The Things That Fell to EARTH

How NASA can predict when space junk will fall in your back yard.

by James E. Oberg

GEORGE GONGORA/CALLER-TIMES

On January 15, 1995, a Japanese rocket took off from Kagoshima, carrying a Russian-made satellite with German scientific instruments. The mission's purpose was to test materials processing techniques in microgravity and then return the samples to a landing zone in Australia.

But the launch vehicle swerved off course and headed for the horizon. Ground controllers in Germany listened for radio signals indicating that the satellite had reached a stable orbit, but they heard nothing. Without such confirmation, they eventually concluded it had fallen back to Earth. Searching for the satellite was never considered since it could have ended up almost anywhere, and all involved with the mission assumed that the Russian spacecraft would never be seen again.

As it turned out, the heat-shielded landing capsule ended up in northern Ghana, near the town of Tamale, after the satellite had limped around Earth twice in a lopsided orbit. The capsule's parachute had opened as planned, and as the craft drifted down, it broadcast homing signals that nobody picked up.

Villagers outside of Tamale witnessed the landing and called the local schoolmaster. It was obvious to him that the vehicle was a spacecraft and, given the Cyrillic characters on its side, probably of Russian origin. The schoolmaster organized a recovery team, who trucked the hardware to a storage room in town. Then he wrote to officials in Accra asking how to contact the satellite's owners.

Months later, news of the space object reached Geoffrey Perry, an amateur satellite tracker in England, who quickly realized it must be the lost Russian vehicle. He knew whom to call in the German space program, and a few months later, staffers from the German embassy in Ghana showed up in Tamale and asked for their payload. Along with the capsule, the Germans were given a bill for the storage fee, which they grudgingly paid.

Had the Germans known the capsule's point of reentry into the atmosphere, they could have avoided the storage fee. Eight years later, another team desperately seeking another failed space vehicle knew its point of reentry. Using models that can predict how space objects fall through

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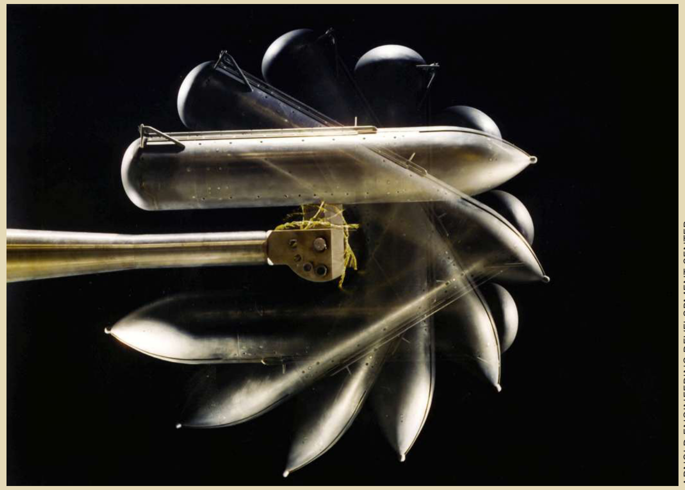
Nicholas Johnson (wearing tie) interviews Barney Corey about an Ariane 5 nose cone found on a Texas beach. Corey dug a hole behind his mobile home, intending to use his find as a hot tub, but the cone was returned to its owners in France. In 1997, a fuel tank from a Delta II launcher landed in Texas (left). Four years later, a titanium motor casing from another Delta II ended up in Saudi Arabia.



ARNOLD ENGINEERING DEVELOPMENT CENTER

Aerodynamicists tumbled a scale model of the space shuttle's external tank to simulate the stress of reentry.

Earth's atmosphere, this team was able to pinpoint not merely the continent, the country, and even the county where something had fallen, but the likely pasture.

For weeks, searchers on foot had combed the ground in east Texas, seeking pieces of the space shuttle *Columbia*, which on February 1, 2003, had broken apart during reentry, killing all seven astronauts aboard. The location of each fragment of the shattered shuttle was carefully documented, and then the parts were transported to a hangar at Kennedy Space Center in Florida, where reconstruction efforts tried to help forensic engineers discover what had gone so terribly wrong.

