues left to resolve are methods of dealing with the transition period to complete ADS-B adoption, validation of ADS-B signals, and the nonsecure nature of ADS-B information.

Transitional periods are always some of the most difficult. Because two systems, neither fully universal, are in use, the possibility for error inevitably increases. One potential method for dealing with the transition to full ADS-B coverage and participation is to use a Wide Area Multilateration (WAMLAT or WAM) network. A multilateration system calculates position from the time differences found between the times of arrival of a signal at multiple antennas. It would be completely independent of ADS-B and so not in danger of failing at the same time ADS-B might, for example, if a satellite should go down.[14] Furthermore, this coverage could be provided regardless of the primary coverage system used.

Multilateration could prove vital in verifying the validity of an ADS-B signal as well. The FAA and other international aviation regulators are addressing concerns about the nonsecure nature of ADS-B transmissions, as there are currently no regulations or methods implemented to prevent the public from accessing ADS-B messages. Thus, there is no guarantee that the precision information is not used inappropriately. It is also possible to produce fake ADS-B messages that spoof aircraft locations or create phantom aircraft to disrupt safe air travel. Another key factor to note is that if ADS-B equipment stops broadcasting, the aircraft is effectively no longer on the map and becomes a danger to others in the airspace. WAM and ground radars, along with the ground broadcasting stations, can be used to prevent these issues, as they are able to verify the validity of a signal and put unequipped or "failed" aircraft back on the map with a "pseudo" information signal.[15] NASA has helped fund research to develop foolproof methods for independent signal verification and validation methods. They are to be used both in the air and on the ground to ensure spoofed signals cannot harm the safety of the national airspace.[16]

Potential applications in aviation ground operations could increase the value of ADS-B technology significantly. The Johns Hopkins University Applied Physics Laboratory and Embry-Riddle Aeronautical University have worked together to make a Comprehensive Real-time Analysis of Broadcast Systems (CRABS) suite of software tools to aid in daily flight operations. Incorporating ADS-B into the software could greatly enhance the situational awareness of ground personnel such as fleet managers, dispatchers, and flight instructors.[17]

There are many other concepts for ADS-B use under development or consideration for the future. ADS-B is an enabling technology of Distributed Air-Ground Traffic Management (DAG-TM). This NASA concept will allow properly equipped pilots to fly under the Autonomous Flight Rules (AFR) and choose routes and maintain proper separation on their own.[18] The low costs of Unmanned Aircraft Systems (UAS) have made them very attractive options for governments, research, and many commercial applications. As their use increases drastically, developing ADS-B equipment that is lightweight and efficient enough to be placed on board these small aircraft is becoming ever more important. ADS-B will make any UAS "visible" to piloted aircraft and thus far safer to operate in the same airspace.[19]

The powerful possibilities offered by ADS-B make it an obvious choice as a key component for the Nation's NextGen. It is an amazing achievement to drastically increase the safety and efficiency of the entire national airspace while at the same time accommodating the huge growth expected in aviation. NASA's role has been a crucial one, and it will continue to help bring new and innovative solutions to the table for aviation's toughest challenges. The ADS-B team is certainly deserving of the Collier Trophy.

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14. A. Smith and R. Cassell, "System-Wide ADS-B Back-Up and Validation" (Integrated Communications, Navigation, and Surveillance Conference, Baltimore, MD, May 1–3, 2006), p. 1.

15. Barmore telephone interview, July 27, 2010.

16. Jimmy Krozel and Dominick Andrisani, *Independent ADS-B Verification and Validation* (Reston, VA: AIAA 7351, 2005), pp. 1, 4, 5.

17. Andrew Ford and Jeffrey Koul, *Present and Future Applications of ADS-B Technology in a Flight Training Environment* (Reston, VA: AIAA 7350, 2005), p. 1.

18. Richard Barhydt and Michael Palmer, "ADS-B Within a Multi-Aircraft Simulation for Distributed Air-Ground Traffic Management" (23rd Digital Avionics Systems Conference, Salt Lake City, UT, 2004), p. 1.

19. Strain, DeGarmo, and Moody, *A Lightweight, Low-Cost ADS-B System*, pp. 1–2.

Hopefully, it will be very soon that as your plane nears the airport runway, you can smile in satisfaction as you watch your plane enter a continuous descent arrival and know that NASA and ADS-B are working hard for you to make your flight safer, smoother, and quicker.

National Aeronautics and Space Administration

Synthetic Vision:
Increasing Safety and Awareness in Aviation

Malcolm Gibson
NASA Headquarters

Aircraft pilots are responsible for guaranteeing the safety of their passengers by ensuring smooth flight operations throughout the duration of the journey. In order to do this, a pilot greatly relies upon his or her physical senses and prior flight experience. The most important physical sense needed to effectively pilot an aircraft is that of sight. Visibility is of the highest importance to provide situational awareness, defensive warning, collision avoidance, and overall guidance to pilots. In many conditions, visibility can be significantly compromised by obstructions, weather, and nighttime skies. All aspects of aviation are severely affected by limited visibility conditions, and additional measures must be taken in order to maintain safety. This is the motivation behind decades of NASA aeronautics research aimed at developing systems such as cockpit displays, terrain databases, advanced sensors, heads-up displays, and what is now referred to as synthetic vision. This technology has contributed to aviation safety in profound ways by giving pilots the ability to fly in virtually perfect visibility, to make more informed decisions, and to enhance safety greatly on every flight.

Introduction

Aircraft safety is a major concern for NASA and the entire aeronautics industry. Limited visibility is a major contributor to a class of accidents referred to as controlled flight into terrain (CFIT), wherein a fully functional aircraft collides with terrain such as the ground, water, or other physical obstacles due to pilot disorientation or lack of awareness. In 2007, reports showed that general aviation accounted for 94.5 percent of all civil aviation accidents and 91.1 percent of all aviation fatalities, with CFIT being the largest fatal accident category.[1] Although general aviation remains the largest contributor to aircraft accidents, the commercial aviation industry is also greatly affected by CFIT occurrences. In 2005, a Boeing Company study reported that over 200 commercial jet fatalities occur every year due to CFIT.[2] These reports exemplify the profound influence that poor visibility conditions place on aircraft safety throughout the aviation industry.

Limited visibility also has a severe impact on ground-based operations such as taxiing, takeoff, and landing. Accidents that occur during these stages of flight are referred to as runway incursions, wherein a plane, vehicle, person, or object on the ground creates a collision hazard with a plane that is taking off or landing. Visibility can be a major concern for pilots on runways due to weather, runway crowding, or mishaps in ground-based operations control. Runway incursion accidents have increased substantially in recent decades, and new technologies are needed to improve the safety of ground-based operations.[3]

Pilots are not the only ones who are impacted by limited visibility conditions for aircraft. The flying public is also greatly affected by these conditions due to their effect on air traffic control and surface operations. The single largest contributor to flight delays is poor weather. Poor weather causes increased runway congestion, degraded airport surface management, and increased air traffic separation distances, all of which contribute to flight-delay times. Aircraft companies also feel this effect by spending additional money on extra fuel used during weather-avoidance maneuvers and landing queues. All aspects of aviation, from both the pilots' and passengers' perspectives, are severely affected by limited visibility conditions caused by weather, nighttime skies, or obstructions.

In the past, pilots have adapted to some of these challenges by using various instruments to give them the necessary cues that their restricted vision cannot. This is commonly referred to as the instrument flight

1. Aircraft Owners and Pilots Association, "2007 Nall Report—Accident Trends and Factors for 2007" (Frederick, MD, 2007).

