
Recovery of the Space Shuttle *Columbia* Avionics

Investigation, Analysis, and Lessons Learned

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Loss of the Space Shuttle *Columbia*



- On February 1st, 2003, the Space Shuttle *Columbia* was tragically lost with its crew during reentry, 16 minutes before the planned landing at the Kennedy Space Center (NASA-KSC) in Florida.
- Telemetry received from *Columbia* was inconclusive in determining the cause of the accident.
- Telemetry did indicate that anomalous conditions existed in the left wing of *Columbia* prior to its loss.

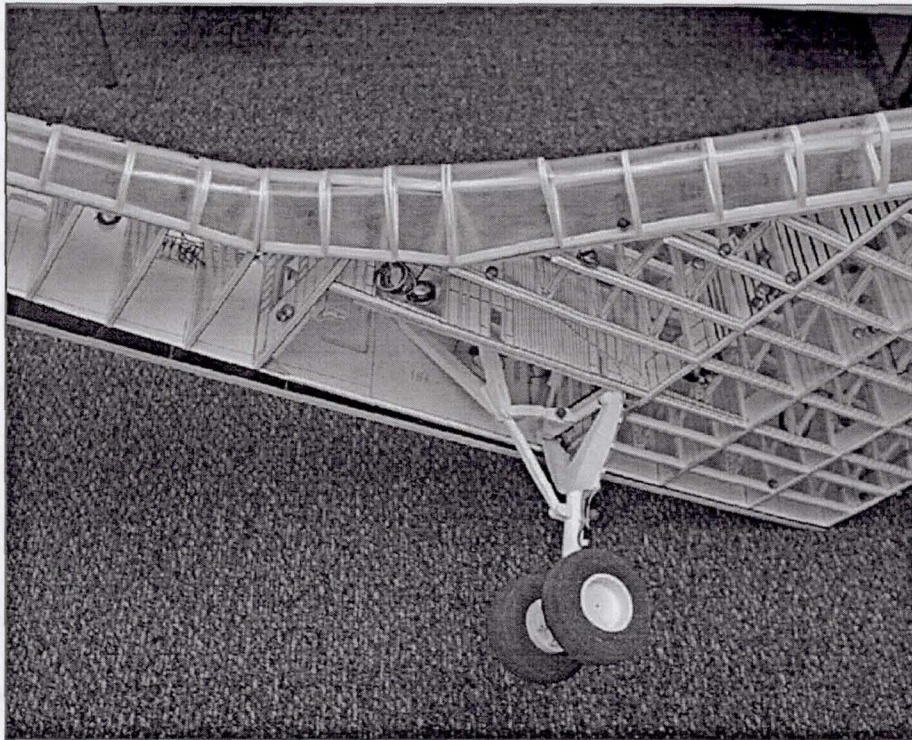


Accident Investigation



- Multiple hypotheses emerged that attempted to explain the data in the telemetry that was received prior to loss of communications with *Columbia*.
- Videos indicated that foam from the external tank had become detached and impacted on the left wing of *Columbia* during launch, but data from the telemetry could not verify that this was a contributing factor.

On-Board Data



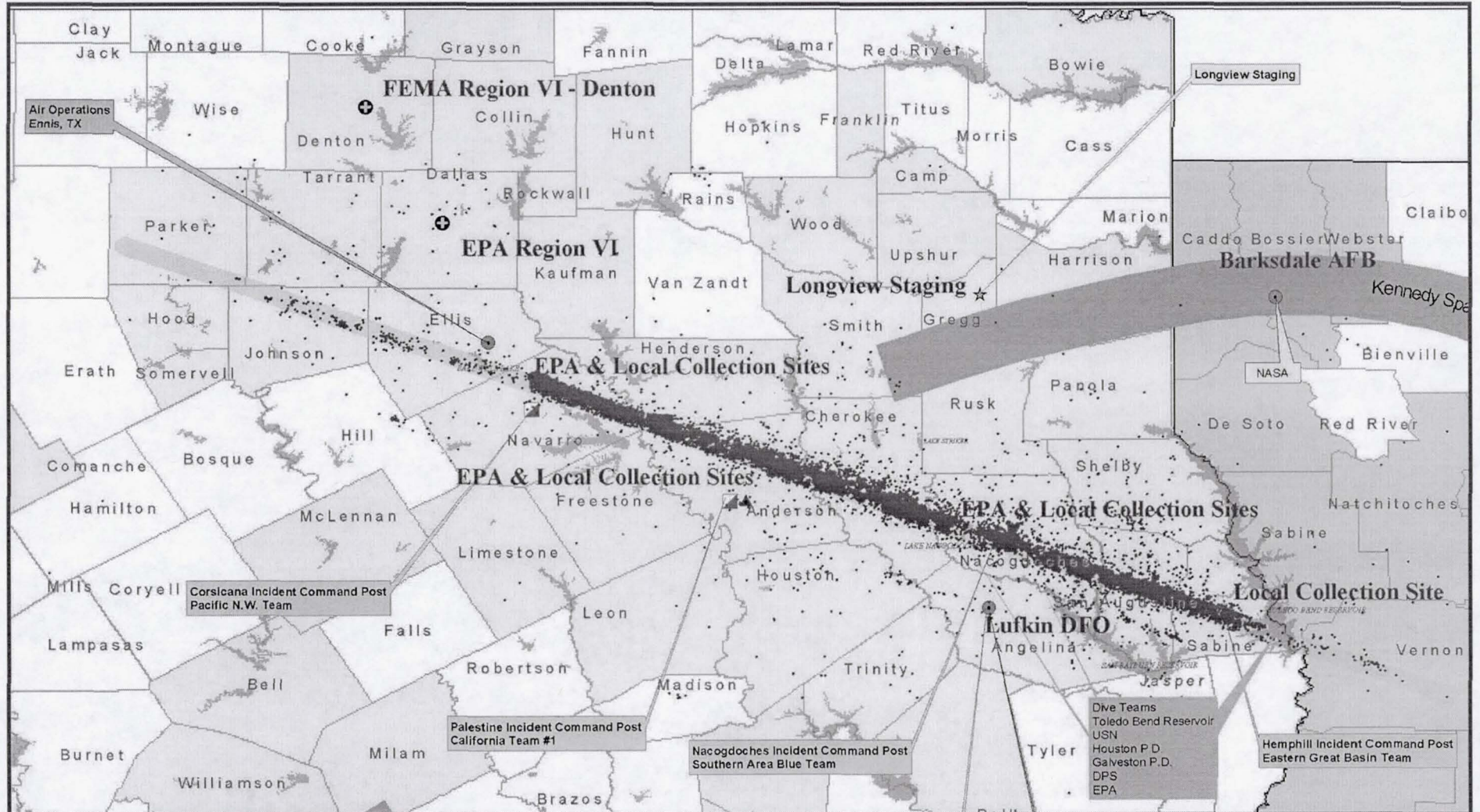
- Data stored in some avionics units were considered critical in helping determine what happened to the left wing, and hence the root cause of the accident:
 - precise time of power loss (after loss of telemetry).
 - sensor data (temperature, acceleration, vibration, etc.) from the left wing not included in the telemetry.
- Locating and recovering these avionics units became a priority for the search teams.

Debris Recovery



- Debris recovery from Columbia took months. Most of the debris was recovered in an area 10 miles wide and 220 miles long.
- Searchers recovered approximately 70,000 items; 37% of *Columbia* by weight.
- Approximately 25,000 people took part in the recovery operation, including more than 130 government agencies, 270 business and volunteer organizations, and numerous private individuals.