On March 18, a recovery team was sent to an area that had already been searched; in fact, it had been marked "completed." This time, though, the team was seeking one particular piece of hardware that had been aboard *Columbia*. Knowing its size and weight, and the distribution of other pieces already recovered, experts in reentry dynamics had concluded that the 58-pound object—a VCR-size box containing potentially valuable flight data on the doomed mission—would lie in the already-searched area.

Sure enough, on a hillside near Hemphill, Texas, technicians found the Orbiter Experiment Recorder, embedded several inches in the ground. It contained time-tagged measurements that were exactly what investigation teams needed to pinpoint the moment *Columbia*'s left wing had collapsed, an event that preceded the breakup of the vehicle.

The insights that led to the search team's discovery had been developed over many years of study at NASA's Johnson Space Center in Houston, Texas, and an earlier instance of spacecraft disintegration made the shuttle searchers confident that they were on the right track.

While out walking her dog with friends before sunrise on January 22, 1997, a woman in Tulsa, Oklahoma, was hit by a man-made object that fell out of the sky. Half an hour before, Lottie Williams had watched an impressive fireball streaking through the sky from north to south. "I noticed in the sky there was this big bright light, like a fire," she told a reporter from the *Tulsa World* newspaper. "I turned to my friends to say look, and when I turned back it was coming towards us." Then two sparks shot from the fireball and disappeared over a building.

The U.S. Air Force runs an observatory in Hawaii that can track orbital debris.

FRANK RIZZO/USAF

Later, when a slowly falling piece of charred woven material brushed Williams' left shoulder and hit the ground "with a metallic sound," she concluded that there was a connection between the two events, especially since the next day's news was full of stories about "space junk" found on the ground in Texas. A large stainless steel fuel tank, which bore evidence of surface melting, had landed in the front yard of a farmer near Georgetown, Texas, partially collapsing on impact. And outside the town of Seguin, a titanium pressurant sphere, undamaged except for some discoloration, had embedded itself halfway into a field.

Nicholas Johnson, chief scientist of the Orbital Debris Program Office at Johnson Space Center, soon got word of the discovered space debris. A few days later, he made the drive from Houston to Georgetown, where he identified the tank as having come from the one-ton second stage of a Delta II rocket booster. The U.S. Space Command in Colorado Springs, Colorado, had been tracking the Delta II for several days. Nine months earlier, it had launched a U.S. Department of Defense payload. After the rocket stage's orbit finally decayed, it had reentered the atmosphere around 3:30 a.m. over the south-central part of the country. The reentry was seen by observers in Texas, Kansas, Missouri, and Arkansas.

The collected orbital debris was shipped to the Johnson Space Center. The fuel tank and the pressurant sphere found in central Texas were obviously from the fireball. But investigators initially doubted that the piece of metal mesh that had fallen on Lottie Williams was from the rocket, since it had been recovered so far upstream of the bulk of the Delta II's debris.

At the Orbital Debris Program Office, Johnson is in charge of NASA's efforts to predict what sorts of space junk can be expected to reach the ground after the natural decay of objects' orbits. Despite the fact that hundreds of fragments of space objects have been found around the world and sent to various government agencies, conventional wisdom is that entering objects burn up. "Some launch companies until recently claimed in commercial launch license applications that spent stages totally burn up in the atmosphere," says Johnson. When the Russians remotely command the supply vehicles that service the space station to reenter the atmosphere, they claim that the vehicles "cease to exist," yet they choose to dump them over the far southern Pacific rather than over Russia—just in case.

According to William Ailor, director of the Center for Orbital and Reentry Debris Studies, between 100 and 200 large (bigger than a breadbox) man-made objects reenter each year. In 1999, Ailor has estimated, for example, that 212 tons of hardware hit the atmosphere, and a quarter of it, about 42 tons, probably reached the surface. And during the first 40 years of the Space Age, Ailor estimates that as much as 1,400 tons of man-made material has reached the

TULSA WORLD

On January 22, 1997, Lottie Williams was grazed by a slowly falling piece of mesh.

surface of Earth. He says, though, that worldwide, only about 250 discoveries of authentic spacecraft pieces have been reported because most pieces have landed in water.