2. J.R. Chambers, *Innovation in Flight: Research of the NASA Langley Research Center on Revolutionary Advanced Concepts for Aeronautics* (Washington, DC: NASA SP-2005-4539, 2005), p. 93.

3. R.V. Parrish et al., *Aspects of Synthetic Vision Display Systems and the Best Practices of the NASA's SVS Project* (Washington, DC: NASA TP-2008-215130).

rule (IFR), as opposed to visual flight rule (VFR), and requires additional training, certification, and flying experience. Flying in instrument-meteorological conditions (IMC) is significantly more dangerous than flying in visual-meteorological conditions (VMC) and puts far more responsibility on pilots. In 2008, the lethality rate for IMC was approximately 58 percent higher than that for VMC when flying under both daytime and nighttime conditions.[4] Even though flying IFR has sufficed in the past for a means of continued operation in poor conditions, it is becoming less effective in today's advancing aircraft fleets and complicated airspace system, and new technologies need to be conceived to ensure adequate safety. In order to address this ongoing problem, NASA has invested in decades of research in technology development to increase pilots' visibility and awareness in these situations. With today's unprecedented advances in computer capabilities, display technologies, and remote sensing devices capable of rapidly and accurately providing models of geographic features, NASA has developed advanced cockpit displays to provide pilots with virtually perfect visibility in all conditions. These new synthetic vision systems (SVSs) provide pilots with a reliable virtual representation of the outside environment using the global positioning system (GPS) and terrain databases, while also providing guidance and instruction to relieve pilots of an overly heavy workload. The implementation of SVS has made tremendous contributions to aviation safety and awareness in low-visibility environments and has improved surface operations in order to ensure heightened efficiency in the air transportation system.

Early SVS Development

The idea of enhancing a pilot's perspective to facilitate better decision making and aircraft control has been around for over half a century. During the 1950s, early ideas of improved cockpit vision originated as part of a joint Army-Navy research project that aimed at replacing the familiar blue-over-brown artificial horizon instrument with something more informative and useful in low visibility or at night.[5] Other efforts within civil and military communities focused on developing artificial guidance concepts and more intuitive cockpit displays. This early interest lead to the development of various onboard sensor-based systems that used technologies like forward-looking infrared, millimeter-wave sensors, passive radar, or other information systems to interpret the environment outside the aircraft. These emerging systems were termed Enhanced Vision Systems (EVSs), and they would continue to be of great interest to the aviation industry for decades to come.

NASA recognized the importance of this new technology and began research in the early 1970s toward new concepts for futuristic cockpit displays. Langley Research Center conducted research on conceptual "pathway-in-the-sky" technology, which superimposed a flightpath in front of the aircraft (figure 1) and offered pilots more guidance and maneuverability in low-visibility weather. Despite a future promise in aircraft safety, this technology was not an absolute necessity and, consequently, did not receive very much early interest from the commercial industry at the time.[6] In the early 1980s, Langley continued its research by studying flight problems common to general aviation, such as inadvertent loss of control, that often occurred in low-visibility conditions or when flying under IFR. During the same time, new research was underway at Ames Research Center to investigate the use of heads-up displays (HUDs) (figure 2) as a

4. Aircraft Owners and Pilots Association, "2008 Nall Report—Accident Trends and Factors for 2008" (Frederick, MD, 2009).

5. Stephen Pope, "The Promise of Synthetic Vision: Turning Ideas into (Virtual) Reality," *Avionics* (Midland Park, NJ: AIN Publications, June 1, 2006).

6. J.R. Chambers, *Innovation in Flight: Research of the NASA Langley Research Center on Revolutionary Advanced Concepts for Aeronautics* (Washington, DC: NASA SP-2005-4539).

means for conveying clearer information to the pilot without the need to transfer his or her vision between the display gauge panels and windshield. This research found that pilots preferred the HUD displays to traditional dashboard displays and that HUD displays can improve pilot reaction time by up to 90 milliseconds.[7] This early NASA research showed that new display technologies had the potential to improve pilot performance and enhance safety in aviation. The emergence of enhanced-vision concepts, along with new HUD proof of concepts, helped premise the future of more reliable, more accurate, and safer cockpit technology. With the early success of new cockpit-display concepts, NASA remained interested in advancing these new technologies. During the late 1980s and early 1990s, NASA research teams continued to develop more efficient enhanced-vision systems by investigating new sensor technologies such as passive radar and varying wavelength infrared systems. These new integrated sensors would help interpret the outside environment and give pilots an enhanced view during poor weather conditions. Despite the strong motivation behind the development of EVS for increased safety reasons, the research also exposed many difficulties such as its high cost, complexity, and failure to provide reliable results in extreme weather conditions.[8]

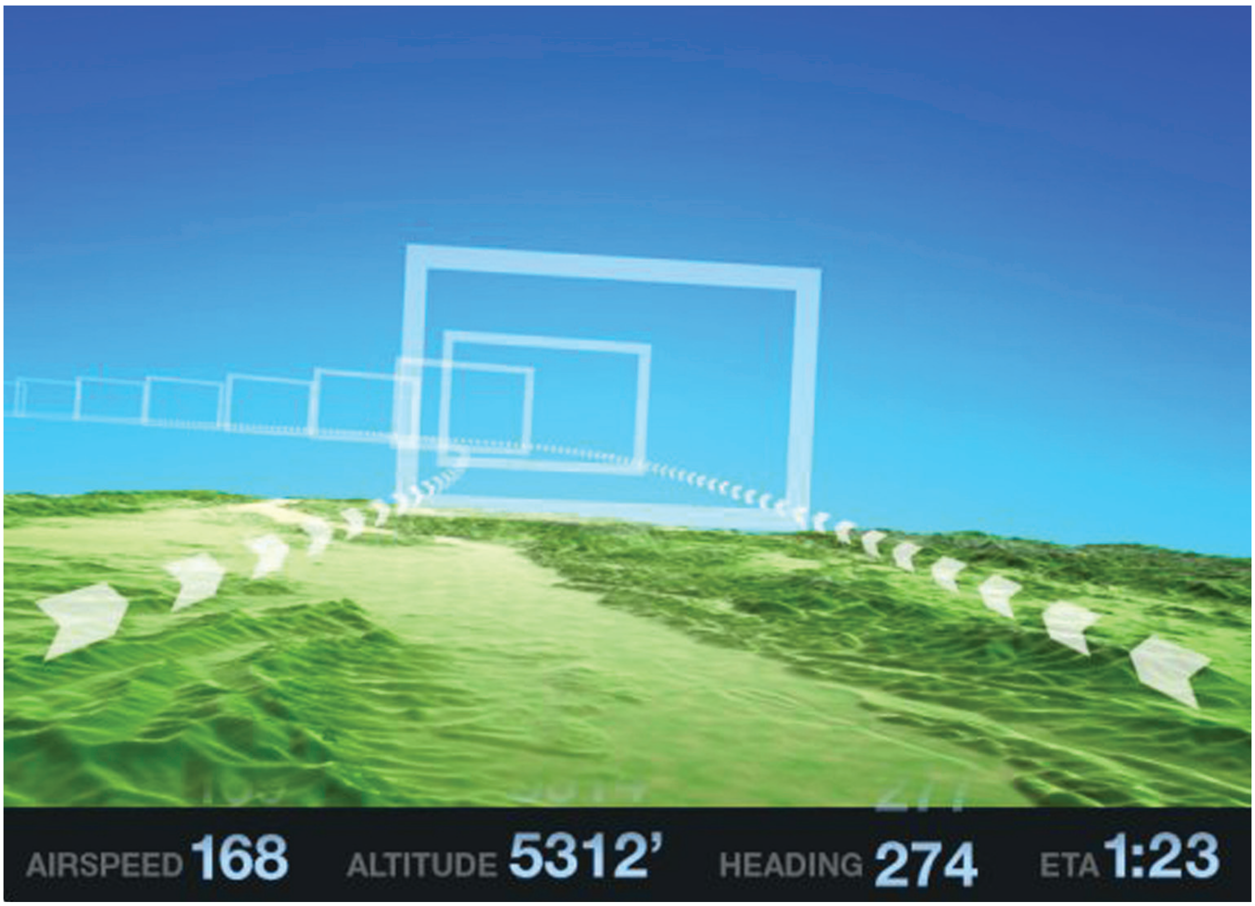

Figure 1: "Pathway in the Sky" guidance concept (NASA SP-2005-4539).

