How AFRL Researchers Are Making Fatal Aviation Mishaps a Thing of the Past

Air Force Research Lab - Aerospace Systems Directorate
Flying a fighter jet just got a whole lot safer, thanks to a new collision-avoidance system developed by Air Force researchers. The system, known as Auto GCAS, compares a plane’s flightpath to a sophisticated 3-D terrain map; if it detects that a jet is on a collision-course, it takes control a split-second before impact to nudge the aircraft onto a safe trajectory. Convincing airmen to surrender control in moments of crisis wasn’t easy, but since being rolled out on late-model F-16s in 2014, the system has already saved 7 lives. Now, Auto GCAS -- along with a related system that keeps tabs on other aircraft, and intervenes to prevent mid-air collisions -- is being rolled out on other platforms, and is expected to save 57 aircraft, worth a total of $6.8 billion, by 2040.

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IMAGE INFO
Page #1: Source, U.S. Air Force photo by Senior Airman Janiqua P. Robinson
On May 5, 2016, an Arizona Air National Guard student pilot was flying at 17,000 feet above the American southwest in an F-16 fighter jet, receiving training in basic fighter maneuvers (BFM) — better known as dogfighting. With an instructor cruising nearby in a second F-16, the pilot executed a tight turn, banking sharply and pulling back hard on the side-stick that controlled his jet.

The sudden turn, executed at a speed of more than 450 knots, subjected the pilot to 8.3 times the gravitational forces now holding you in your chair — a level of stress that the F-16 was designed to withstand, but that the human body was not.

As the F-16 arced through the sky, the soaring G-forces forced the pilot’s blood into his extremities and away from his brain, which, starved of oxygen, began to shut down. Imperceptibly at first, the color drained from the pilot’s vision. Then, all too rapidly, a grey fog spread across his peripheral vision, constricting to a dwindling, desaturated circle in the center of his visual field. Then — nothing.

As the pilot, call sign “Sully 2,” slumped unconscious in his cockpit, the uncontrolled F-16 skewed into an inverted dive, its afterburner still flaring. The pilot’s airspeed gauge began to tick giddily upwards, past 500 knots, 550 knots, 600 knots, 650 knots.

“Two, recover!” barked the instructor by radio as the F-16 dived through 12,000 feet, then 11,000. As the altimeter began to blink down faster and faster— 10,000 feet, 9,000 feet — the instructor shouted again, louder and increasingly desperately: “Two, recover! Two, recover!”

The pilot did not respond, but as his F-16 plunged down out of the clear blue sky, two glowing chevrons appeared on the edges of its heads-up display (HUD), and began rapidly sliding inwards, converging on the center of the screen. As the chevrons’ tips met, forming an X, the word FLYUP appeared in the center of the HUD — and miraculously, without any input from its incapacitated pilot, the F-16 snapped to wings level and abruptly performed a 5g pull up to break out of the dive, and bring its nose back safely above the horizon.

About 12 seconds after he had passed out, the pilot regained consciousness, feeling for a brief, disorienting moment, as though he’d just woken up in his own bed. With his instructor’s panicked cry of “recover!” still ringing in his ears, he took control of the aircraft, and flew safely back to base. ¹

Jinxx. Trojan. Cools. Bong. Ice. These are some of the call signs used by USAF fighter pilots who’ve died in recent years in collisions, either with terrain or with other aircraft.

Behind each call sign lies a story like that of the Arizona Air National Guard pilot’s: a fleeting lapse of judgement during BFM training, a moment’s disorientation or distraction on an aggressive strafing run, or a G-induced loss of consciousness (GLOC) episode. But unlike Sully 2, these pilots’ stories didn’t end with a miraculous recovery, but rather with tragedy: families torn apart, spouses widowed, and children left to grow up without a parent.

That the Air National Guard pilot’s story didn’t end the same way isn’t due to luck or divine intervention, but rather to thousands of lines of computer code embedded in his jet’s avionics and flight-control systems. Those lines of code make up the Automatic Ground Collision Avoidance System (Auto GCAS)— a software-based, turbo-charged autopilot capable of detecting when a fighter jet is on a collision course with the ground, and intervening at the last possible instant in order to steer it to safety.

Auto GCAS is the fruit of a decades-long push spearheaded by researchers at the Air Force Research Laboratory (AFRL)’s Aerospace Systems directorate, working in close partnership with NASA, OSD, Lockheed-Martin, Swedish researchers, and the Air Force Test Center (AFTC).

Though first conceived of in the 1980s, Auto GCAS has faced a long and sometimes frustrating struggle to achieve operational status. In recent years, however, it has gained wide acceptance, and been fielded on more than 600 recent-model F-16s. The technology is due to be deployed on around 330 older F-16s and thousands of F-35s in coming years, likely alongside a spin-off
technology called Automated Air Collision Avoidance System (Auto ACAS), which tracks nearby planes to automatically prevent midair collisions.\(^2\)

Taken together, Auto GCAS and Auto ACAS are expected to prevent almost three quarters of the U.S. Air Force’s operations-related aircraft losses. By virtually eliminating what aviation experts call Controlled Flight into Terrain (CFIT) incidents, Auto GCAS alone will prevent 75 percent of operations-related pilot fatalities.

“It’s very hard to initially transition a system, for multiple reasons,” says Amy Burns, the Automatic Collision Avoidance Technology (ACAT) program manager at AFRL. “But it’s been great, over the last few years, to see how many saves the system has had.”