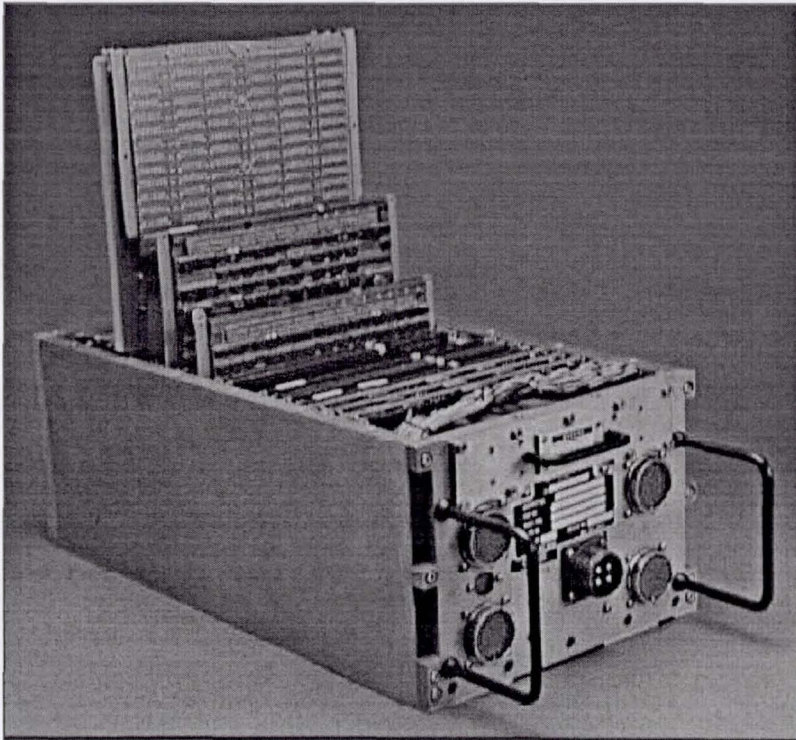
Search Area (FEMA map)



- Blue dots indicate locations where debris was found



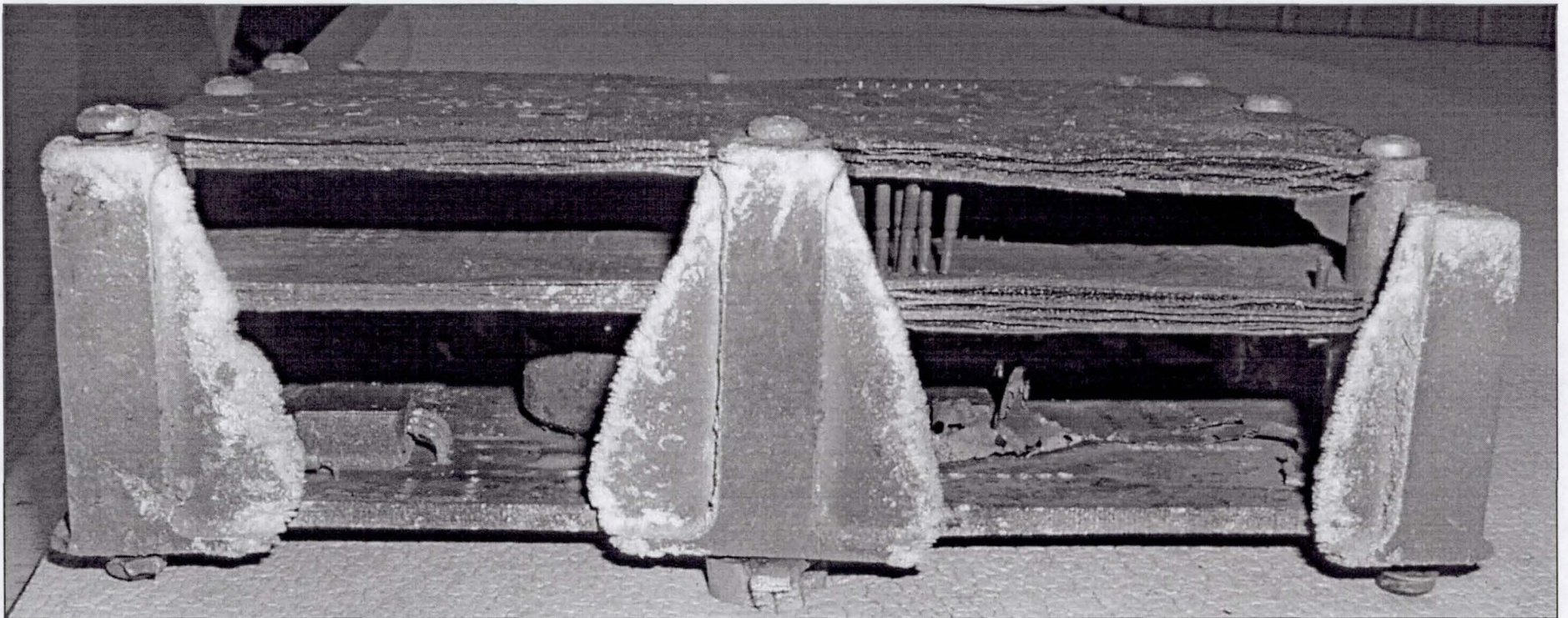
Recovery of *Columbia's* Avionics



- *Columbia's* avionics were subjected to extreme levels of temperature, shock, and vibration during breakup of the Orbiter.
- Unknown factors contributed to the survival of any particular avionics unit; some units survived relatively intact (e.g. MAGR, OEX Tape Recorder), while others were destroyed (e.g. GPC, MEDS ADC).
- Two important units that survived will be examined in detail:
 - Military Airborne GPS Receiver (MAGR)
 - Orbiter Experiments (OEX) Tape Recorder



Recovered Avionics: MEDS ADC



Military Airborne GPS Receiver (MAGR)



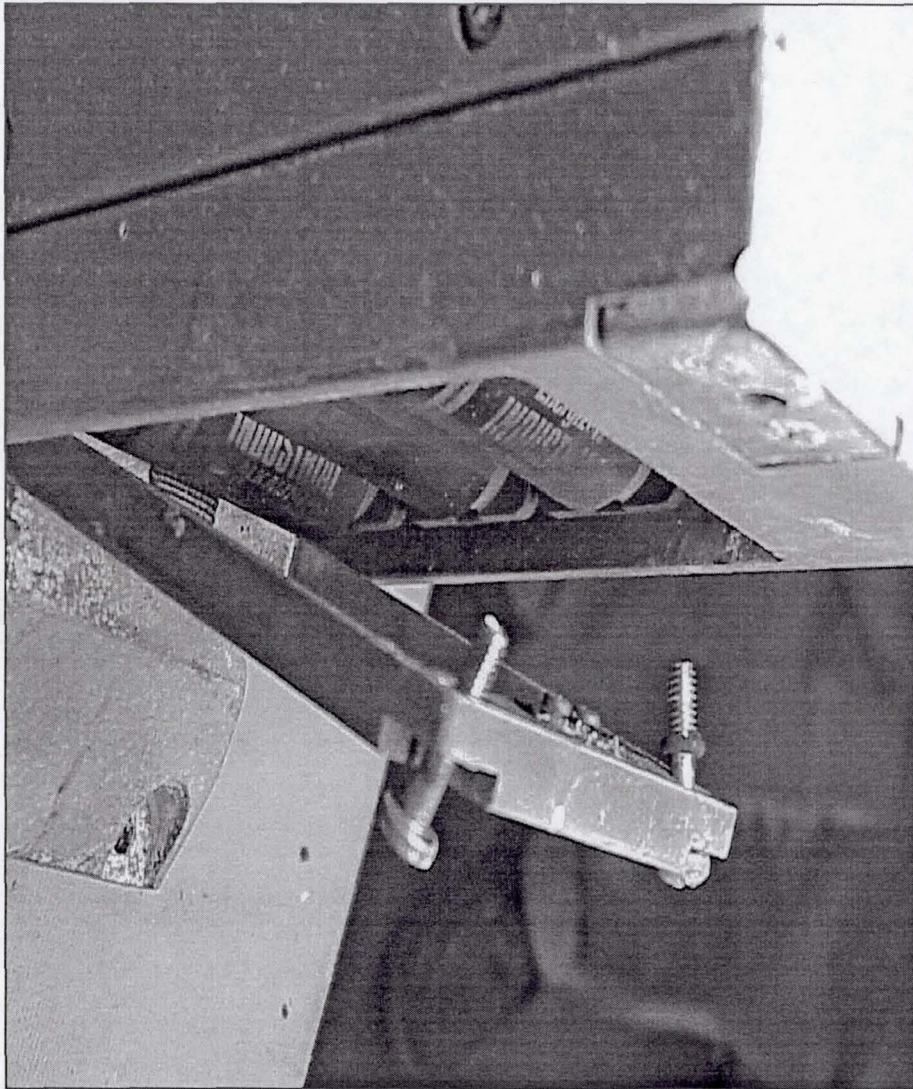
- The MAGR is a modified GPS receiver, built by Rockwell Collins, that is also used on a number of U.S. military aircraft.
- The MAGR provides position information to the Orbiter's General Purpose Computers that is used for navigation.
- MAGR's have flown 28 flights since 1996 before becoming certified for full operational use in September 2002.
- Each Orbiter (including *Columbia*) has one MAGR.