7. D.J. Weintraub, R.F. Haines, and R.J. Randle, "Head-up Display (HUD) Utility. II—Runway to HUD Transitions Monitoring Eye Focus and Decision Times," *Proceedings of the 29th Human Factors Society Annual Meeting*, vol. 1 (Santa Monica, CA: Human Factors Society, A86-33776 15-53, 1985), pp. 615–619.

8. Parrish et al., *Aspects of Synthetic Vision Display Systems*, p. 4.

Figure 2: A HUD visualizing a potential runway hazard (NASA Ames Research Center).

The high-frequency radar and infrared sensors used in these systems showed degraded range in conditions of heavy rain, and the low- and mid-frequency systems had improved range, but at the consequence of significantly decreased resolution.

As researchers looked toward new solutions to solve these problems, they conceptualized a less expensive system that did not greatly rely upon physical sensors and would therefore have no vulnerability to dynamic weather. In order to achieve this, the new system would have to focus on integrating new GPS technology and terrain information to portray an accurate, virtual view of the outside environment. This new "synthetic vision" concept represented an opportunity for VFR flight in all weather conditions and was thought to be unlimited in capabilities due to its reliance on GPS and terrain data as opposed to physical sensors. SVS also presented itself as far more cost effective and lower maintenance than existing EVS technology. In order to bring this new concept to reality, the aeronautics industry needed reliable and precise GPS along with an accurate terrain database, neither of which would exist for years to come.

In the early 1990s, NASA began comprehensive research into SVS technology concepts such as Highway-In-the-Sky (HITS), low-visibility surface operations, obstacle avoidance, and airspace management in order to prepare for the next generation of air transportation safety. SVS had emerged as a promising new concept that would hold great promise to the future of aeronautics and the safety of air transportation for general aviation and commercial transport alike.

Enabling Technologies

The development of SVS technology started with fundamental research in many enabling technologies. NASA conceived various research programs that were aimed at developing the tools needed to promote the growth of new electronic cockpit displays. One of these programs was the Terminal Area Productivity (TAP) program, which was established in 1993 to prepare for anticipated increases in air travel demand.[9] The program set goals to increase airliner throughput at the Nation's airports by 12 percent over the existing system. The TAP program was divided into four interrelated subprojects, one of which was Low Visibility Landing and Surface Operations (LVLASO). Under this new project, researchers developed two technologies applicable to future SVS systems, namely Taxiway Navigation and Situational Awareness (T-NASA) and Rollout Turnoff (ROTO). The T-NASA project focused on using HUD and NAV displays with moving map functions to provide the pilot with accurate guidance on airport taxiways. The ROTO project used a HUD to guide pilots in braking levels and situational awareness for runway turnoff operations. These projects contributed to the use of HUDs for delivering information that improves pilots' performance during high-stress operations where safety is most important. NASA's existing High Speed Research (HSR) project also made significant contributions to technologies that would one day become essential to synthetic vision. The HSR program was interested in developing new cockpit display technologies in an attempt to reduce weight and increase efficiency for supersonic civil transports. Unlike the Concorde, a nondrooping nose configuration is highly desirable, mainly because it reduces the overall weight by thousands of pounds. Such a configuration would require the use of external cameras and sensors to create a simulated cockpit view (figure 3). XVS incorporated many aspects similar to those in previously developed, enhanced vision systems. In order to fuel XVS development, NASA's HSR program established an Integrated Technology Demonstrator (ITD) Team that was tasked with performing new XVS research and development for use on future air vehicles. NASA's Langley Research Center conducted this research from 1993 to 1999. The increased development of new cockpit display technologies under the TAP and HSR programs brought NASA and the aviation industry one step closer to realizing the use of synthetic vision in modern avionics.

The greatest challenges in the development of SVS were the acquisition of a reliable and comprehensive terrain database and the use of accurate GPS technology. In the early stages of SVS research, neither of these resources had been sufficiently developed and the progress of SVS research greatly relied upon the advancement of these two enabling technologies. The first GPS satellite was launched in 1978, and the remaining 23 satellites were launched and operational by 1995. When the first GPS satellites became fully operational, they were intended for use only by the Department of Defense until, in 1983, President Ronald Reagan opened GPS for limited civilian use after a Korean Air Lines commercial airliner was shot down by Russian interceptors when it strayed miles into Soviet territory.[10] In 2000, the United States cleared civilian GPS users to receive a level of precision equal to that of military forces. This dramatically expanded the utility of GPS satellite networks. This increased civilian GPS accuracy tenfold and allowed SVS research to reach new levels of success.

In the early stages of SVS development, researchers greatly relied on computer graphics engines to transform existing topographical data into a usable 3D rendering of the environment. In the 1980s and early

9. R.A. Rivers, "Introducing Synthetic Vision to the Cockpit," Case 11, *NASA's Contributions to Aeronautics*, vol. II (Washington, DC: NASA SP-2010-570-Vol 2, 2010).

10. Ibid., p. 635.

Figure 3: Simulated cockpit view using external vision systems (XVS) technology (NASA High Speed Research program).

1990s, the state-of-the-art graphics generators limited terrain portrayal to simple line segments and polygon structures. Without the invention of more capable graphics generators, SVS displays lacked the ability to effectively recreate the outside environment. It was not until the development of raster graphics engines and texturing capabilities in the mid-1990s that SVS displays were able to create photo-realistic representations of the terrain (figure 4). Computer processing power and graphic engine development were key enabling technologies to the development of the SVS used in today's aviation.

The acquisition of a reliable and comprehensive terrain database was also essential for the progression of SVS research. In order for SVS to operate, it must determine the precise location of the aircraft at all times and match it to that location in a digital topographical representation of the terrain. Until the year 2000, the existing terrain databases were not very detailed and did not have sufficient resolution for a system as critical to safety as SVS. In September of 1999, the Shuttle Radar Topography Mission used a single-pass radar interferometer to produce a digital elevation model of Earth's surface between about 60 degrees north and south latitude.[11] This mission and other Shuttle missions have supplied NASA with topographical data for about 80 percent of Earth's total surface (99.96 percent of the land between 60°N and 56°S latitude). With these data, NASA could use computer rendering tools to create a synthetic topographical map of Earth's terrain for use in synthetic vision.

11. T.G. Farr and M. Kobrick, "The Shuttle Radar Topography Mission: A Global DEM" (Pasadena, CA: Jet Propulsion Laboratory, 1999), p. 1.