Though it has only been installed on the F-16 platform for three years, Auto GCAS is already saving lives. Between 2000 and 2014, when Auto GCAS was first fielded on block-40-plus F-16s, the Air Force lost 18 F-16s and 15 pilots due to CFIT incidents, and an additional 11 jets and 5 pilots to mid-air collisions. Since 2014, however, there hasn’t been a single preventable CFIT incident involving an Auto GCAS-equipped aircraft — and there have been at least six confirmed “saves,” with seven aviators (including a pair in a two-seater F-16) being recovered before collisions and living to fly another day.

“This is a very, very critical achievement, from a safety perspective— there are seven pilots walking around now that unfortunately might not have been,” says Mike Huggins, the Aerospace Systems Directorate’s chief engineer. “We take pride in that.”

A business case drafted by the Office of the Secretary of Defense (OSD) in 2016 projected that adding Auto GCAS and Auto ACAS to all F-16 and F-35 aircraft would save at least 57 aircraft and 40 lives through 2040, even assuming the early retirement of the F-16 platform and a long phase-in period for the technology on the F-35. That would save the Air Force about $6.8 billion in lost...
and damaged aircraft, the report found, not counting the human cost of the lost pilots or the financial impact of training their replacements.\textsuperscript{3}

One 1995 AFRL study pegged the additional cost of replacing lost pilots at up to $4 million per airman, depending on their level of experience.\textsuperscript{4}

It’s been estimated that over their operational lifespans, Auto GCAS could save as many as 9 percent of the fighter-attack jets upon which it is installed from CFIT incidents.\textsuperscript{5}

Even the most conservative benchmarks, which exclude human costs and use a low replacement cost for lost aircraft, suggest that Auto GCAS and Auto ACAS will save scores of lives in coming decades, and deliver $21 in cost savings for every dollar that is spent to field them.

### Decades in the Making

That’s a huge success even by the standards of the Aerospace Systems Directorate, which has delivered countless major technological breakthroughs over the years. The directorate was formed in 2012 with the merger of AFRL’s Propulsion and Air Vehicles Directorates, bringing under a single umbrella everything from spaceflight to biofuels research, and creating a unified lab tasked with helping U.S. airmen to fly higher, faster, and smarter than their opponents.

The directorate— which is mostly housed at Wright-Patterson Air Force Base, in central Ohio, but also maintains facilities at Edwards Air Force Base in California and at Arnold AFB in Tennessee— has changed plenty over the years, and not just organizationally, says Huggins, who has been with AFRL almost three decades, working mostly on rocket propulsion technologies.

“\textbf{In the old days, when I was a young pup, build \texttt{.em} and bust \texttt{.em} was the mentality,}” he says. \textquoteleft\textquoteleft You were hardware-rich but computationally poor, so you had to build a lot of different types of hardware to really find the right solutions.”

These days, Air Force laboratories have access to full-scale supercomputers, as well as powerful computing clusters capable of crunching vast amounts of data, Huggins says. \textquoteleft\textquoteleft We have an improved likelihood of success because we can chase out a lot of the problems computationally.’’

That’s certainly been the case for the ACAT team, says Burns, a lifelong airplane enthusiast whose grandfathers worked as engineers and mechanics at Wright-Patterson. Burns spent her childhood going to the base’s huge Air Force museum to gawk at airplanes. The ACAT team has used sophisticated simulators, at Wright-Patterson and other USAF bases, and at facilities operated by F-16 contractor Lockheed-Martin, to troubleshoot the fiercely complex algorithms on which Auto GCAS depends.

Once a pilot is airborne and raises his aircraft’s landing gear, Auto GCAS begins running calculations multiple times a second to compare the plane’s location, trajectory, and other in-flight data to a precise 3-D model of the planet’s surface. Simultaneously, the system models the plane’s trajectory during a recovery maneuver— a swift roll to bring the wings level, then a 5g pull to bring the nose up — in order to determine the last possible instant at which such a procedure could be performed without hitting the ground.

That’s both computationally taxing, given the endless permutations of real-world scenarios with which the program must cope, and incredibly high-stakes: a single coding error or glitch in the system could cost a pilot his or her life. Even with the new revolution in aerospace computing and simulation, it takes a special kind of researcher to develop software that can be relied upon to yank control of a fighter jet away from its pilot in a moment of crisis, Huggins says.

\textquoteleft\textquoteleft Think about all the brain power and computational power behind those few lines of code,” Huggins says. \textquoteleft\textquoteleft The goal is to save the pilot and save the bird, so you really have to fully vet it out.’’

Reaching that point has taken decades. Auto GCAS was first developed in the mid-80s not as a safety net for pilots, but rather as a backup system for an experimental F-16 being flown out of Edwards Air Force Base in southern California. Researchers at Wright-Patterson’s Wright Aeronautical Laboratories — a precursor to the current AFRL— were working with General Dynamics to develop automated weapons systems that could fly an F-16 testbed low and fast across the surrounding flatlands.
nine months, from June 1985 to Feb. 1986, to design and implement an effective automated GLOC collision-avoidance system for the AFTI/F-16.

In 1986, in one of the earliest reports on the technology, researchers were remarkably upbeat about its potential, pointing out that during the time it had taken to develop and test the system, two Air Force pilots had been killed in CFIT episodes.

“With a simple application of current technology, we have the capability of preventing most fighter accidents,” wrote John D. Howard of the Air Force Flight Test Center and Ann M. Johnston of General Dynamics. “This system should be integrated into current tactical aircraft as soon as possible.”