For years, researchers had no reliable numerical models to predict which pieces of a space vehicle would survive entry and reach the ground intact. Estimates were made "by guess and by golly," says Johnson. But in the 1990s ITT Systems in Alexandria, Virginia, developed a numerical model that took all known thermal processes into account in order to predict the fate of entering objects. Around the same time, a team of engineers from NASA and Lockheed Martin worked jointly to create a numerical model called Object Reentry Survival Analysis Tool (ORSAT).

Johnson and his team at NASA have found the ORSAT program particularly helpful in understanding what happens to an object after the stress of deceleration causes it to disintegrate. Once a satellite breaks up, for example, and its individual components—often in the form of spheres, cylinders, and plates—are streaking in on their own, the reentries of the basic shapes are much easier to predict than those of the irregular shapes common to most intact satellites. "Tumbling titanium spheres survive reentry totally intact," says Johnson. Further, components with protuberances are affected by aerodynamic drag differently than smooth components, with the protruding parts forming a "tail," so that the front end of the object gets really roasted (some of NASA's reports contain photographs of recovered spheres with burn holes opposite the protuberances).

Johnson's group has applied the ORSAT model to known entry events, including the reentry and breakup of the nuclear-powered Russian satellite Kosmos 954, which rained radioactive debris over Canada on January 24, 1978. As the ORSAT model predicted, Kosmos 954's beryllium fuel rods became very hot during reentry. But the rods survived because they were made of beryllium. "This is because of the extremely high heat of fusion of beryllium," says Johnson. Steel and metals such as titanium and nickel share beryllium's ability to handle the heat, while aluminum and copper objects usually vaporize soon after breakup.

Johnson is particularly proud of the ORSAT model's results for debris from the Delta II rocket stage that reentered over Texas in January 1997. Using data such as size, weight, and composition for the fuel tank, pressurant sphere, and rocket nozzle, the ORSAT model indicated that all three pieces would survive reentry, which they did. Additionally, the ORSAT program's prediction of the landing sites for all three pieces matched well with the actual locations.

Unlike the fuel tank and the pressurant sphere, the Delta II's rocket nozzle is made of the metal columbium, which is mechanically weak but can withstand high temperatures. The ORSAT model showed the rocket nozzle being heated quickly, then cooling quickly and eventually falling to the ground at a speed of about 33 feet a second (compared to the impact speed of the heavier tanks, 260 feet a second). As the nozzle approached the ground, it was already at air temperature. "Our research has shown that the material does survive reentry," wrote Johnson in a NASA report, "and that it 'floats' down, landing approximately 30 minutes after the steel tank impact and 500–600 kilometers uprange."

AP/WIDE WORLD PHOTOS

Authorities in northwestern Canada had the unpleasant task of gathering radioactive debris from Kosmos 954, a Soviet nuclear-powered satellite that broke apart during reentry on January 24, 1978.

What about the piece of mesh that hit Lottie Williams: Had it also been shed from a Delta II? Williams has never loaned the object to NASA, but she did send a fragment to the Center for Orbital and Reentry Debris Studies, which concluded that its composition is consistent with Delta II insulation. Because the mesh has no identifying marks or numbers, though, it cannot be proven to have come from a particular rocket. Still, the "circumstantial evidence is highly convincing," says Johnson, who points out that the mesh's location and time of landing are consistent with the 1997 Delta II reentry.

When an object reenters the atmosphere and breaks up, the debris is scattered along a field, or footprint, with lighter fragments landing near the "heel" of the footprint and heavier objects traveling farther downrange toward the "toe"; this explains why Williams' mesh floated down in Oklahoma, far uprange of the heavier pieces that plowed into Texas. The ballistics characteristics of the heavy pieces also ensure that they'll travel at a higher velocity—and reach the ground sooner—than the lighter pieces.

Lottie Williams wasn't happy with these results, however. "I was thinking I had something celestial," she told the *Tulsa World* reporter. "And here I got something man-made."