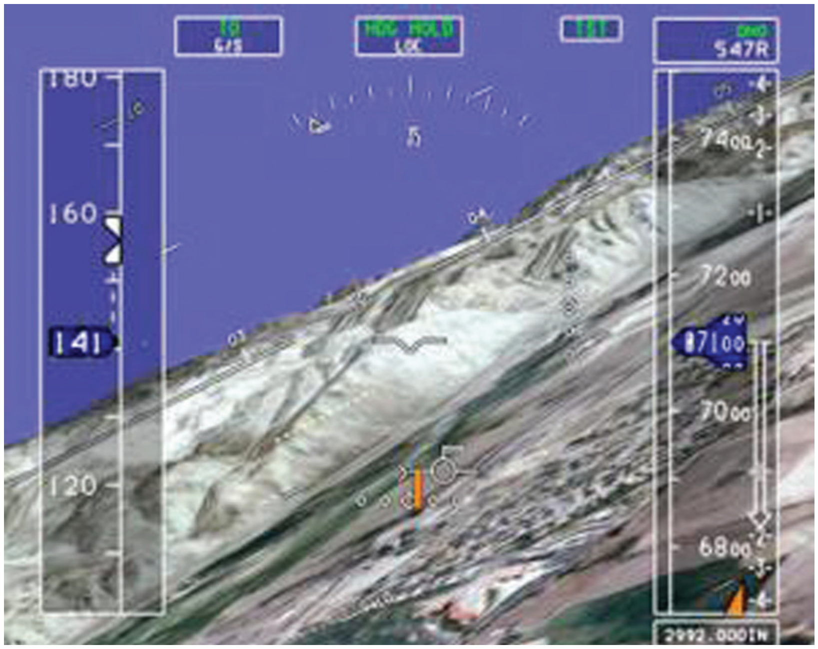

Figure 4: An SVS display showing photo-realistic terrain portrayal (NASA SP-2005-4539).

The progression of synthetic vision from concept to reality lasted nearly three decades. During this process, it was transformed and greatly improved through the refinement of various enabling technologies. With breakthrough advances in computer power, geographic mapping, display technology, and GPS, synthetic vision had finally reached the brink of application to military, commercial, and general aviation aircraft by the end of the 20th century.

NASA's Flight Test Research

At the turn of the century, NASA increased research on new SVS instruments in order to prepare for the growing number of aircraft fleets and the expanding airspace system. In 1997, NASA created an Aviation Safety Program (AvSP) to research and develop technologies that would meet the national goal of reducing the fatal aircraft accident rate by 80 percent by 2007. One NASA program, namely the Advanced General Aviation Transport Experiment (AGATE) program, was focused on revitalizing many aspects of general aviation, including the development of more intuitive cockpit instruments. Langley Research Center was responsible for a large portion of SVS research and development, although other Centers made unique contributions as well. While Langley was primarily focused on developing SVS for use in general aviation and commercial aircraft, Johnson Space Center was also performing significant work on SVS and sensor fusion for use with remote piloting of the proposed X-38 reentry test vehicle.[12] From 1994 to 1996, Langley conducted a series of workshops focused on "Highway-in-the-Sky," external vision systems, and other advanced vision concepts. These workshops helped NASA reassess previous projects and integrate existing research, in order to highlight some of the key challenges that remained in SVS development. In 1998, NASA issued a competitive cost-sharing contract focused on the development of the first phase of a HITS display. The contract was awarded to AvroTec during further development of a new Lancair Columbia

12. Rivers, "Introducing Synthetic Vision to the Cockpit," p. 629.

aircraft.[13] This contract represented one of the very first efforts to develop a fully functioning SVS display. With a new emphasis on SVS research, NASA's Aviation Safety program continued to push efforts toward development and flight-testing of new SVS displays.

On October 1, 1999, NASA announced the new SVS project, which allocated $5.2 million[14] to charter the development and support of synthetic vision implementation for use in commercial transport, business-class jets, rotorcraft, and general aviation over the next 5 years. Its motivation stemmed from the need to greatly improve aviation safety and efficiency of operations for the next generation of air vehicles by targeting pilot situational awareness. The SVS program was split into three subprojects, namely commercial and business, enabling technologies, and general aviation, with each subproject focusing on key aspects of SVS development. In order to accelerate new progress, NASA partnered with industry talent under Cooperative Research Agreements (CRAs) that would match the NASA funding and take SVS concepts to application in the next 5 years. The eight chosen CRA teams and the prominent contractors for the SVS program are shown in table 1. As the SVS project evolved, the main challenge became integrating existing surface-display concepts, such as taxi-path navigation, hold locations, and surface traffic management (from the LVLASO project) with in-flight display concepts such as HITS, terrain representation, and obstacle avoidance. By integrating this research, NASA was able to develop effective SVS systems capable of greatly improving aviation safety both on the runway and in the air.

Under the new SVS project, NASA increased emphasis on flight-testing many of the SVS concepts that had emerged over the previous two decades. As part of the Aviation Safety program, various SVS concepts were tested in 1999 using the Total In-Flight Simulator (TIFS) (figure 5), a highly modified Convair 580 with two cockpits, one for safety and one for research display purposes. During these tests, three evaluation pilots flew over 60 approaches with the guidance of SVS.[15]

Another interesting concept was "Highway-in-the-Sky," a technology that was pioneered by the Navy's George W. Hoover during the early stages of advanced vision research. HITS is a concept that overlays a virtual pathway over the existing forward-looking display in order to help guide inexperienced pilots during Instrument Flight Rule (IFR) conditions or complex maneuvering. In July 2000, a HITS system was successfully installed on a production Lancair Columbia aircraft and demonstrated at the Experimental Aircraft Association (EAA) AirVenture 2001 air show in Oshkosh, WI.[16] This demonstration exposed the public to some of the new display technologies that they could expect to see in general aviation before the end of the decade. With the rising popularity of synthetic vision research, Langley research teams began initial investigations of retrofitting issues, heads-down display size, and other considerations aroused by the onset of commercial application.

NASA continued flight-testing of SVS research throughout the duration of the 5-year project. Just a year after the start of the program, in September and October of 2000, NASA's Langley Research Center team, along with industry research partners such as Rockwell Collins, the Federal Aviation Administration's (FAA's) Runway Incursion Reduction program, Rannoch, Jeppesen, Ohio University, and the Dallas-Fort Worth Airport Authority, conducted an extensive flight evaluation of commercial SVS at Dallas-Fort Worth airport. The testing was done aboard the Langley Boeing 757-200 Airborne Research Integrated Experiments System (ARIES) research aircraft with installed SVS. During this evaluation, 6 pilots flew

13. Chambers, *Innovation in Flight*, p. 100.

14. "Synthetic Vision Would Give Pilots Clear Skies All the Time," Langley Research Center Online Factsheet (Hampton, VA: FS-2000-02-48-LaRC), available at *http://www.nasa.gov/centers/langley/news/factsheets/SynthVision.html.*

15. Parrish et al., *Aspects of Synthetic Vision Display Systems*, p. 107.

16. Chambers, *Innovation in Flight*, p. 100.

CRA Teams with SVS Project	Contractors to the SVS Project
BAE Systems, Inc., CMC Electronics, Inc., BAE Systems Astronics, and Nav3D Corporation.	The Boeing Company and Boeing Phantom Works.
Rockwell Collins, Inc., Jeppesen Sanderson, Inc., The Boeing Company, American Airlines, Delft University of Technology, Embry-Riddle Aeronautical University, Flight Dynamics, Inc., and the University of Iowa.	Cambridge Research Associates, ConITS Team (Raytheon Company, NCI Information Systems, Inc., Analytical Services & Materials, Inc., Aerospace Computing, Inc., and Genex System, LLC.)
AvroTec, Inc., Avidyne Corporation, Lancair International, Inc., Massachusetts Institute of Technology, Raytheon Aircraft Company, Seagull Technologies, Inc., and FAA Civil Aeronautical Medical Institute (CAMI).	Gulfstream Aerospace Corporation, Lockheed Martin Corporation, and Logistics Management, Inc.
Research Triangle Institute, Archangel Systems, Inc., Flight International, Inc., Seagull Technologies, Inc., Dubbs & Severino, Inc., Crew Systems, Inc., and FLIR Systems, Inc.	Max-Viz, Inc., Research Triangle Institute, and Rockwell Collins, Inc.
Jeppesen Sanderson, Inc., Marconi ADR, Darmstadt University of Technology, Allied Pilots Association, American Airlines, Alaska Airliners, Lufthansa German Airlines, and Marinvent Corporation.	
Avionics Engineering Center of Ohio University	
Rannoch Corporation	
Seagull Technologies, Inc., LambCon, Rockwell Collins, Inc., Stanford University, and Raytheon Aircraft Company.	