Recovery of the MAGR S/N 11



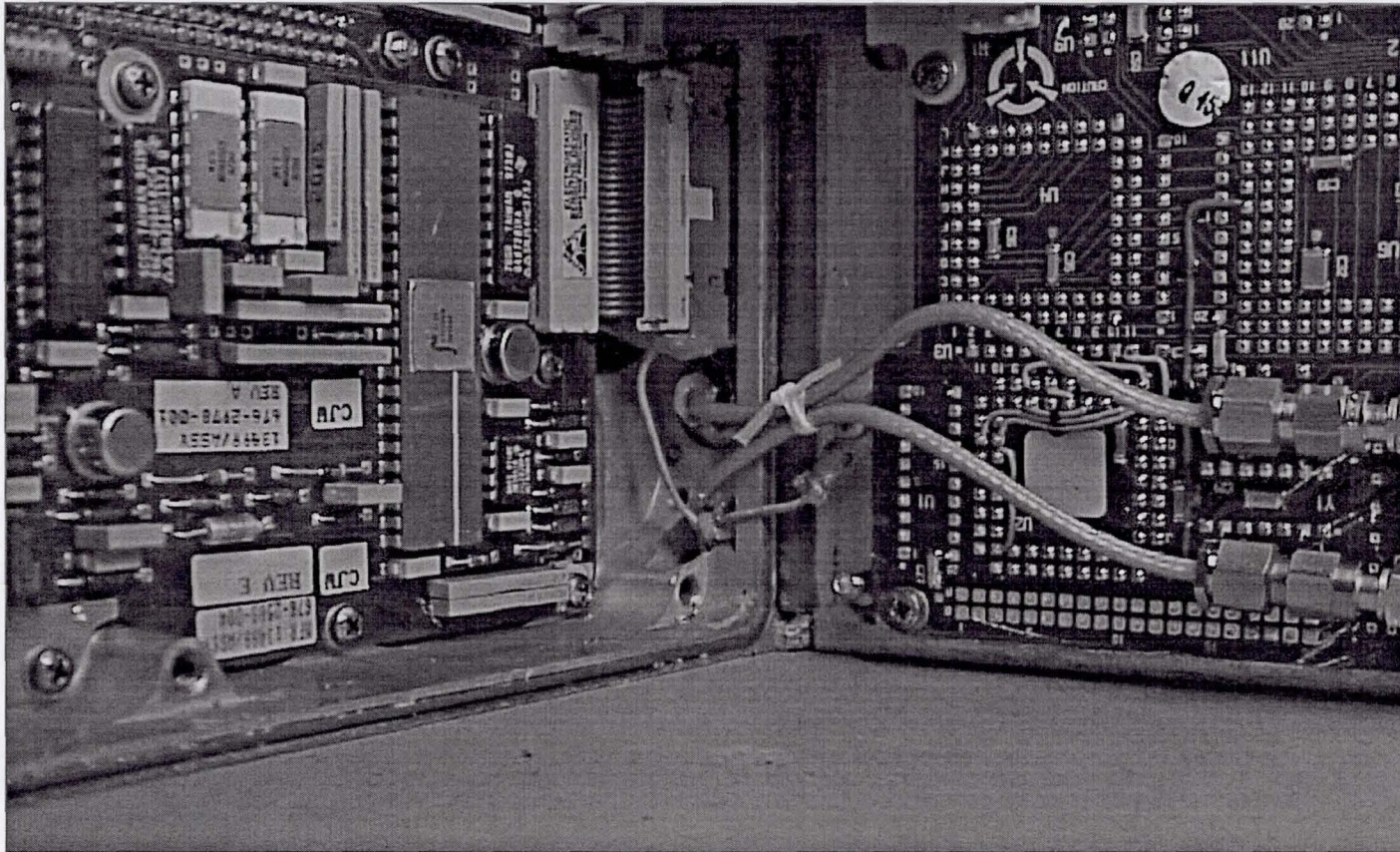
- S/N 11 was found about 350 yards from the Texas shore of the Toledo Bend Reservoir on February 28, 2003.
- It was sent to its manufacturer, Rockwell Collins, to determine if data could be retrieved from its battery-backed RAM.
- Data from the MAGR's memory could confirm the time when the MAGR lost power.

Recovery of the Data from the MAGR



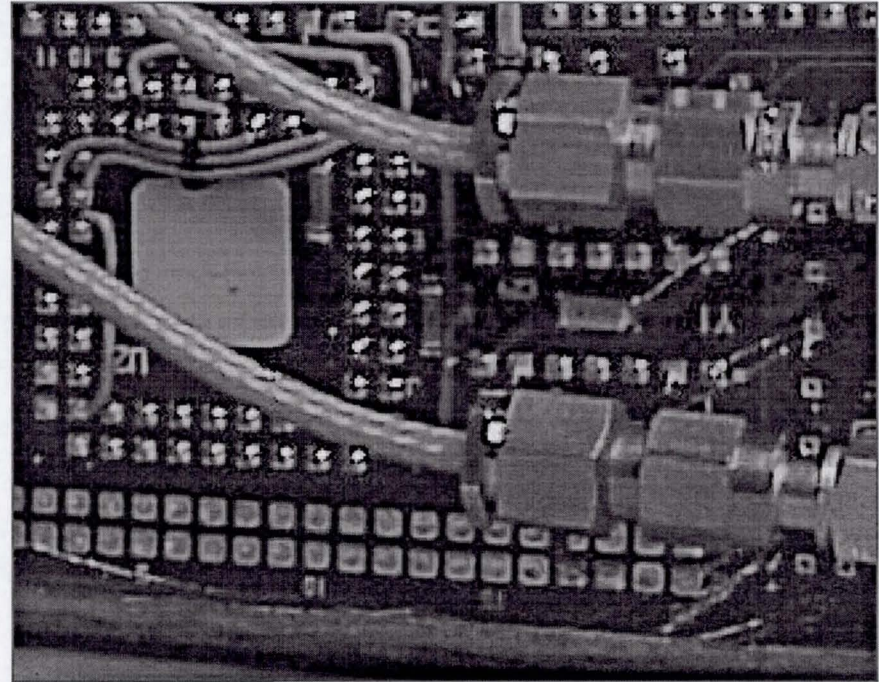
- Evidence of thermal damage and solder re-flow was present on some of S/N 11's circuit cards.
- The card containing the battery-backed RAM was mounted in the innermost portion of the MAGR chassis and did not show any evidence of heat damage.
- It was quickly determined that the batteries (three C-cells) were still good and that the RAM had sufficient voltage to retain data.
- The MAGR was left on internal battery power; connecting an external power source before memory contents could be extracted was deemed too risky.

Recovery of the Data from the MAGR (continued)



- Damaged MAGR circuit cards were replaced with good cards from another MAGR.
- Internal processors were halted to prevent inadvertent overwrite of the memory.
- Data was extracted directly from memory via a bus monitor.