In the end, though, it took another three decades before Auto GCAS was fielded for the first time, on late-model F-16s. That was partly due to technical challenges, Burns says: to install Auto GCAS requires a digital flight computer, and many early military platforms — including the pre-40 block F-16s — used analog controls.

There were also concerns about whether the computers installed on the jets of the period would be able to handle the complex computations needed to run Auto GCAS, while also managing all their other tasks.

“The capability to put the system on board really wasn’t there” in the early years, Burns says. “When we implemented Auto GCAS, it was just a software update since the necessary hardware upgrades had already occurred on the production F-16s from product improvements.”

Radar-based avoidance systems couldn’t cope with complex terrain, so Auto GCAS had rapidly evolved into a passive system that operated by tracking an aircraft’s location relative on a 3-D map of the surrounding area. To achieve that required two other critical technologies: a reliable location system, and accurate maps of its surrounding terrain, neither of which were readily available in the 1980s and early 1990s. It wasn’t until the development of an integrated GPS and INS system, in the late 90s, that the problem was fully solved.

“We could get an 80 percent solution with the system the way it was, with that INS, but they didn’t feel like that was
a good enough solution,“ Swihart says. “Once they put the GPS in there, that was the biggest thing.”

And knowing the location of the plane was only half the battle: it was also necessary to know the location of the ground. Solving that challenge required a trip into space: in 2000, the space shuttle Endeavor spent 11 days bombarding the Earth with radar beams. Over the course of 176 orbits, the shuttle used two separate antennae—one mounted on the shuttle, the other dangling 200 feet away on the end of a slender mast—to detect the radar signals bouncing back off the planet’s surface.7

By comparing the two signals, researchers were able to generate an unprecedentedly accurate map of the planet’s surface, creating a 3-D topographical model known as Digital Terrain Elevation Data, or DTED. The data set—carefully combed for errors and artifacts—forms the basis of modern Auto GCAS technology. It’s known as Shuttle Radar Topography Mission (SRTM) DTED. The ACAT team verified the accuracy of this dataset for use in Auto GCAS.

Even with terrain mapping and location sensing figured out, plenty of work remained for the ACAT team. Much of their testing focused on when, exactly, a recovery maneuver should be performed. Unlike previous collision-warning systems, Auto GCAS is based not on an aircraft’s altitude above the ground, but rather on its projected time until impact. Auto GCAS continuously calculates the last possible moment at which a recovery trajectory could be flown without hitting the ground.

That instant—the moment at which a 5g pull-up would leave the plane bottoming out at zero altitude, with its belly skimming the daisies—is what the ACAT team call “zero second.” Depending on conditions, Auto GCAS activates its recovery maneuver at a predetermined time before zero second, leaving a margin of safety that is carefully calculated to ensure the jet’s safety without

An Air Force F-16 Viper performs an extreme aerial climb during the Australian International Airshow and Aerospace & Defense Exposition in Geelong, Australia, March 2, 2017. The Viper is assigned to the F-16 demonstration team from Misawa Air Base, Japan. Air Force photo by Master Sgt. John Gordinier
interfering with its pilot’s normal activities, including low-altitude flight and aggressive strafing runs.

Fine-tuning that safety margin involved some stomach-churning test flights, says Mark Skoog, who worked with Swihart on the AFTI/F-16 project, then in the mid-1990s moved to NASA to head up the Auto GCAS flight test program. During the early days of Auto GCAS, Skoog explains, AFRL researchers had test pilots fly directly at the ground, and determined that no pilot would voluntarily fly their F-16 on a trajectory that took them within about 1.5 seconds of the point when a pilot must begin a 5g recovery to avoid ground impact.

“There are pilots that literally have grey hair because of the testing they did,” Skoog says. “It scared the living daylights out of them, but now it’s proven.”

Though terrifying, the tests were vitally important because it allowed the ACAT team to carve out an activation window far closer to impact than the pilots’ 1.5-second comfort zone, ensuring that the system wouldn’t activate accidentally during normal operations. That all but eliminated the “nuisance” activations that had plagued previous altitude-based systems.

“Why didn’t the other systems work? Because after the first or second false warning, the pilot tuned them out or turned them off. When they needed it, they didn’t pay any attention,” Skoog says. With Auto GCAS, thanks to Skoog’s pilots’ grey hairs, that isn’t an issue.

Subsequent testing by both NASA and Air Force pilots helped further improve and validate the Auto GCAS system, in part through a poignant series of tests in which pilots recreated all the CFIT incidents for which records were available.

“We looked at all the historical incidents of CFIT and we found we could protect against almost all of them,” Burns says. The only exceptions were one or two incidents in which planes flew into electrical wires, which aren’t included in the DTED data-set.

Pilots also flew a wide range of standard missions, to ensure that Auto GCAS didn’t interfere with regular operations. “Having a system that’s nuisance free is really critical,” Burns says. “We had pilots go off and fly their typical day-to-day missions, and we were able to show them that the system wasn’t going to constantly activate, and they could do their missions without it coming on.”

The hard work paid off: pilots are always wary of handing over control of their aircraft to a computer, Burns says, but hands-on testing is usually enough to win over the skeptics. Even for an amateur, flying in an F-16 simulator equipped with Auto GCAS is an eye-opening experience. It’s easy to convince yourself that you’re invulnerable: no matter how recklessly you dive or how perilously low you swoop through canyons, the simulator gently but insistently nudges you back onto a safe flightpath, like a patient parent ensuring that an over-excited child doesn’t run into traffic.