Table 1. The eight chosen CRA teams and the prominent contractors for the SVS program.

76 landing approaches with different SVS displays and accumulated 18 flight research hours.[17] Two of the concepts tested were Runway Incursion Prevention System (RIPS), which integrated surface communication, runway navigation, and airport surveillance, and an opaque HUD designed to enhance night operations. The evaluation resulted in increased pilot awareness and positive conclusions about the immersive feeling of HUDs.

Figure 5: The TIFS dual-cockpit research airplane (NASA Image EL-199-00568).

Just under a year later, in August and September of 2001, Langley and its partners conducted another demonstration of SVS technology at Eagle County Regional Airport in Colorado.[18] This demonstration was aimed at testing the robustness of SVS technology by placing the pilot in an operationally realistic environment with challenging terrain surrounding the runway. The Vail-Eagle airport is nestled in a valley surrounded by mountains on three sides; pilots were required to make an area-navigation procedure (RNAV), wherein the aircraft must follow rising terrain, turn to miss a large mountain, and then fly up a canyon.[19] The ARIES research airplane was also used for this demonstration; it was flown by seven evaluation pilots from United, American, Delta, the FAA, and the Boeing Company, who accumulated more than 11 research hours over 106 airport approaches. Special new panels, including two new HUDs, an 18.1-inch flat panel display, and four new heads-down displays were evaluated for SVS and XVS research by the program team.

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17. Ibid., p. 110.

18. Lynda J. Kramer, Lawrence J. Prinzel III, Randall E. Bailey, Jarvis J. Arthur III, and Russell V. Parrish, *Flight Test Evaluation of Synthetic Vision Concepts at a Terrain Challenged Airport* (Hampton, VA: NASA TP-2004-212997, 2004), p. 2.

19. J.W. Ramsey, "Synthetic Vision: No Longer Futuristic," *Avionics* (February 1, 2004), available at *http://www.aviationtoday.com/av/categories/military/731.html.*

These two flight demonstrations gave validation and credibility to emerging SVS displays designed for future use in commercial aviation.

As SVS became an emerging technology in aviation safety, Langley participated in an important FAA activity involving the use of SVS in Alaska. The Alaskan Region Capstone program is an accelerated FAA effort aimed at improving aviation safety in Alaska. Alaska's accident rate for small aircraft was five times greater than the national average in the year 2000.[20] Unlike many states, Alaska greatly relies upon aviation to provide many of life's bare essentials, although the state ranks near the bottom of U.S. aviation safety due to the climate, terrain, and lack of a robust communication infrastructure. The original program provided over 150 aircraft with a datalink system and GPS avionics package to increase pilots' situational awareness. In 2001, the FAA released a request for proposal for a Capstone Phase II project that would implement even newer technologies such as SVS displays in cockpits in Alaska. The use of SVS technology to improve safety in Alaskan aviation represents one of the first major efforts to use synthetic vision for commercial application after decades of intensive, dedicated research. Langley Research Center contributed to the development of these technologies and directly participated on the technical evaluation board. This program allowed NASA the ability to effectively focus its efforts toward FAA-requested certification.

In the years to follow, Langley shifted focus toward flight-testing of SVS for use in general aviation aircraft. General aviation aircraft comprised 85 percent of the overall number of civil aircraft in the United States and 65 percent of all fatalities. In order to continue the advancement of SVS, NASA looked further into terrain portrayal for heads-down displays (TP-HDD) and a series of tests examined the effects of digital resolution and terrain texturing in order to further optimize SV displays. The TP-HDD project used the Langley Cessna 206 research aircraft (figure 6) and evaluated eight different terrain portrayal concepts. Fifteen pilots of various qualifications accumulated over 75 hours of dedicated research time at the News-Williamsburg International and Roanoke regional airports in Virginia from August through October of 2002.

The Air Force was also becoming increasingly interested in emerging synthetic vision technology for adaption to low-level military approaches. In November of 2002, more than 20 flight-tests were performed using the Air Force's C-135 Speckled Trout aircraft to evaluate displays for a completely blind approach to landing at an assault strip. The research was done under a partnership between the Air Force and Rockwell Collins, and it exemplifies industry adoption of emerging, NASA-developed, synthetic-vision technology.

In 2003, Chelton Flight Systems received the first FAA approval for synthetic vision and HITS technologies.[21] In July 2004, Langley's consortium of partners in SVS research culminated an impressive demonstration of accelerated technologies for prototype SVS concepts, including an in-depth series of flight-tests at Reno-Tahoe International Airport. New general aviation SVS displays were tested on a Gulfstream V airplane employing the new Gulfstream EVS, which uses a nose-mounted infrared sensor to provide information depicted in terrain displays on an HUD panel. The new system also included better terrain modeling, pathway-in-the-sky details, enhanced integrity monitoring, and voice recognition for display control. The system also incorporated a cross-checking tool that would ensure accuracy by matching the real outside environment perceived by sensors to the SVS virtual environment created from GPS and terrain databases. As of 2004, 82 units of this EVS had been produced for Gulfstream customers.[22] The response to this highly successful demonstration of technology was very positive and highly enthusiastic. Pilots agreed that the system decreased the pilot workload and provided significant improvements in safety, especially during low-visibility conditions.

20. Chambers, *Innovation in Flight*, p. 120.

21. Ramsey, "Synthetic Vision: No Longer Futuristic."

22. "Gulfstream Enhanced Vision System in Service in 100 Gulfstream Aircraft," *Gulfstream News Release* (July 19, 2004), available at *http://www.gulfstream.com/news/releases/2004/040719b.html*.

Figure 6: The Langley Cessna 206 research aircraft (NASA SP-2005-4539).

The SVS project was an expansive research effort carried out by NASA's Langley Research Center and was completed in 2005. Over the course of this project, many technologies emerged that have had a profound effect on the state of the art in synthetic vision cockpit displays. The concept development, fundamental research, and collaborative flight evaluations have earned synthetic vision a place in both commercial and general aviation. As the enabling technologies of SVS development continue to advance, modern pilot-vision systems will continue to increase awareness and visibility in all conditions and ensure a safer future for the entire aviation industry.