Processing of MAGR Data



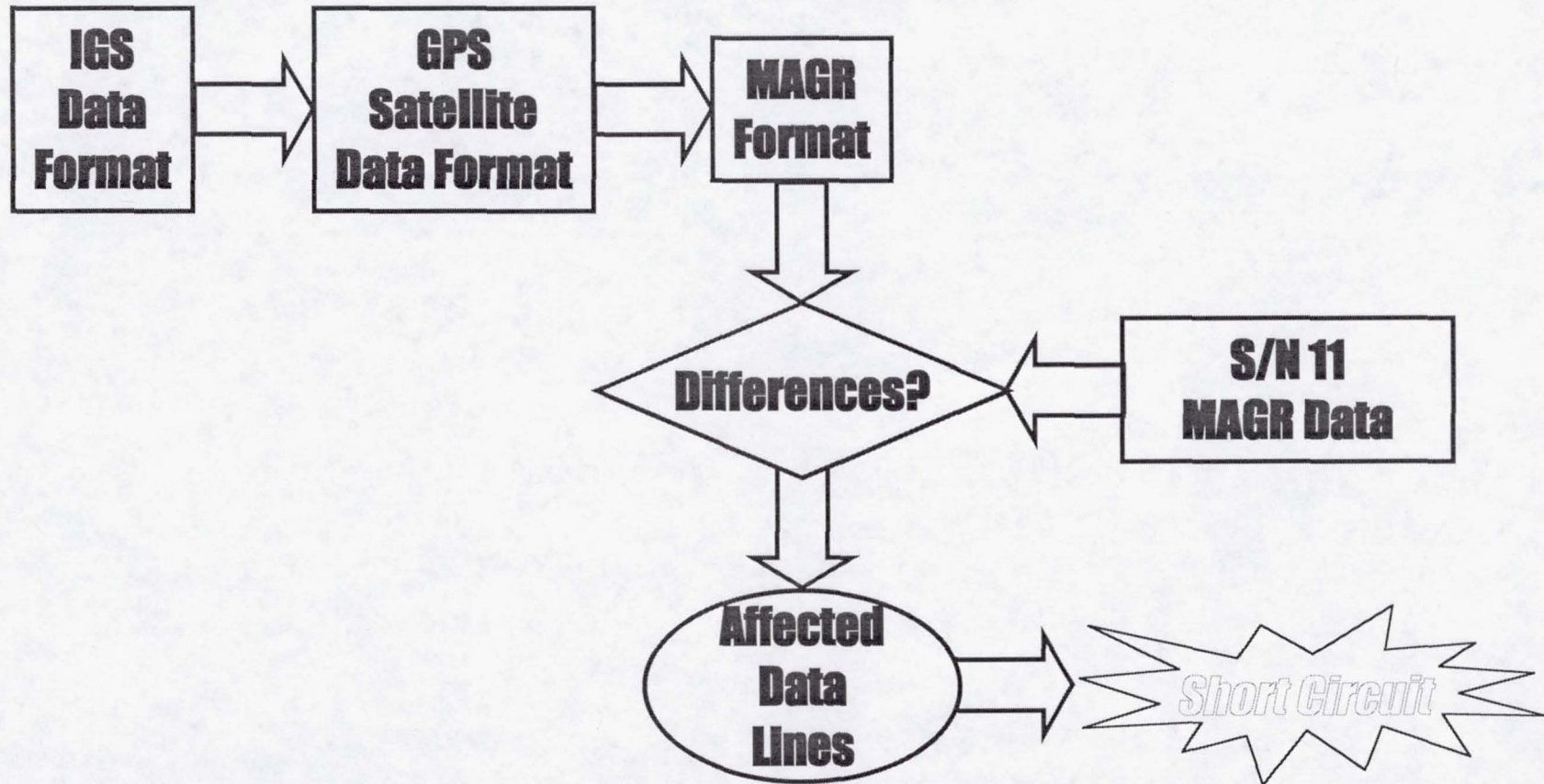
- Data from the MAGR was checked against expected data values; although overall quality was good, some time and position values, though of valid format, were considered suspect.
- Further examination of the data at the binary level revealed that flipping some bits would change the data to a value that was more in line with expected values.
- In order to determine exactly which bits should be flipped, comparisons were made with reliable ground data.

Finding the Bad Bits

- GPS satellites continuously broadcast *almanac* and *ephemeris* data in addition to time code.
- This data has been recorded by many ground stations as part of the International GPS Service (IGS) project, which uses GPS data for non-navigational purposes (e.g. measurement of plate tectonics, ionosphere monitoring, etc.).
- By comparing, bit by bit, almanac and ephemeris data recorded at ground stations with data stored in the MAGR's memory, engineers were able to determine that two data lines were the source of all suspect bits, and that these lines were most likely shorted together.
- Examining the MAGR's memory card more closely, a short circuit, caused by solder splash, was discovered between these lines.
 - Previous examinations of the MAGR's memory card were limited by the potential for inadvertently affecting the MAGR's memory contents as a result of the examination.
- Removal of the short circuit and re-reading the memory showed immediate correction of all of suspect bits.