That sense of security has actually been a source of concern for developers, who fretted that pilots, believing themselves to be bulletproof, might take additional risks, or use the sliding-chevron alerts that precede an automated fly-up to push themselves beyond their usual limits. In practice, that doesn’t seem to happen: interviews with F-16 pilots at all the bases where Auto GCAS has been fielded found no changes in how they handled their aircraft.

**Momentum Building**

Implementing Auto GCAS has required not just technological innovation, but also sweeping changes to how the military approaches safety issues. To begin fielding Auto GCAS required a years-long campaign of advocacy and evangelism — described by one senior OSD staffer as a “crusade.”

One reason building momentum has been difficult is that CFITs have been part of aviation since the industry’s earliest days. The Wright brothers, who perfected the first powered airplane on the ground where the Air Force Research Laboratory now stands, famously refused to fly together, so that if one died in a crash, the other would live on to continue their work. In 1908, five years after his inaugural flight at Kitty Hawk, Orville Wright had the dubious honor of also being involved in the first fatal airplane crash, when a broken propeller sent his Model A biplane into a nosedive from a height of around 75 feet.
Since then, aviation has advanced, but CFIT incidents have remained a constant threat, and have often been viewed as the price the U.S. pays to remain at the forefront of military aviation. In his autobiography, flying ace Chuck Yeager famously claimed that accidental fatalities were part of a process of “weeding out weak sisters.”

Brig. Gen. Michael E. DeArmond, who trained as a fighter pilot in 1951 and flew 47 combat missions over Korea in an F-86 Sabre jet, similarly recalls that at the Air Force bases where he trained, accidental deaths were seen as the cost of producing competent pilots.

“I believe the year I went through, Luke lost about fifty pilots, Nellis lost about forty-five or fifty, and nobody gave a damn,” he said in 2006. “The attitude was sort of, ‘That’s the way you weed out the weak pilots.’”

Over time, that attitude has changed—Brig. Gen. DeArmond says he noticed a big uptick in professionalism and safety consciousness in the buildup to Vietnam—but vestigial traces of Yeager’s “Right Stuff” mindset linger on.

Recent research shows that it’s actually highly competent and experienced pilots who are at most risk of CFIT mishaps, likely because they push themselves harder and take on tougher missions. Still, several Auto GCAS advocates say that even in the past decade or so, they’ve run into three or four-star generals who’ve told them that it’s better to accept continuing CFIT incidents than to graduate pilots who lack the skills to avoid them.

Generally, though, such gung-ho approaches to safety have grown less common over the years, not least because the cost of CFIT incidents, in both blood and treasure, has grown more palpable as military aviation as a whole has grown safer.

The Naval aviation fatal-mishap rate fell from more than 50 mishaps per 100,000 flight hours in 1954, when the Navy lost 776 aircraft, to just 1.15 mishaps per 10,000 hours in 2009, for instance, thanks to sweeping improvements in safety and maintenance procedures.

But CFIT rates haven’t significantly changed over that period in either the Navy or the Air Force, despite the introduction of a succession of manual anti-collision systems that flash warnings or sound alerts as pilots approach the ground.

Manual systems tend to be plagued by false-positive warnings, leading pilots to override or disable them, Swihart says.

“The problem with a manual system is that it needs a warning for the worst pilot,” Swihart says. “And a lot of them aren’t that bad, so they ignore them.” It was in part because of the limited success of earlier collision-avoidance systems that Auto GCAS was such a hard sell, Swihart adds. In the mid-1990s, the Auto GCAS program almost fell by the wayside, and only an injection of cash from the Swedish military helped keep the program alive.

It took a year of tragedies to rekindle interest in the Auto GCAS system. In 2002, the U.S. Air Force saw its major accident rate leap by 30 percent, with 22 fatalities and 19 destroyed aircraft.

“While I would like to think that our mishap experience is an anomaly, I am concerned it may be a negative trend,” wrote then-Chief of Staff Gen. John P. Jumper in an end-of-year memo, warning Air Force personnel that the service “cannot tolerate, nor sustain, this level of loss.” The following spring, Secretary of Defense Donald Rumsfeld joined the call for an increased focus on operational safety, challenging each service to cut their mishap rates in half by 2005.

“World-class organizations do not tolerate preventable accidents,” Rumsfeld declared.

As part of the effort to meet that challenge, Rumsfeld created the Defense Safety Oversight Council (DSOC) and placed the DOD’s Under Secretary of Defense for Personnel & Readiness, Dr. David S.C. Chu, as its chairman. A senior Pentagon SES, Joseph Angello, served as the DSOC executive secretary, heard of Auto GCAS through DSO channels.

His interest piqued, Angello sent his newly assigned USAF fighter pilot, Col. Mark “Tex” Wilkins, to Wright Patterson AFB to get briefed on the technology and report back. It was there, in early 2006, that a pilot-physician named Col. Peter Mapes, accompanied by NASA’s Mark Skoog, briefed Wilkins on the struggling Auto GCAS project.
After stripping out the excess costs, Mapes says he found that the projected return on investment from installing Auto GCAS on the Air Force’s jet fighters sharply increased. “All of a sudden the ROI went up to 63 to one, which makes Auto GCAS the most financially prudent modification that has ever been done to any military aircraft,” he says. “That’s ‘you should’ve done it yesterday, dude.’ Every day you wait, you’re wasting the taxpayer’s money.”

For the more expensive F-35 platform, Mapes calculated, the return would soar to 137-1. “For every dollar you spend on Auto GCAS, you preserve $137 in airframe costs in F-35,” he says. “And none of those figures count the value of the lives — those are airframe costs only.”