The ORSAT model can accurately predict entry heat loads on falling objects because it factors in the actual processes at work. In contrast, the idea that air friction is the cause of reentry heat is persistent but misleading.

Atmospheric entry heating of man-made objects was first noted in 1944, when Nazi Germany's V-2 rocket warheads hit the atmosphere over London at about 6,000 mph. As they reentered, compression-induced shock waves heated the air ahead of the plunging warheads enough to prematurely detonate the explosives inside. German engineers solved the problem by lining the warheads with plywood to serve as a heat shield.

But after the Bell X-1 rocketplane made its sound-barrier-breaking flight on October 14, 1947, confusion began to set in about atmospheric heating. The X-1 and other high-speed aircraft, such as the North American X-15, which first flew in 1959, faced severe thermal environments. Supersonic air rubbing across the aircraft's outer skins created frictional heating, which had to be endured or actively cooled. And from then on, the notion of atmospheric heating was indelibly linked with air friction in media explanations and thus in the public mind.

But air friction has little to do with the process that heats objects entering Earth's atmosphere. The key source of the heating is compression: Air molecules in front of an incoming object can't move out of the way fast enough, so they pile up, or compress, which makes them very hot. The air molecules get "aggravated," as the late Max Faget liked to say when he explained how he invented the heat shield for the spacecraft of NASA's Mercury manned space program. Or as space engineer Jim Davis says: "This is due to the spacecraft performing work on the atmosphere like a piston in a cylinder."

The air molecules caught up in the shock wave created by the incoming object can heat up to 11,000 degrees Fahrenheit, as hot as the surface of the sun. This heat reaches the reentering object mainly by conduction, as the superheated air molecules repeatedly strike its surface. At higher reentry speeds—say, when the U.S. Apollo manned space capsules returned from the moon at 25,000 mph—the compression-induced shock wave becomes so hot that it transfers much of its heat into the reentering object through direct thermal radiation. And at the speeds at which meteors hit Earth's atmosphere, up to 150,000 mph, nearly all of the heat transfer is through radiation.

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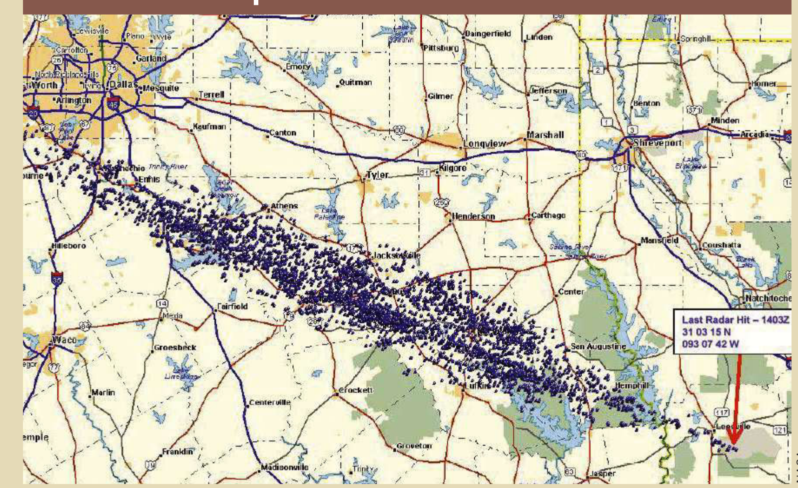
Just as computer models of reentry dynamics predicted, after Columbia *broke apart, its flight data recorder (left) came down on a hillside in the eastern Texas town of Hemphill.*

Space Shuttle Debris Field



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Understanding how objects break up and scatter in the atmosphere is a relatively new science for NASA, but one with a wide range of applications. During space shuttle launches, for example, the external fuel tank, which weighs 44 tons empty, hits the atmosphere an hour or so after launch and breaks apart, with metal fragments scattering along a footprint in the Atlantic Ocean. Mission planners must place the entire footprint in a region that sees little commercial sea and air traffic, and for some launches, planners had difficulty finding a big enough dumping ground. But then a Lockheed Martin computer analysis showed that the external tank was breaking up at a substantially lower altitude than first estimated and the pieces were scattering over a correspondingly smaller area. Once the computer prediction was confirmed by direct observation, shuttle mission planners had more leeway in calculating where the remnants of the tank could plunge.