Data Comparison Technique

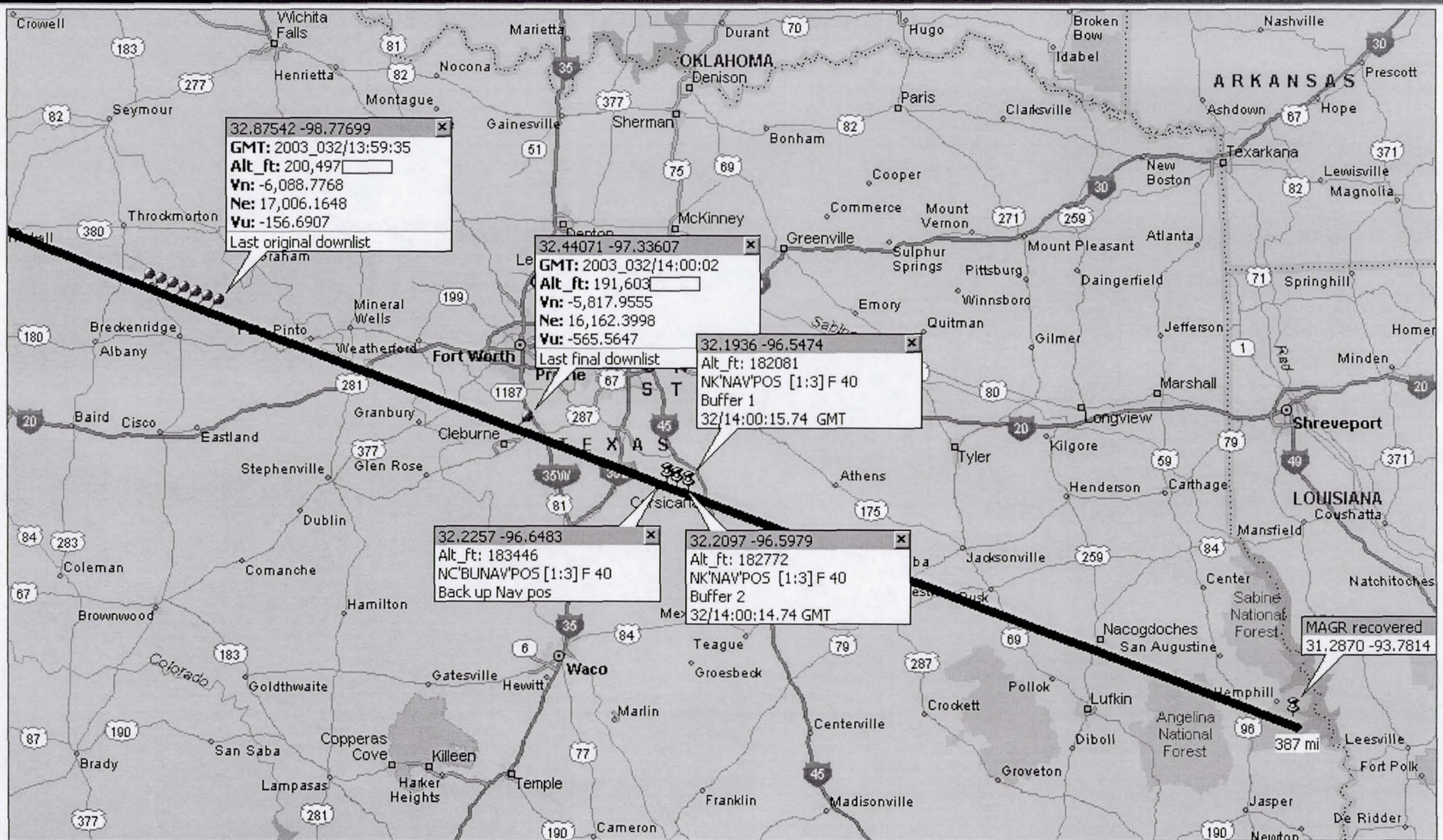


Use of Recovered MAGR Data

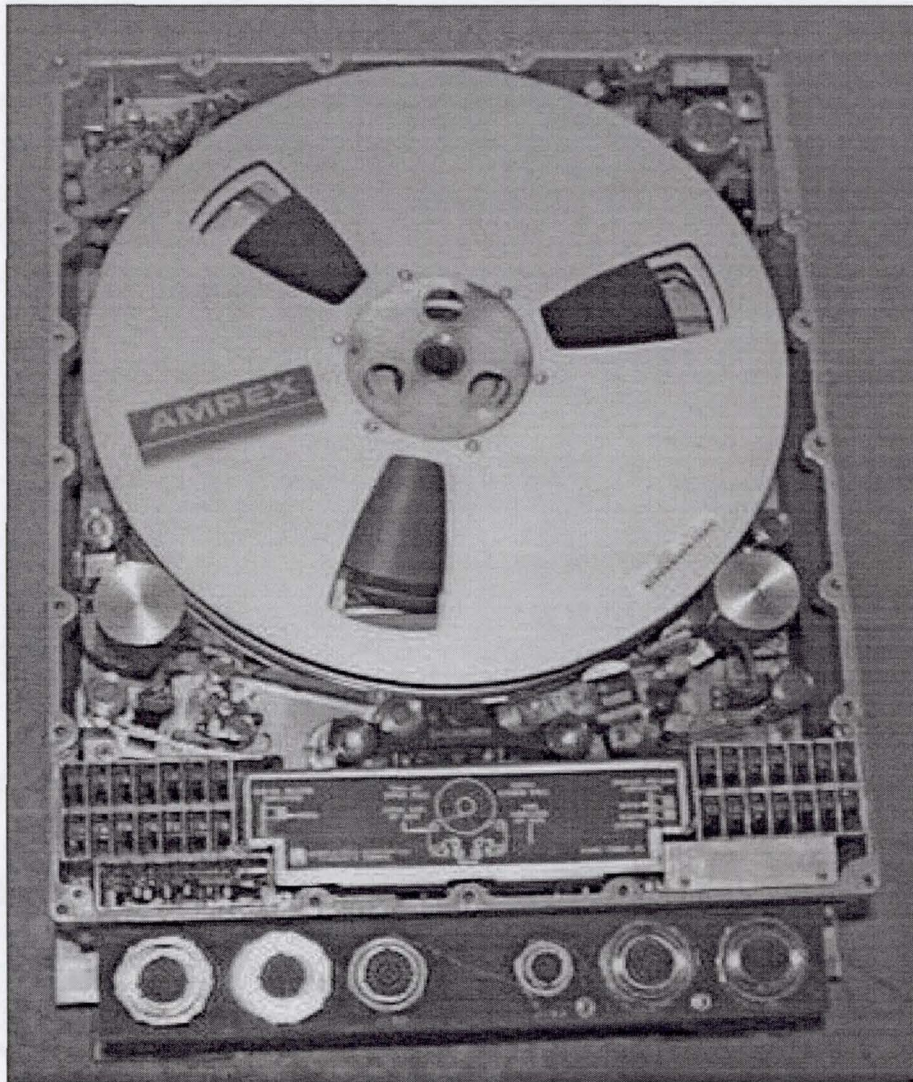


- High-resolution time code data from the MAGR was used to determine when the receiver lost power, which in turn gave investigators insight on the degradation of *Columbia's* physical condition.

MAGR Time & Trajectory Data

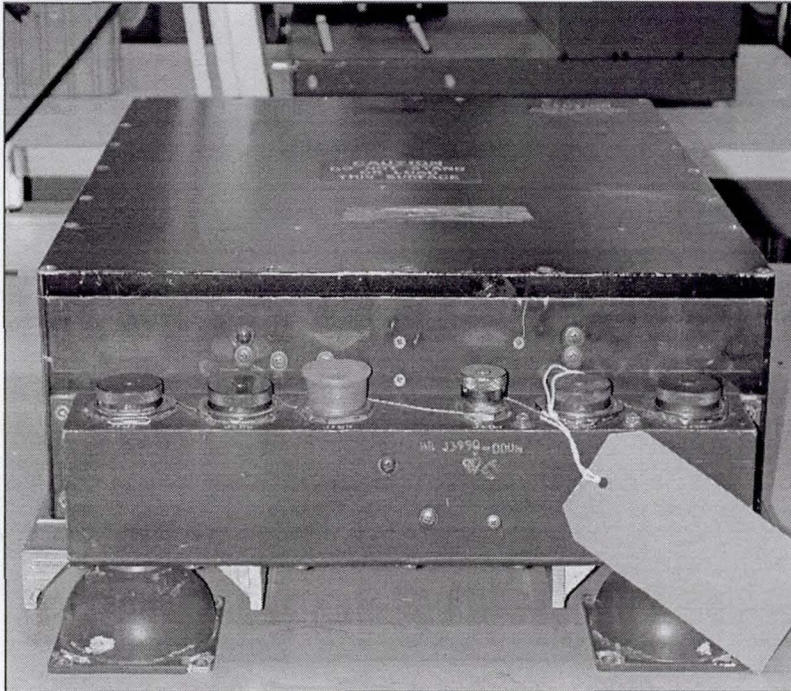


Orbiter Experiments (OEX) Tape Recorder

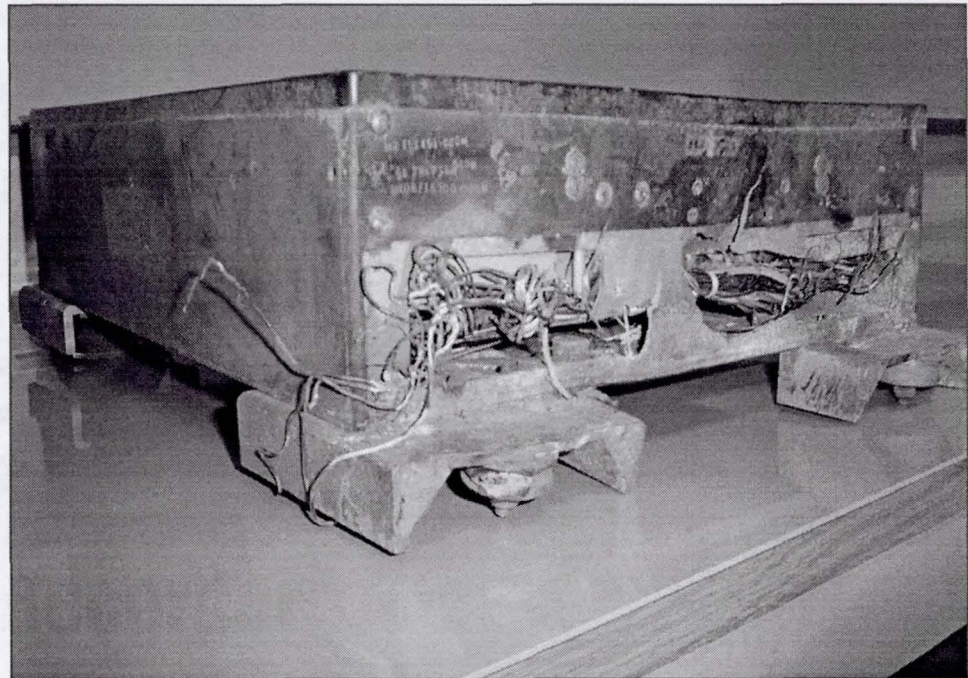


- Modified Bell & Howell MARS instrumentation recorder, introduced in 1966.
 - *Columbia's* unit, S/N 1001, was purchased in 1978.
- Records a variety of sensor data (temperature, strain gauge, accelerometer, etc.) from different Orbiter systems, predominantly main engines and structures.
- OEX is a remnant of flight test instrumentation that was flown on *Columbia's* first six missions.
- Comparable instrumentation is flown on all Orbiters, but *Columbia* had the greatest number of sensors.
- OEX data is not telemetered; it can only be retrieved post-landing.