Mapes started presenting his own, far more optimistic business plan to anyone who would listen, not always with positive results. He recalls being shouted down by one group of acquisitions experts after a meeting in 2005.

Mapes, a prickly character with a flair for math and a doctor’s intolerance for bureaucratic heel-dragging, had been recruited a few years earlier by AFRL leadership to re-crunche the numbers for a study of CFIT incidence across different airframes. An epidemiologist by training, Mapes says he quickly spotted a fatal flaw in the study— the contractor responsible had simply tallied CFIT incidences, making it hard to meaningfully compare CFIT rates across platforms.

Mapes started from scratch, calculating the CFIT rate per 100,000 flight hours — and as he dug into the numbers, he says he realized that past analyses had dramatically understated the potential benefits of Auto GCAS.

In particular, he found that the business cases used to dismiss Auto GCAS as expensive and unsustainable in the late 90s had included numerous additional costs, such as expensive computer upgrades, that couldn’t properly be attributed to the Auto GCAS program.
“They said, ‘Nothing’s ever going to take control of a fighter aircraft in the U.S. Air Force except a fighter pilot, this is not going to happen,’” he says. “They booed me out of the room.” Still, Mapes’ blustery determination made an impression on the people he spoke with, and his status as a pilot-physician made it easier for him to speak frankly to senior military officers.

“He’d given all the generals their physicals, and so when he was in the briefing rooms at these places, talking to three and four-star generals, he’s talking to them like I’m talking to you, because they know him,” Swihart laughs.

That approach didn’t work so well with “Tex” Wilkins, a former F-15 pilot with a drawl to match his nickname.

These days, Wilkins says he’s “probably the DOD’s chief advocate for Auto GCAS and Auto ACAS”— but in March 2006, when Skoog and Mapes first briefed him on the technology, he was skeptical. Mapes came out with such vigor that he wound up scolding rather than seducing his audience, Wilkins says.

“I was sitting there getting briefed, and I’m starting to turn red, and I’m looking at the civilian contractor and I’m about to turn to him and say, ‘Get your stuff, we’re leaving.’” Wilkins laughs. That’s when Skoog—just as passionate about Auto GCAS, but rather more diplomatic— took over the meeting, giving a more restrained and deferential explanation of Auto GCAS that managed to win Wilkins over.

Soon Wilkins was on board. He and Skoog have remained the principal advocates for the technology for much of the past decade, with Wilkins increasingly making it his personal mission to shepherd Auto GCAS through the development cycle.

Wilkins has faced his share of skeptical audiences. “I recall briefing some Air Force senior leaders in ’07, and them poking their fingers in my chest, and saying ‘I’ll be a smoking hole in the ground before you put Auto GCAS on my F-16s,” he says. “It’s like it was a badge of honor — if we lose a tenth of our fleet by training hard and preparing for the next war, it shows we’re working hard.”

Gradually, the ACAT Team’s determination and Skoog and Wilkins’ patience and political savvy started to win people over.

“When I showed up at OSD, and they threw Auto GCAS in front of me, I said, well, I know exactly how to make that happen, but it takes time— years and years and years of just slogging away,” Wilkins says. “You know how you eat an elephant? Well, one bite at a time, and eventually you’ll get through it.”

As Wilkins had predicted, it took years to convince senior civilian and military leaders to back an automated safety system. Mapes left the Auto GCAS program in 2006, but Wilkins began to tread the corridors of power, often with Skoog at his side, pitching Auto GCAS and Auto ACAS to everyone with whom he could get a meeting. Along the way, he produced a new business plan that he believes is more accurate than Mapes’ original plan, in part because it factors in the long lead-in time for new technologies, and calculates cost-savings based on the number of aircraft added to service each year. That yields a lower ROI than Mapes’ plan — a 23-1 return, versus the 63-1 return predicted by Mapes — but its more conservative approach has made it an easier sell to Air Force leaders who scoffed at some of the team’s original, more ambitious predictions.

While they differ in their estimates of the exact scale of the benefits of Auto GCAS, Wilkins concedes that Mapes’ early calculations were crucial in generating initial support for the Auto GCAS program at OSD and among the higher-ups at the Pentagon.

“Pete did a wonderful thing, and that was getting GCAS the attention of DSOC,” Wilkins says.

That cleared the way for Wilkins, and other advocates like Skoog, to gradually build support for Auto GCAS, from the flying community and from senior military leaders.

The biggest breakthrough, Skoog says, came in the late 1990s, when AFRL began cycling pilots through their testing program for the F-16 Auto GCAS system.

“Many would come in wanting Auto GCAS to fail, and they’d walk away going ‘Wow, this actually works,’” Wilkins says. “That’s when people started getting on
The increasing grassroots support for Auto GCAS coincided with an uptick in support from senior Air Force and DOD officials, including a number of generals, and other officers who’d lost friends to CFIT incidents — and led, in 2014, to the rollout of Auto GCAS on the post block-40 F-16s.

The introduction of Auto GCAS on operational fighter jets meant the start of a nerve-wracking wait, while the ACAT team and advocates watched to see how their baby would perform in the real world.

Within months, they had their answer. A pilot in combat over Syria, target fixated, pressed his strafe attack too far, and was saved from an impending CFIT by Auto GCAS.

“There was no doubt this kid was going to drive into the ground, and Auto GCAS kept him from doing it,” Wilkins says. “When that video circulated through the F-16 community, everybody was on board.”

In May 2016, the GLOC incident above Arizona won over any remaining doubters.

“Now, it just sells itself,” Wilkins says.