U.S. Forest Service workers (right) found the bulk of debris from Columbia *lying along a 260-mile swath beginning near Fort Worth, Texas, and extending across the border into Louisiana.*

Knowing what kinds of materials and structures are likely to survive entry and reach Earth intact also enables NASA to calculate more reliable probabilities of property damage and personal injury. In 2001, such calculations ended the mission of the Compton Gamma Ray Observatory when it was shown that the satellite's heavy structural materials presented a greater than 1-in-10,000 chance of harming property and people. The satellite had a gimpy control system, so instead of waiting for it to fail and leave ground controllers with no means of directing the craft's reentry, mission control dumped the satellite into the far southern Pacific Ocean while it was still controllable.

Following the 2003 *Columbia* disaster, the Center for Orbital and Reentry Debris Studies became involved in assessing the scatter pattern of fragments from the shuttle. On March 17, coincidentally just a day before *Columbia*'s flight data recorder was recovered, CORDS director William Ailor testified before a public hearing of the *Columbia* Accident Investigation Board in Houston. Because the *Columbia* accident investigators needed to know whether the damage they saw on recovered fragments resulted from events that happened earlier in the shuttle's flight (and that may have led to the disaster) or from the stresses endured during reentry, they were interested in learning how different materials react to entering Earth's atmosphere. The *Columbia* accident investigators also wanted a way to judge how thorough their search was by comparing the weight of recovered *Columbia* material to calculations of how much should have reached the ground.

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"For unprotected space hardware, the heating and loads will gradually tear it apart," Ailor explained to the investigators during the hearing. "The kinds of things that we've seen that survive reentry are things that you would probably guess might—things like steel sometimes, glass, titanium, and then parts that are sheltered by other parts. One

KSC/NASA

Forty percent of Columbia *has been found and shipped to Kennedy Space Center in Florida, where engineers reconstructed the remains in an attempt to understand the shuttle's fate.*

of the things about the reentry breakup process is that the heating is like, in a sense, cooking an onion. You basically start from the outside, and then as you heat the pieces up to a point where the materials will fail, that will expose some new materials. They'll go through the same process and the object can be broken apart. We do have objects that are melted and shedded away, things like aluminum [and] solar panels.

"For example, when an object comes off of a parent body, it now experiences the air stream that exists there, and it will respond based on its own characteristics. If you've got a very lightweight piece that comes off of a heavier object that's coming through the atmosphere, it's like throwing a piece of paper out of a car. That will decelerate very quickly, and the same things happen even at Mach 20."

Ailor went on to explain how timing and release conditions can affect survivability, both of particular significance in the hunt for *Columbia* debris. "If an object comes out late in the reentry, after being shielded for a portion of the reentry, that means a lot of the energy has been taken out of that trajectory prior to that object's release, and that object is more likely to survive," he said. This shielding effect explains why *Columbia* searchers found documents, videotape, cloth patches, and astronaut remains among the items that made it to the ground.

Ailor estimated that anywhere from 10 to 40 percent of a space object would actually survive reentry. The odds of its being found, however, are much lower, even with the models that CORDS has developed.

Careful study of the debris field from the *Columbia* accident helped improve the odds of success in that search. As truckload after truckload of debris was gathered, NASA engineers began to hope they could find particular pieces. "We did analyze some specific components," says Nicholas Johnson. "Most already had been found, and we were asked to go back and use our models to look at those locations. We had very close agreement."

Insights from such computer simulations and a reconstruction of the moments of *Columbia*'s breakup enabled accident investigators to take the next step. With the Orbiter Experiment Recorder still missing, but with pieces known to have been installed near it found, the region where it ought to have fallen was carefully plotted, leading to its recovery and its use to solve the more heartbreaking mystery of what destroyed the space shuttle.