Recovery of S/N 1001 OEX Recorder



BEFORE

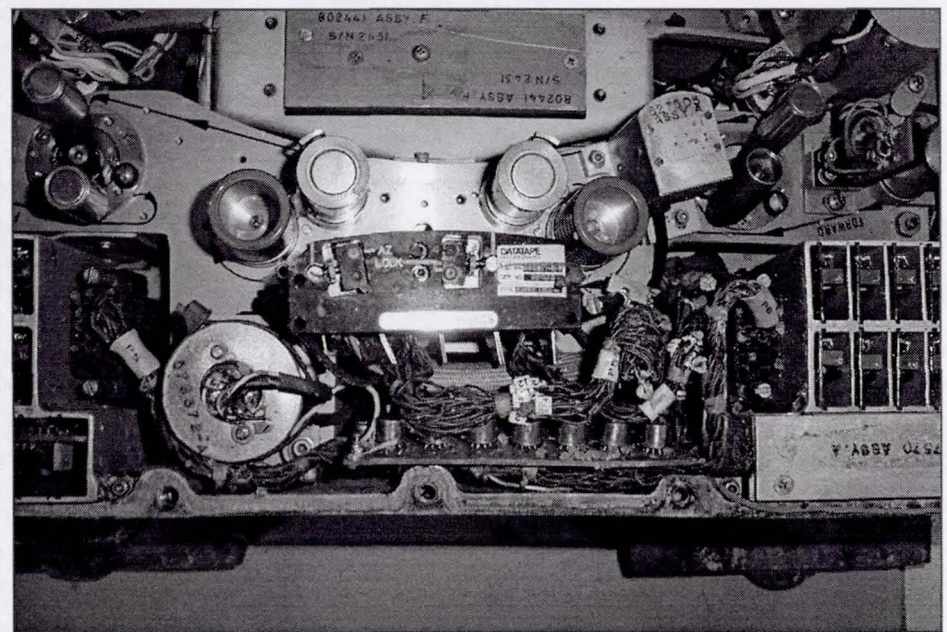
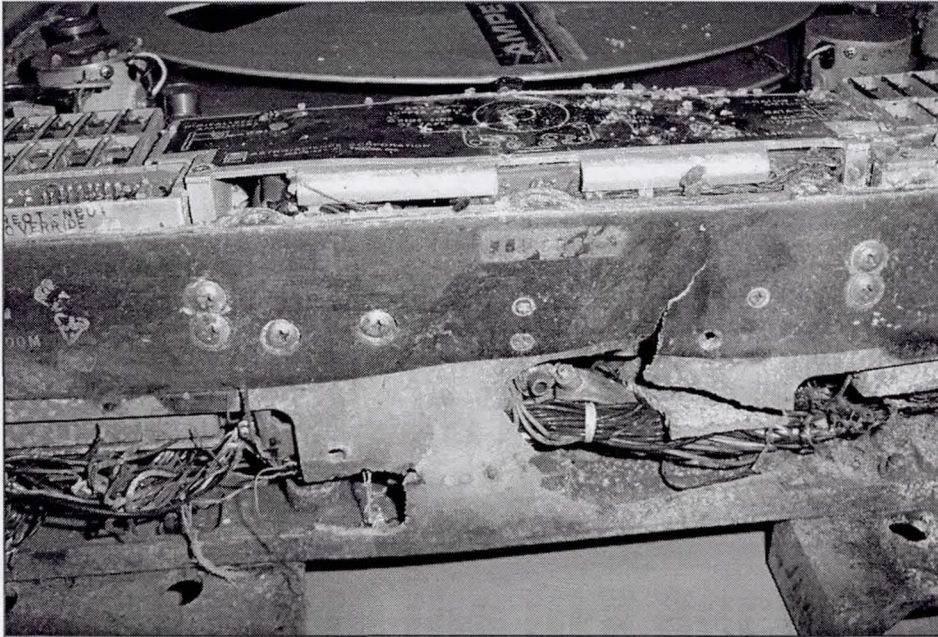


AFTER

- S/N 1001 was found near Hemphill, TX on March 14, 2003.
- It was immediately shipped to the Johnson Space Center (NASA-JSC) in Houston, TX for preliminary evaluation.
- Other than the loss of the front connector panel and some exposure to rain, the recorder appeared to be in good shape.
- It was then sent to Imation, Inc. in St. Paul, MN for removal and processing of the magnetic tape.