Modern Synthetic-Vision Systems

NASA's extensive research efforts in fundamental pilot-display technologies, computational methodology, enabling avionics, and flight demonstrations have outlined the path of success for SVS and advanced-vision displays in modern aviation. This research has taken early display concepts, such as enhanced vision, pathway-in-the-sky, and external vision, and integrated them into reliable, comprehensive synthetic-vision displays. Modern synthetic vision utilizes cutting-edge technology in advanced displays, navigation and guidance, computer vision, and operations management to ensure safety for pilots and the flying public. Today, leading companies like Gulfstream, Rockwell Collins, Honeywell, Garmin, and others offer advanced synthetic vision displays on business class and general aviation aircraft. Commercial airliner companies also remain heavily invested in the implementation of similar systems in the near future. Today, advanced vision research is still improving, and new technologies are being developed. Areas such as sensor fusion, transparent HUDs, advanced computer vision, and graphics processing power all contribute to the advanced synthetic-vision systems of the future. One day, cockpit vision systems may be able to detect accurate weather conditions, wind patterns, thermals, or other phenomena by integrating complex sensor systems with virtual environments generated by SVS. These displays will continue to heighten pilots' awareness and therefore increase safety and operations from the ground up.

The advanced displays used in today's aircraft cockpits are the result of many decades of intensive research by NASA and industry partners. NASA's persistent concentration on futuristic systems and operations has made it an industry leader developing technology beyond that which is emerging today. The implementation of modern SVS displays in cockpits would not be possible without the decades of early research by Langley research teams. The early research paved the way for developments like EVS, XVS, and HUDs, which have all greatly contributed to the SVS displays implemented in today's modern cockpits. NASA's expertise and experience in SVS development represent a national asset that is being applied to solve visibility-related concerns and ensure increased safety for the U.S. aviation fleet now and for many years to come.

National Aeronautics and Space Administration

FACET: Helping Adapt National Airspace

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Introduction to the Air Traffic Issues

If you have ever had to deal with the hot, dirty, and congested conditions of a city, it is easy to look into the skies and wish you could leap away from the confines of the ground and into the freedoms of the sky. Even driving on an open highway, it would be so liberating just to lift off and see what is over the hill blocking your view. If we could overcome the noise and security measures at the airport, would not flying be a quick and exciting method of transportation over any distance?

While the beauty and appeal of the sky can be very enticing, and while we would love to be able to use air travel for even our shortest commutes, there is a vastly more complicated story to see and understand beneath this seemingly simple and exciting form of transportation. For the end user, it can be as simple as buying a ticket, getting on a plane, enjoying the ride, and disembarking at our destination. If we were to start flying ourselves, however, we would quickly come to understand what a challenging and incredible feat this really is. The congestion of our traffic on the ground is not unique (figure 1). Consider, for example, that there are over 87,000 flights per day, with over 5,000 planes in the air at any moment over the United States.[1]

Figure 1. Air traffic congestion can occur both in the air and on the ground at airports (reprinted with permission from the Raleigh, NC, *News & Observer*).

In order to ensure the safety and efficiency of flights today, a very robust air traffic management (ATM) system must be in place to facilitate their travel. There is so much to consider that it may seem overwhelming at first. Airspace is shared between commercial, private, cargo, taxi, and military users. The aircraft must have timely and synchronized loading and fueling times; coordination between takeoffs and

1. "Air Traffic Control: By the Numbers," National Air Traffic Controllers Association, available at *http://www.natca.org/mediacenter/bythenumbers.msp* (accessed June 20, 2010).

touchdowns; and careful attention paid to the details of flight conditions, including route, weather, altitude, proper aircraft separation, and more.

With the possibility of air traffic tripling by 2025 from 2004 levels, an even better ATM system is desperately needed to handle increased traffic needs in an already overburdened system.[2] The challenge is to increase system capacity and flexibility to accommodate air traffic growth and user preferences while also maintaining and improving the current levels of safety.[3] This is where cutting-edge software research at NASA plays a vital role in meeting these future needs.

Since the early 2000s, a team of scientists at Ames Research Center in Moffett Field, CA, has been designing software that enables the development and evaluation of advanced ATM concepts through models and simulations. This software is known as the Future ATM Concepts Evaluation Tool (FACET), and it is funded by NASA's Airspace Systems program. The goal is to use FACET to find new, safer, and more efficient methods of managing air traffic over the United States. In fact, FACET is so impressive and so promising that it won NASA's 2006 Software of the Year competition.[4]

The FACET Software—Capabilities

We now understand the need for a better air traffic management and control system. Rapid growth in air traffic has generated traffic congestion in the air as concerning as can be found on the ground at times. This need has facilitated the creation of the FACET software by researchers at NASA. Through FACET, NASA and industry are trying to quickly make accommodations for the anticipated growth in air traffic demands. They want to make the transition to the new generation of flight as smooth and as safe as possible.

To make this transition a reality, the FACET software has been designed with a host of powerful capabilities in mind. Its primary function is to create the simulation environment necessary to explore, develop, and evaluate advanced ATM concepts. The simulated environment must be as accurate as possible. Although the software was initially intended to deal with local or small regional conditions, it was realized early on that any location was influenced by the events surrounding it. It was thus decided to instead build a tool capable of understanding air traffic control on a large scale.[5] This is in part what now makes FACET so valuable. Under its current design, it can model airspace operations over the entire contiguous United States.[6]

Modeling such a large and detailed system is an incredible feat requiring the integration of many complex functions. As part of this process, FACET uses vast amounts of data from a wide variety of sources. These sources include databases on aircraft performance, airspace, weather, air traffic conditions, and more. For example, it can interface with the Enhanced Traffic Management System (ETMS) for necessary air traffic information such as an aircraft's track, flight plan, and schedule, allowing it to react to air traffic congestion.[7]

Weather data can be taken from the Rapid Update Cycle, version 2 (RUC-2), made available by the National Center for Environmental Prediction. It is updated on an hourly basis, with a resolution of 40

2. Joint Planning and Development Office (JPDO), *Concept of Operations for the Next Generation Air Transportation System*, v. 3.0 (Washington, DC: JPDO 01157015, 2010), p. 1-1.

3. Karl Bilimoria, Banavar Sridhar, and Kapil Sheth, "FACET: Future ATM Concepts Evaluation Tool" (3rd U.S.A./Europe Air Traffic Management and R&D Seminar, Naples, Italy, June 13–16, 2000), p. 1.

4. NASA, "Comprehensive Software Eases Air Traffic Management," *Spinoff* (Washington, DC: United States Government Printing Office [GPO], 2007), p. 44.

5. Johanna Schultz, "Future Air Traffic Management Concepts Evaluation Tool," *Ask* 27 (summer 2007): 43.

6. Bilimoria, Sridhar, and Sheth, "FACET: Future ATM Concepts Evaluation Tool," p. 1.

7 Richard Hallion, *NASA's Contributions to Aeronautics: Aerodynamics, Structures, Propulsion, and Controls*, vol. 2 (Washington, DC: NASA SP-2010-570-Vol 2, 2010), p. 147.

kilometers horizontal and 37 isobaric levels vertical (roughly sea level to 53,000 feet). Airspace features including jet routes, victor airways, and other navigational aids are modeled. Users can then translate across the airspace, zooming in and out of any area they need to display.

Modeling the wide variety of aircraft in service is a challenge of its own. Such data are largely contained within a FACET Performance Database. This database contains performance specifications for 66 different types of aircraft. It can also map more than 500 other aircraft types that are recognized by the Federal Aviation Administration (FAA) to the 66 primaries. Aircraft performance parameters include climb/descent rates, cruise speeds, takeoff distances, and many other key characteristics, all of which are contained in versatile data lookup tables. FACET uses these aircraft models with weather and traffic information and round-Earth kinematic equations to accurately simulate four-dimensional aircraft trajectories.

The capabilities of FACET modeling do not stop there. Recent importance placed on affordable space access is expected to increase significantly the number of Space Launch Vehicle Operations in the near future, especially in commercial space flight. FACET has accordingly been designed to be easily adaptable in order to accommodate and incorporate new vehicle class models that will arise to fill such future needs.[8] It also attempts to decrease the impact of space launch vehicles by minimizing the "show-stopping" time out and no-fly zones over their launch sites.