**Expanding the Scope**

Skoog, who is now NASA’s principal investigator of automatic systems, is a patient man, and also a tenacious one. In 2011, he suffered a concussion that left him struggling to retain the information he read. It was a major setback for any aerospace engineer, but one that Skoog learned to overcome through hard work, and through the help of his colleagues, he says.

Skoog brought a similar determination to the Auto GCAS program, first working diligently to test the new system, then over time becoming one of its chief advocates — and not just in the military sphere.

At one point, while trying to convince officials to back Auto GCAS, Skoog figured out a way to port the algorithms onto a cellphone. He did so mostly as a marketing stunt: when people started asking him about the computing requirements for Auto GCAS, he’d pull out his phone and explain that he had walked in with a fully functioning GCAS in his pocket.

“It’s kind of silly, but I wanted folks to understand, this technology is very attainable,” he says. “You can see the impact it has on an audience, especially at a higher level — you’ve got to say something that shakes their paradigm.”

Now that Auto GCAS has gained broader acceptance, Skoog works in his spare time to turn his cellphone app into a fully featured tool for general aviation pilots. A cellphone can’t take control of a civilian Cessna, Skoog says, but general-aviation aircraft also aren’t flying as fast as fighter jets, or performing the same risky maneuvers as a military pilot. That means that an app-based Auto GCAS system can provide a warning signal far earlier than it would for an F-16, giving pilots plenty of time to respond and steer themselves to safety.

There isn’t much commercial interest in a civilian Auto GCAS system, in part because commercial airlines have low CFIT rates: worldwide, there were just 13 commercial CFIT incidents resulting in fatalities between 2007 and 2016, according to a Boeing report.12

Still, Skoog believes that private pilots might find the system valuable: hundreds of private pilots die in CFIT mishaps each year, and Skoog says he’s happy to give up his evenings and weekends to try to develop and distribute an Auto GCAS system that could save their lives.13

Skoog is also working to push automated collision-avoidance systems into the field of unmanned flight. As companies like Amazon begin to develop delivery drones, Skoog says, the skies will grow more crowded, and safety issues — including ground collisions and midair mishaps — will become a major concern.

Skoog’s team has already worked to adapt Auto GCAS for small UAVs, and another group has ported Auto GCAS onto a Learjet, as a stepping stone towards implementing Auto GCAS on C-130s and other large military aircraft.14

Skoog is also working with the Federal Aviation Authority to develop new autopilot certification processes that could one day make it easier to put fully automated GCAS systems onto both civilian planes and drones.
“AFRL’s trying to build and field a widget; I’m trying to create a whole industry framework around that widget,” he explains.

While Skoog expands the scope of Auto GCAS, AFRL’s researchers are also working on new applications for the technology. Their chief focus, these days, is on a spin-off called the Automatic Air Collision Avoidance System, or Auto ACAS, which offers automated protection against midair collisions.

Past efforts to shield pilots against midair collisions have focused on traffic awareness, using audio or visual warnings emulating the functionality of an air-traffic controller. Auto ACAS takes things a step further: it’s specifically designed to protect fighter-pilots engaged in BFM training, during which Air Force rules allow pilots to fly within 500 feet of each other at combined speeds of well over 1,000 knots.

“We don’t lose airplanes to midair collisions in combat — we lose them in training,” says Capt. Andrew Petry, the ACAT deputy program manager. “So while it would be great to have a system that could apply to any airplane in any condition that it’s ever going to see, we chose to focus on the training environment.”

To achieve that, Burns’ team developed a data link that piggybacks on the P5 pods currently used to track aircraft during training exercises and war games. The wing-mounted pods, designed to look like air-to-air missiles, continuously stream data to one another, sharing information about their locations and trajectories, while also calculating and trading information about their potential recovery maneuvers.

If two Auto ACAS-equipped planes sense that they’re on a collision course, they execute a coordinated maneuver to veer apart at the last second, or “bunt” vertically in order to leapfrog one another.

“Just like Auto GCAS, it’s designed to make a maneuver at the very last instant, quickly recover the aircraft, and then give control back to the pilot,” Burns explains. The system even works if only one of the planes has Auto ACAS, with the Auto ACAS-equipped plane using tracking signals or radar locks from the other aircraft to steer itself to safety.

Auto ACAS has already been fully developed, tested, and proven, both in the lab and on the test ranges, Burns says. As with Auto GCAS, the team strove to create a system that waited until the last possible instant to nudge planes off a potential collision course. That’s evident in data from the most recent round of flight testing: after recreating dozens of historical mid-air collisions, the team found that on average Auto ACAS led the planes to roar safely past one another at an average distance of just 179 feet.

That means that Auto ACAS won’t interfere with aircraft engaged in dogfighting, Burns says — but it’s still a large enough margin to all but guarantee the safety of the pilots concerned.

Given the complexity of the calculations involved, Auto ACAS had only been intended to shield against 75 percent of midair mishaps, but testing found that in practice the system was far more effective.

“We went and looked at all the midair collisions since 2000, and we believe our system would have protected against every single one of those,” Burns says.

The remaining challenges mostly revolve around integrating Auto GCAS and Auto ACAS together into a single system — dubbed the Automatic Integrated Collision Avoidance System, or Auto ICAS — to ensure that ground-avoidance maneuvers don’t lead to midair collisions, and that midair recovery maneuvers don’t lead to CFIT incidents.