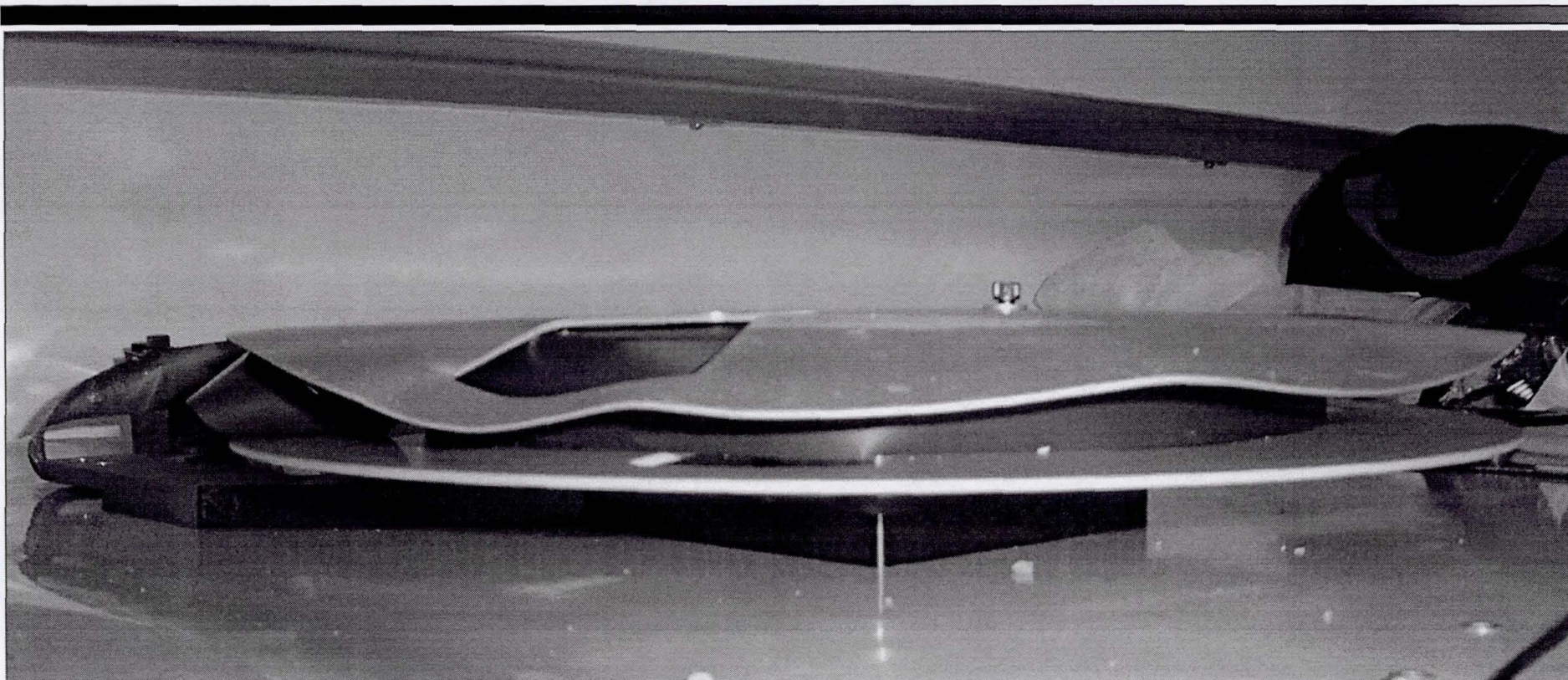


Damage to the OEX Recorder



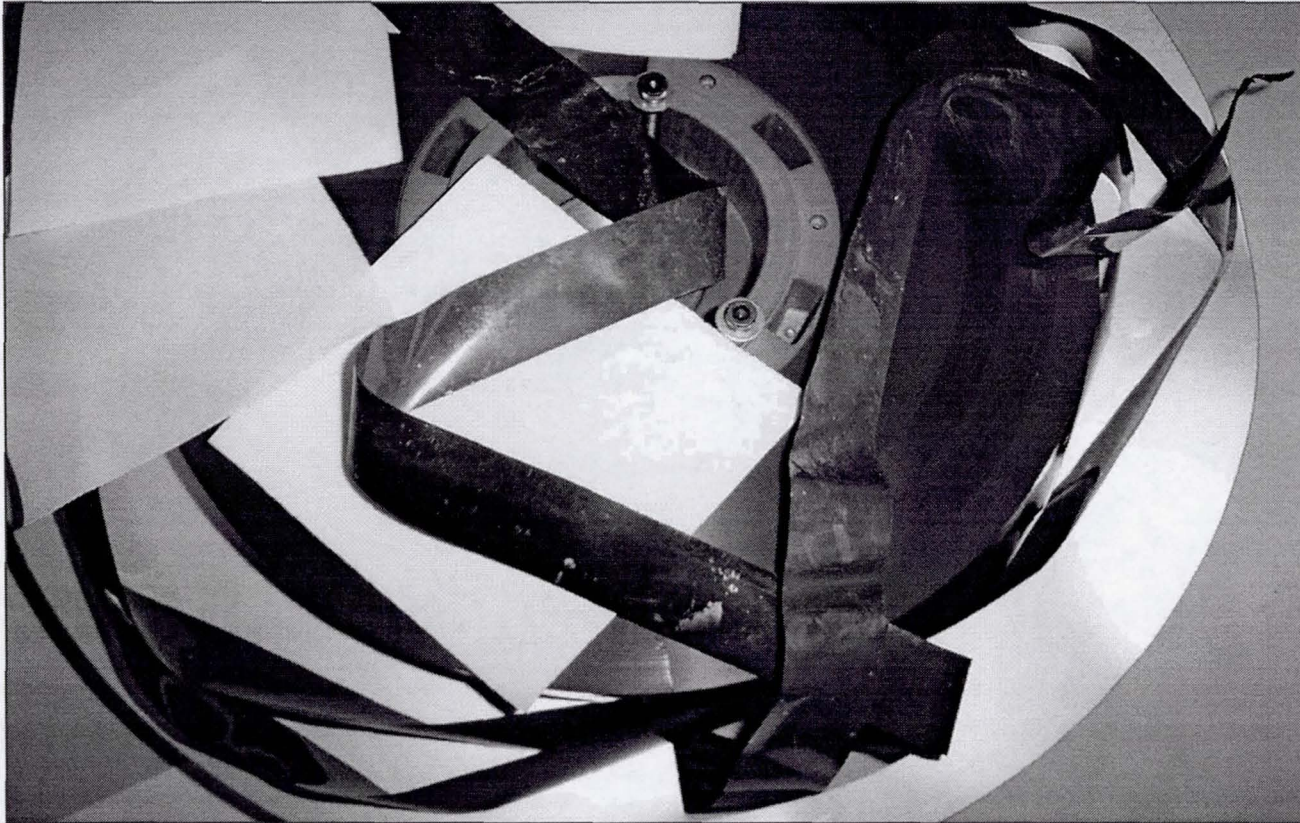
- After removal of the lid, the apparent lack of damage to the recorder was proven optimistic; many internal recorder components had been severely damaged.
- Separation of the front connector panel (which presumably stayed with the connected cables) allowed hot gases and debris to enter the chassis.
- The hot gases re-flowed solder off of circuit cards and wires, and melted some of the Kapton drive belts.
- Mechanical forces on both the top and the bottom of the recorder deformed portions of the chassis and many internal components, including the tape reels.

Mechanical Damage to the Magnetic Tape



- Pressure on the top of the recorder drove the chassis down to the limit of the shock mounts, and beyond.
- The recorder's lid deformed inward wherever there was free space in the chassis, which bent the tape reel over the tape itself.
- Pressure from the bottom drove components upward, sandwiching the tape reels between the two forces and severely damaging the reels and tape.

Temperature Damage To The Magnetic Tape

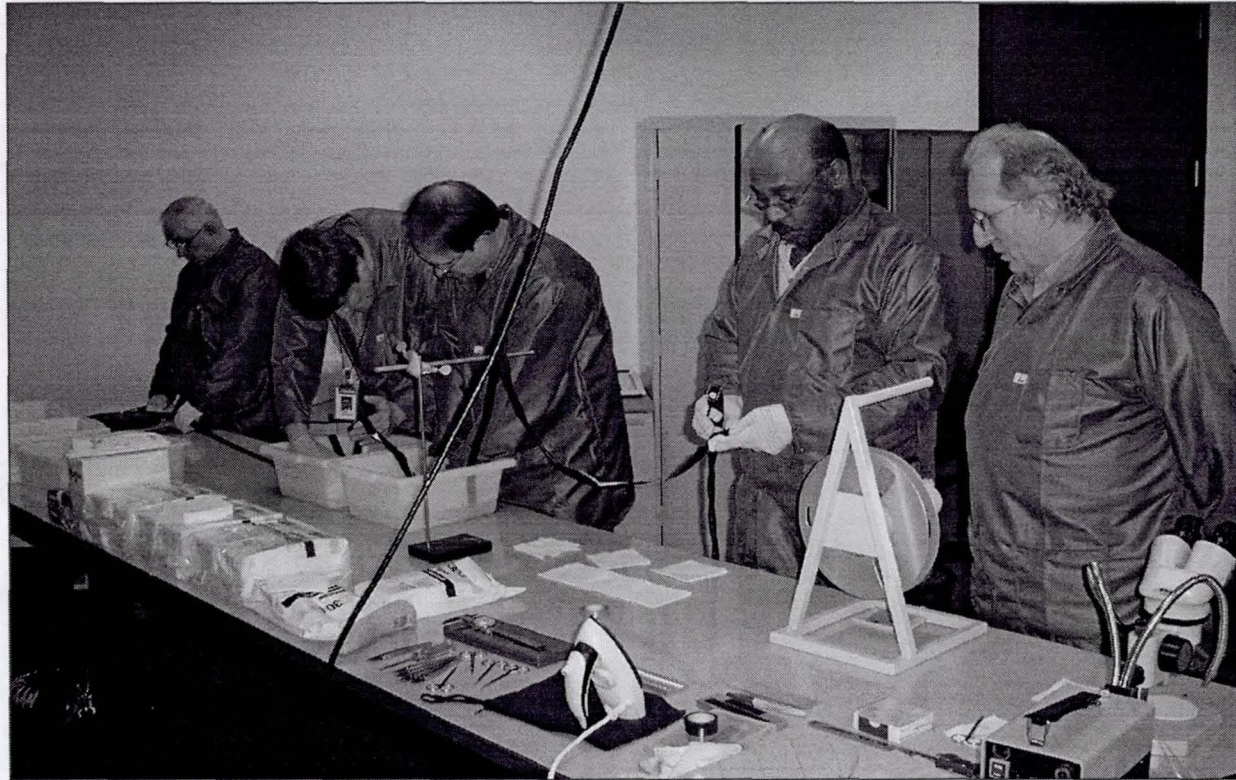


- Hot gases entering the chassis damaged and discolored the tape near the front of the recorder, eventually melting through the tape.
- The now-loose tape ends fluttered within the reel and folded back upon themselves multiple times.
- Tight packing on the rest of the tape reel spared it from much of the damage. Of the 4650 ft. of recorded tape (total length 9300 ft.), 241 ft exhibited heat and water damage.

Damage To The Magnetic Tape (close-up)



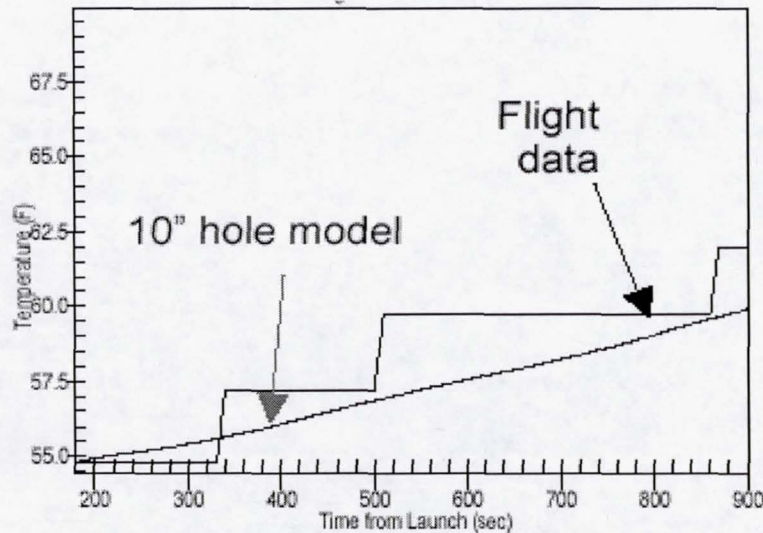
Processing The Magnetic Tape



- Small portions of the tape were coated in Fe_3O_4 colloid to visually reveal the magnetic data structure.
- The tape was then examined under a microscope to determine where recorded data ended. The tape cut past the end of recorded data.
- The tape was washed in two baths of de-ionized H_2O to remove debris.
- The tape was dried, repacked by hand on a reel, and spliced to a new tape.
- The tape was then shipped to NASA-KSC for playback.
- All flight data was successfully recovered from the tape