Putting all of these detailed models and databases together makes FACET a very powerful simulation tool. It simulates air traffic conditions over the contiguous United States in an effort to manage traffic flow and to discover and mitigate problems further in advance. Because traffic loads will also exceed the handling abilities of human controllers, advanced traffic-flow management techniques are necessary to ensure safety and efficiency.

The powerful simulation environment created by FACET allows for real-time planning applications, data visualization, offline analysis, and the evaluation of advanced, future ATM concepts.[9] In fact, there are four distinct operational modes: Playback (to play back a real scenario), Simulation (most appropriate for tests and evaluations because it generates trajectories using initial conditions obtained from track and flight plan data), Hybrid (alter variables in a real scenario to observe other possible outcomes), and Live (for real-time display and analysis). All modes can be used for data visualization and offline analysis as well.[10] FACET is able to help controllers reconfigure or adapt local airspace sector boundaries and to reroute aircraft to change the pattern of traffic flow. This adapting process creates a "dynamic density" of air traffic and helps to minimize the "airspace complexity" of the system.

While FACET was originally intended only for the modeling of airspace trajectories, its flexibility and adaptability have been vital in allowing other features and capabilities to be added as required by individual ATM concepts and applications. For example, it has been made hierarchically compatible with the Center-Traffic Radar Approach Control (TRACON) Automation System (CTAS).[11] This enables efficient operations planning by airliners, allowing them to perform detailed and timely risk assessment and accurate handling of departures and congestion. It also allows for the prediction of problems much further in advance than any current system and helps to suggest optimized solutions for problems that do arise.

Through all of its development, FACET has been designed to maintain a careful but vital balance between fidelity and flexibility. It has a scope ranging from a national scene to an individual aircraft. It thus has "what-if" decision-making capabilities for a large and complex system, including capabilities to handle

8. Bilimoria, Sridhar, and Sheth, "FACET: Future ATM Concepts Evaluation Tool," pp. 2–8.

9. Kapil Sheth, "Future ATM Concepts Evaluation Tool (FACET)" (Modeling, Optimization, and Software in Air Traffic Management Workshop, 45th Institute of Electrical and Electronics Engineers [IEEE] Conference on Decision and Control, San Diego, CA, December 12, 2006), p. 5.1.

10. Schultz, "Future Air Traffic Management Concepts Evaluation Tool": 44.

11. Bilimoria, Sridhar, and Sheth, "FACET: Future ATM Concepts Evaluation Tool," pp. 2, 7.

over 10,000 aircraft, 1,000 decision makers, and 100 major airports.[12] To enable such powerful and versatile computing power, the FACET software has been written in two languages. Computations are handled by code written in C, while the display of information and interaction with users is handled by a graphical user interface (GUI) written in Java. This unique and powerful combination of C and Java allows the FACET software to run on various platforms including Unix, Linux, Windows, and Mac computers. In fact, it is so powerful and efficient that it can even handle over 5,000 aircraft at a time on a simple desktop computer (figure 2). Such cross-platform languages also make for good collaboration tools with other organizations, as these languages allow for easy interfacing of systems and infrastructure.[13]

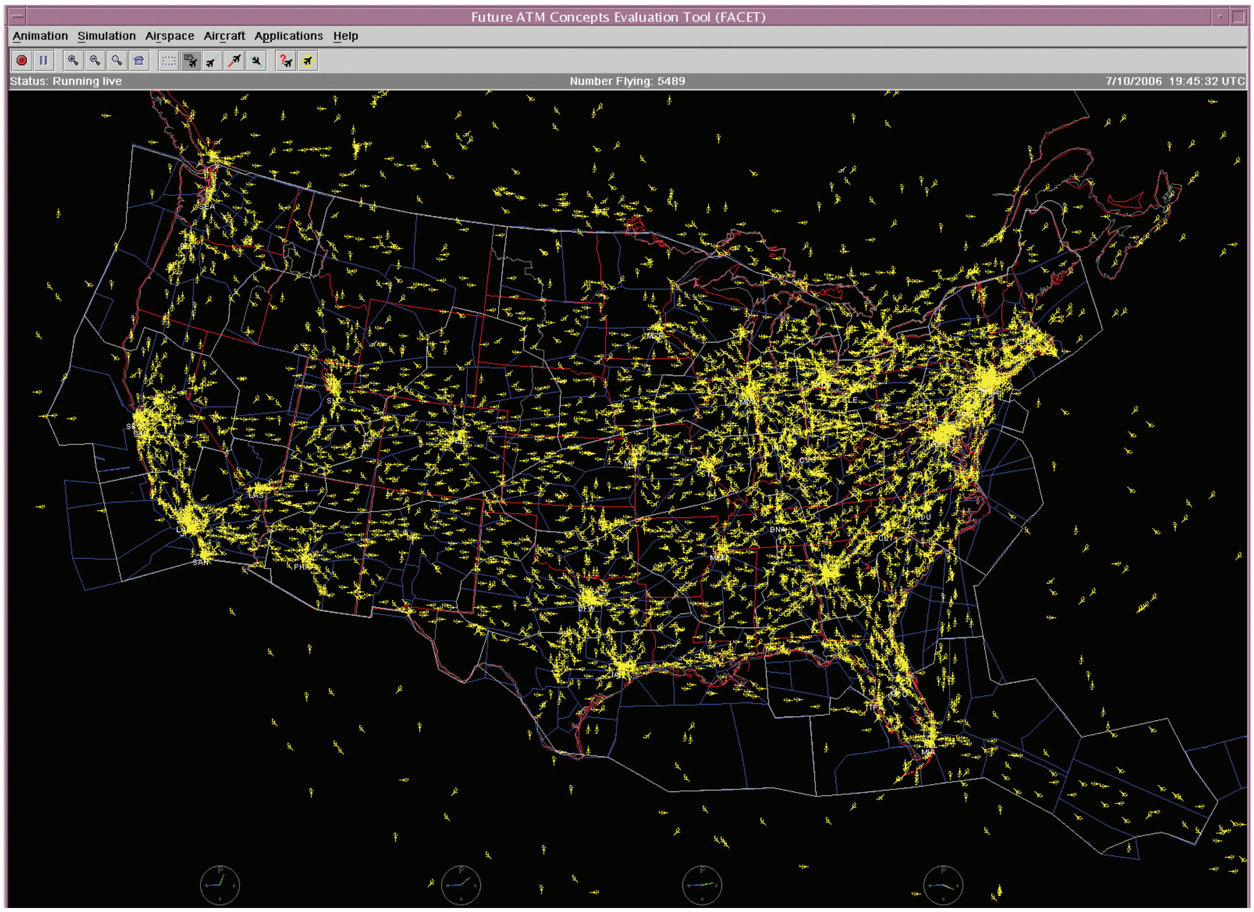

Figure 2. Here is an example of air traffic over the contiguous United States as generated by the FACET software (*http://www.nasa.gov/centers/ames/images/content/155080main_facet_hr.jpg*).