Burns’ team has been working on Auto ICAS since 2014, alongside partners at Lockheed, NASA, and OSD and in fall 2017 completed a second round of flight-testing for the integrated system. Auto ICAS is now fully functional, Burns says, and her team is working to iron out some remaining questions surrounding the data-link technology ahead of an anticipated rollout on the F-16 and other platforms.

There are still some complex software issues that will need to be resolved in order to put Auto ICAS on fighter jets, especially the older F-16s, says Ed Griffin, the Skunk Works program manager for Auto GCAS at Lockheed Martin. Older planes are essentially powered by 1980s or 1990s-era computers, so tasks that would be easy for a modern laptop — or even Mark Skoog’s cellphone— can be tricky to implement effectively on older jets.
“The flight control computer is near capacity,” Griffins says. “To put GCAS and ACAS and other capabilities on there, there’s some software reworking that needs to be done.” Even given those constraints, though, Griffin says there’s no doubt that the AFRL team is successfully finding ways to do things that nobody had previously thought possible.

“A lot of people in aviation see automation as the thing of the future,” Griffin says. “If you look at Auto GCAS system, it’s kind of the leading edge of automation on fighter jets right now.”

**More Advocacy**

The United States, despite inventing Auto GCAS, has sometimes lagged behind its allies in fielding the technology. The United Arab Emirates insisted that Auto GCAS be added to its Block 60 F-16s, and between 2005 and 2010 the UAE took delivery of 80 jets equipped with the technology. Sweden, meanwhile, rolled out Auto GCAS across its entire fleet of JAS 39 Gripen fighter jets as part of a software update in early 2016.

Early efforts to convince the U.S. Navy to add Auto GCAS to its F/A-18 Hornets and Super Hornets, on the other hand, fell flat, largely because the Navy— which between 2006 and 2016 lost 40 F/A-18s and 15 aviators to mishaps, at a cost of $2.6 billion— had committed to an alternative collision-avoidance system called TAWS. Though more effective than previous warning-based systems, TAWS lacks the ability to take control of an aircraft, and so it cannot recover pilots who become incapacitated.

The Marine Corps is now investigating Auto GCAS integration on their F/A-18 C/D fighters, while the Navy has no current plans for inclusion on the Super Hornet.

The Air Force hasn’t been uniformly receptive to Auto GCAS, either. The F-22 program office backtracked on plans to install Auto GCAS amidst concerns over the cost required for their desired implementation, to run Auto GCAS solely in the flight control computer. Building a centralized Auto GCAS system would have increased implementation costs, and would have meant finding ways to condense down the system’s mapping data for storage on the F-22’s flight computer.

Presently, F-22s are flying with a less functional Auto GCAS-based system called Line in the Sky, in which pilots set a minimum altitude and an automated recovery maneuver is triggered to prevent penetrating that altitude. That’s an improvement over past manual systems, and can save pilots from some mishaps, but it provides less protection than Auto GCAS, is more nuisance-prone, and requires more pilot interaction to operate.

In early 2017, Michael Lippert, an F/A-18 and F-35 test pilot with Naval Air Systems Command, wrote a controversial essay for Proceedings, the magazine of the U.S. Naval Institute, calling on the Navy to implement Auto GCAS.

The article drew a dismissive response from retired Vice Admiral Robert F. Dunn, the former Deputy Chief of Naval Operations for Air Warfare. “What the Fleet — Navy and Marine Corps — really needs is increased flight hour funding,” not collision-avoidance technologies, Dunn said, arguing that more competent and better-practiced airmen would be able to avoid CFIT mishaps.

Lippert countered with statistics, gleaned from AFRL research, showing that while increased air time might improve safety, it wouldn’t offer the same protections as implementing Auto GCAS.

“There is a path forward with mature technology to combat the loss of manpower and materiel with a clear return on investment,” Lippert wrote. “This isn’t something we’re guessing— this is an achievable, effective solution.”

That kind of advocacy, by the very pilots who are putting their lives on the line, is more effective than anything that AFRL researchers, or their supporters in the Pentagon, can do, Wilkins says.

“When they want it and they’re pushing for it, it makes it a whole lot easier,” he says. The increased advocacy for Auto GCAS by pilots has paid dividends, and paved the way for the program’s expansion.

Based on the success of the post block-40 F-16s, Burns’ team figured out a way to convert Auto GCAS for use on earlier analog systems, using spare card-slots in the older F-16s to host software that translates Auto GCAS’s digital commands for the older jets’ analog brains.
Flight testing of the hybrid Auto GCAS system will begin in spring 2018, and run through the summer; if all goes well, the country’s 330 early-model F-16s will receive Auto GCAS by late 2020.

The Auto ACAS midair-mishap system has also won high-level support in recent months, and Wilkins says he’s optimistic that the integrated Auto ICAS system will be made a requirement for future jets.

“We’ll get there, but it’s going to take more advocacy,” he says.

In perhaps the biggest sign that automated collision-avoidance is now seen as the future of American military aviation, the Joint Strike Fighter Configuration Steering Board in mid-December 2017 signed off on proposals to accelerate Auto GCAS integration into the F-35. Instead of waiting for a projected 2026 rollout, the committee agreed that Auto GCAS should be installed on all F-35 variants as soon as possible.

Engineering and development work is expected to start in early 2018, and it’s hoped the technology will be fielded on F-35s in early 2019. Based on current CFIT rates, that accelerated timeline should save at least three F-35s and their pilots, and yield cost savings of at least $300 million.\(^{18}\)

“Those martinis were never sweeter,” Wilkins wrote in an email, after an evening spent celebrating the news of the decision to expedite the rollout.