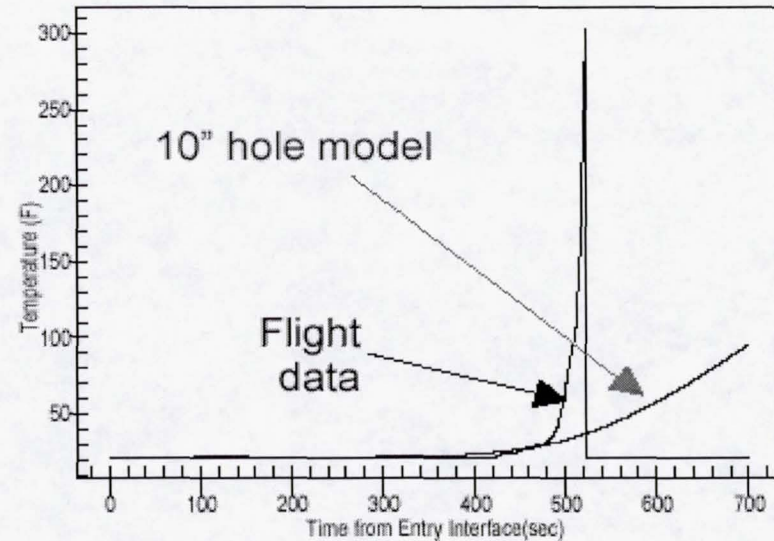
Data From the OEX Recorder

Spar Temperature
Ascent Heating



(CAIB/NAIT Working Scenario, 8 July 2003)

Spar Temperature
Entry Heating
Model includes 10% Sneak Flow

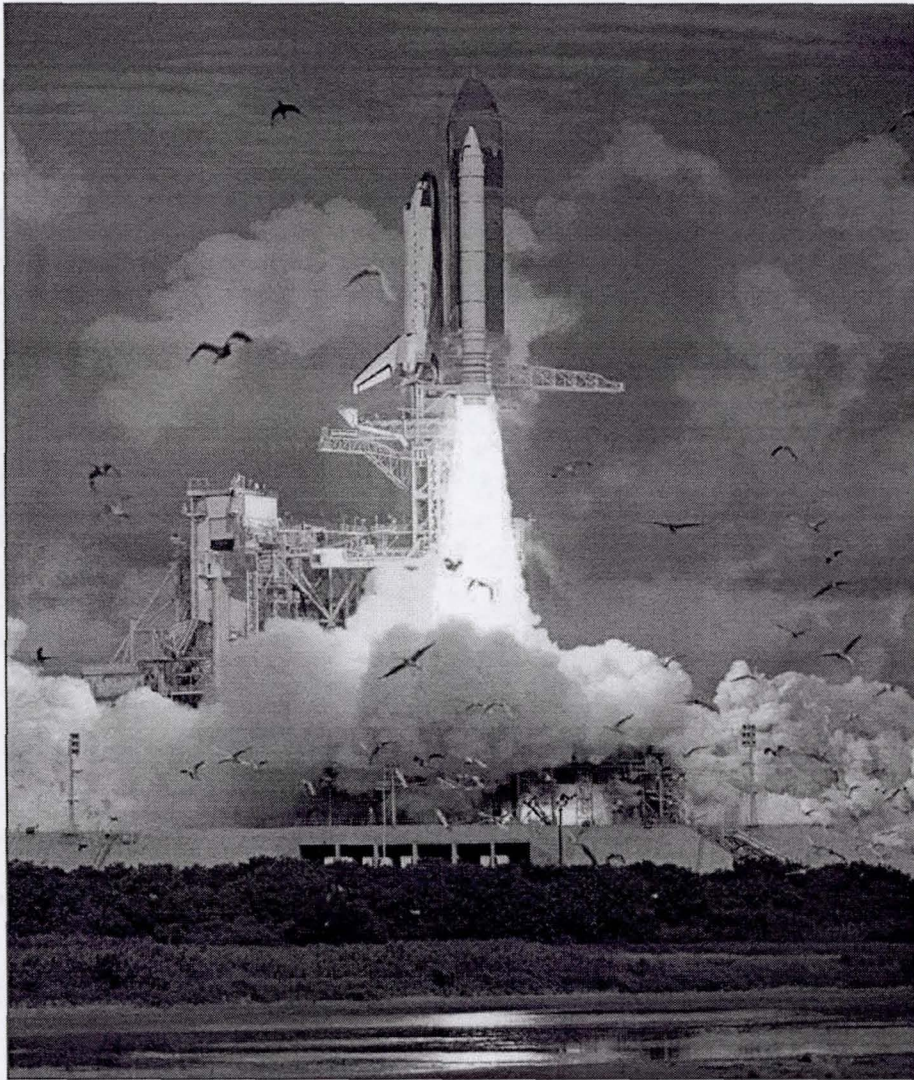


(CAIB/NAIT Working Scenario, 8 July 2003)

- Telemetry for the left wing comprises 11 different sensors.
- OEX data for the left wing comprises 143 different sensors.
- OEX launch accelerometer data detected an event in proximity to the RCC panel, close to the observed location of the foam impact.
- OEX landing data helped determine internal temperature increases in the wing, which were then correlated with foam impact test data and math modeling.



Lessons Learned

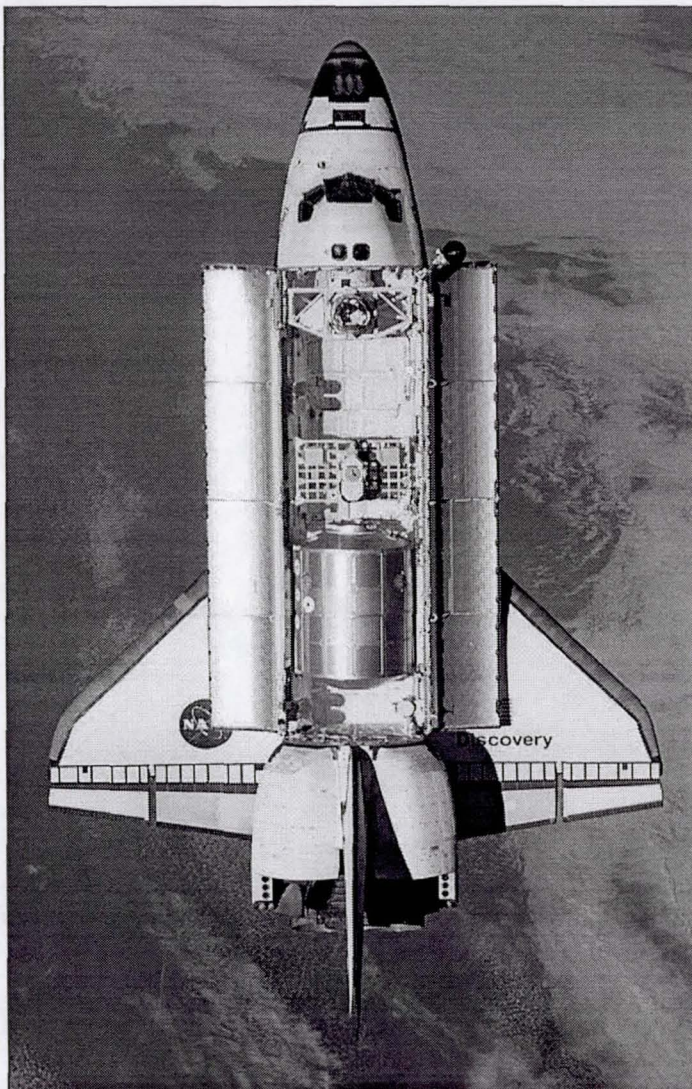


- Avionics data can play a critical role in the investigation of a “close call” or accident.
- Avionics designers should think about the role their systems might play in an investigation.
- Know your data, down to the bit level.
- Know your spacecraft - follow the data.
- Internal placement of circuit cards can affect their survivability.
- Think about how to reconstruct non-volatile memory (e.g. serialize IC’s, etc.)
- Use of external assets can aid in extracting data from avionics.

➔ **PLAY THE “WHAT IF” GAME CONTINUOUSLY**



The Future



- Quick-disconnect cables on avionics chassis to minimize structural damage (e.g. OEX recorder)?
- Put known patterns in memory to aid with data reconstruction (e.g. MAGR)?
- Near real-time spacecraft status displays?
- On-orbit playback for all data?
- Crash recorders for spacecraft?
- RF tracking of specific avionics units?

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Acknowledgements

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