FACET Concepts Under Evaluation

Advanced concepts under analysis by FACET include distributed air/ground traffic management systems, traffic flow management techniques using dynamic density predictions for airspace redesign and aircraft rerouting, new decision-support tools for direct routing, and integration of space launch vehicle

12. Sheth, "Future ATM Concepts Evaluation Tool (FACET)," pp. 5.1, 5.4.

13. Bilimoria, Sridhar, and Sheth, "FACET: Future ATM Concepts Evaluation Tool," pp. 1–2.

operations into the U.S. national airspace system. Each concept is meant not only to work with existing air traffic control operational procedures, but also to advance better ones for the future.[14]

To this end, one of FACET's greatest potentials lies in its usefulness as a research test bed in the development of procedures and algorithms allowing future ATM systems to feature airborne self-separation. Rather than have air traffic controllers separate traffic, a workload-intensive process resulting in many bottlenecks, the goal is to allow pilots to ensure proper separation on their own.[15] Through the delegation of separation requirements and responsibilities to the pilots to prevent airborne conflict, officially known as conflict detection and resolution (CD&R), a much better, safer detection system is created. Flight operations used by pilots directly between aircraft should be faster than those relayed through ground operations first. Airborne self-separation is thus an advanced ATM concept for mature free flight operations, hopefully allowing for a more dynamic airspace.

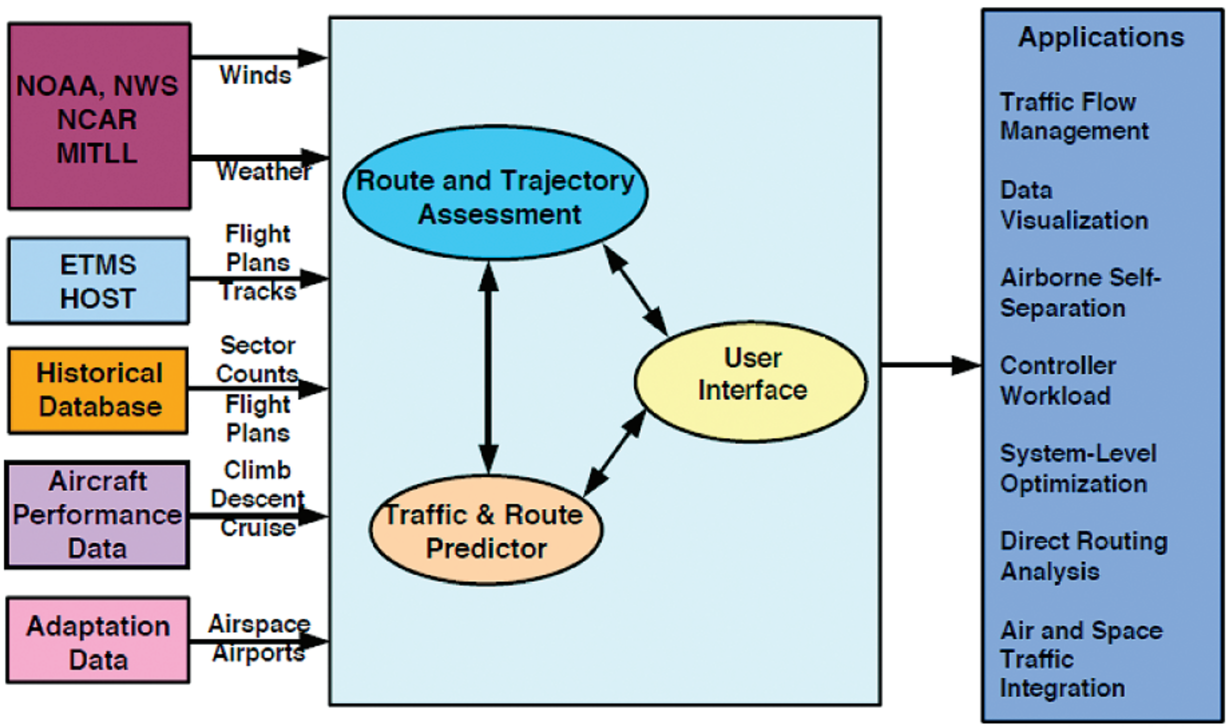

Figure 3: The architecture of the FACET software (Kapil Sheth, NASA Ames Research Center).

The modular software architecture of FACET (figure 3) enables not only the possibilities of self-separation, but also the rapid prototyping of other diverse ATM concepts. Another concept under evaluation and mentioned earlier is a decision-support tool for direct routing called the CTAS Direct-To Tool. By flying user-preferred direct routes (with no layovers) rather than the current ATC-preferred routes, it is anticipated that a national airspace-wide savings of up to $200 million per year could be realized.[16] Less time in flight means fewer costly resources are required for flight and maintenance.

14. Ibid., p. 1.

15. Schultz, "Future Air Traffic Management Concepts Evaluation Tool": 43–44.

16. Bilimoria, Sridhar, and Sheth, "FACET: Future ATM Concepts Evaluation Tool," pp. 6–7.

FACET Users

With so many impressive capabilities and concepts under evaluation, the FACET software is very attractive to a host of different parties outside of NASA. Some of the greatest interest is coming from schools, such as the Massachusetts Institute of Technology (MIT); the FAA; airlines; and other businesses and organizations involved with ATM systems. A quick look at some of these users will show how FACET is already making big impacts.

The FAA is highly interested in FACET due to its ability to help safely usher in the next generation of air transportation. The adaptation of FACET to existing FAA-operated systems has been its greatest measure of success for ATM projects thus far. One such adaptation and integration has been with the Jupiter Simulation Environment for Airspace Flow Program (AFP) impact analysis. FACET can also create powerful "what-if" decision-support capabilities for evaluating bad weather and congestion. These decisions reduce or avoid delay through strategic routing and aircraft spacing, while real-time reroute monitoring ensures conformance to safety standards. The FAA also makes evaluations of ATM concepts and air traffic situations using the historic playback capabilities of FACET.[17]

As one would expect, airlines have been very interested in the potential FACET might hold for their operations. They were so interested, in fact, that in March 2001 the Airline Dispatcher's Federation (ADF) team requested NASA to develop dispatcher tools for the team. FACET was then adapted to work with the Aircraft Situation Display to Industry (ASDI) data system. NASA worked with ADF and the Ohio State University to develop parameters and identify research issues important to all parties involved. Identified issues included the following: the ability to enable efficient operations planning by airlines, the integration of weather and traffic information, detailed risk assessment, and departure planning with congestion management.

Commercialization of the FACET software has taken place through other key industry players as well. The Ames Commercial Technology Office began licensing the software to Flight Explorer in 2005. Flight Explorer is one of the leading vendors of aircraft situation display systems in the world. Their customers include almost 80 percent of major U.S. airlines, 22 regional airlines, all cargo airlines, and many executive jet operators. FACET was partially integrated with the Flight Explorer software in the first quarter of 2006 in the Flight Explorer 6.0 release. It was a fully integrated feature of the Flight Explorer Professional Edition (version 7.0). In Flight Explorer, FACET is used to predict sector congestion and airport rates available to users.[18] It even allows for color coordination. Airports at 80 percent capacity or less are labeled in green; airports at greater than 80 percent capacity but less than 100 percent are colored yellow; and airports at 100 percent or over capacity are colored in red.[19]

All of this is only the beginning for FACET. Its power and adaptability ensure a growing role in our aviation industry. Such attributes will allow for new capabilities, systems integration, and widespread usage. As the air transportation industry continues to grow, even past the capabilities of human operators to manage and control it, FACET will be vital in ensuring that the required safety and efficiency standards are met or exceeded. With the help of FACET, perhaps flight will one day become as standard as driving and as free-form as that of the birds we hope to imitate.

17. Sheth, "Future ATM Concepts Evaluation Tool (FACET)," p. 5.3.

18. Ibid., pp. 5.4, 5.5.

19. NASA, "Comprehensive Software Eases Air Traffic Management," *Spinoff* (Washington, DC: GPO, 2007): 44.

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