Active-duty Air Force officers demanded the shift — a sign, Wilkins says, that the original Auto GCAS evangelists have now successfully convinced a critical mass of serving fighter pilots and squadron commanders to push for the technology’s adoption.
“We’re getting to the point where it’s not just me and Mark and Pete Mapes. It’s gone from a half dozen of us to dozens,” he says. “It’s a bunch of Air Force lieutenant colonels that are leading the charge, and they’re winning because they’re committed, and they believe in it, and they aren’t going to take no for an answer.” It’s far harder for the Air Force’s decision-makers to pass over Auto GCAS when the flyers themselves are insisting that it be added to their planes, Wilkins adds.

“We’re winning,” he says. “I don’t think there’s any stopping it now.”

The efforts of the AFRL team, and the technology’s advocates, has now irrevocably changed the way that high-performance aircraft are designed, says Griffin, the Skunk Works program manager.

“I think you’ll see this tech going on all future platforms, whether manned or unmanned,” he says. Huggins, the Aerospace Systems chief engineer, agrees: “I absolutely believe this will be a system in all future aircraft,” he says. Just as you can’t now buy a car that lacks airbags and seatbelts, Huggins says, so Auto GCAS — and, eventually, Auto ICAS — will be fitted as standard on all new Air Force fighter jets.

That’s a triumph for scientists like Swihart, who’ve spent their life working on the technology, Huggins says, and also for the new generation of researchers, like Burns and Petry, who’ve taken up the baton and seen the program through to fruition.

The biggest victory of all, though, is for the Air Force itself, which will save billions of dollars, and scores of aircraft and pilots, by implementing the technology.

“The real crowning achievement from the technologist’s point of view is that we transitioned,” Huggins says. “But for the Air Force, it’s that we now have a safer system for those pilots.”

**Nickel on the Grass**

The ACAT team is well aware of what its success means. One of the first Auto GCAS saves involved a pilot with 480th Fighter Squadron who was practicing BFM when he lost track of his altitude—a common problem, especially over water where there are fewer visual cues—and attempted to pull through a turn on a trajectory that would have taken him straight into the ocean. Auto GCAS kicked in, yanking his F-16 in the opposite direction, and allowing him to recover safely. The pilot, who had recently lost two friends in CFIT incidents, later wrote a letter to Burns’ team thanking them for saving his life.

“The first question a pilot always asks is ‘what can we do to prevent further fatalities?’ Now, for the first time in history, we have a resounding, definitive answer to that question,” he wrote. Auto GCAS “worked as advertised and allowed me the honor to write this letter,” he added.

Swihart, now retired but still a regular presence in the Auto GCAS labs, sits meditatively in an Aerospace Systems conference room while Burns and Petry rattle through a PowerPoint presentation explaining the benefits of Auto ICAS, pointing out the billions of dollars and countless lives that the system will save.

It’s been a long journey for Swihart, and for the technology he helped invent, and he watches quietly as Burns and Petry play video after video showing real-life saves, with pilots careening inexorably earthwards, only to have their jets take over and pull them away from the ground at the last moment.

Swihart says it’s exciting to see the program flourishing under Burns’ leadership, and to see the aviation community finally starting to recognize the value of automated collision avoidance. The aim has never been simply to create a workable technology, he says. It’s been to push the system out into the world, and to start saving lives.

When fighter pilots gather to remember fallen comrades, they sometimes conclude by tossing a nickel onto a patch of nearby grass—a tradition that dates back to the 1950s, and likely has its roots in an old Korean War bar-song, bawled to the tune of a Salvation Army hymn:

*Throw a nickel on the grass, save a pilot fighter’s ass*

*Oh hallelujah, hallelujah*

*Throw a nickel on the grass and you’ll be saved.*
The tradition is a wry acknowledgement of the risks that pilots take every time they buckle themselves into their bucket seats, and a way of mourning the pilots who, tragically, fail to return from their missions.

There’s no way to completely eliminate the risks a pilot takes when they steer a jet fighter through a canyon, strafe a target at 500mph, or skim over a mountain ridge belly-up to minimize their radar shadow. For the men and women who fly fighter jets, such perils come with the turf: people who want absolute guarantees of safety should probably find another profession.

Still, thanks to the work of Swihart, Burns, and the rest of the ACAT team, and thanks to the small group of true believers who’ve fought to get Auto GCAS installed on the Air Force’s jets, there are seven fewer nickels lying in the grass this year than there would otherwise have been. Thanks to their continuing efforts, too, there will be many fewer nickels tossed into the grass in the years and decades to come.

That, at the end of the day, is what it’s really all been about, Swihart says. “It’d have been nice to get there sooner,” he says quietly. “But we got there, and that was the important thing.”

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1 Details from https://www.youtube.com/watch?v=WkZGL-7RQBvW and from interviews & materials provided by ACAT team
2 Details on GCAS, ACAS, & ICAS, here and throughout, sourced from materials provided by ACAT team.
4 Scofield, “Benefit analysis and feasibility of ground collision avoidance systems on United States Air Force aircraft”
5 https://medicine.utah.edu/rmcoeh/files/newsletter_apr2009.pdf
8 Yeager: An Autobiography, p313.
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16 Lippert, USNI Proceedings, “LIFE OR DEATH IN 250 MILLISECONDS”
17 Lippert, USNI Proceedings, “LIFE OR DEATH IN 250 MILLISECONDS”
18 Emails & interviews with Wilkins.
19 From materials provided by ATAC team
TOGETHER, WE’RE INVENTING THE FUTURE