P4.7 USE OF ARCHIVED WEATHER DATA FROM SPACEPORT FLORIDA IN SUPPORT OF SPACE SHUTTLE COLUMBIA ACCIDENT INVESTIGATION

Katherine A. Winters and William P. Roeder
45th Weather Squadron, Patrick Air Force Base, FL

John T. Madura
KSC Weather Office, Kennedy Space Center, FL

Harold C. Herring
Computer Science Raytheon, Cape Canaveral Air Force Station, FL

1. INTRODUCTION

Weather is a critical concern for Space Shuttle Operations. Weather sensitivities are well defined for every operation in which the vehicle is exposed to the environment. Due to these weather sensitivities, a large infrastructure of local weather sensors is used to support operations. Data from these weather sensors is continuously archived to aid in six applications: 1) investigation of operational accidents, 2) investigation of weather disasters, 3) creation of climatologies for mission planning, 4) vehicle design and concept of operations, 5) engineering studies, and 6) operational research for improved weather forecasting (Roeder and Harms, 2000). This paper discusses an example of the first item in this list: the use of archived data as an aid in the investigation of operational accidents, specifically the loss of the Space Shuttle Columbia, hereafter referred to as Space Transportation System (STS)-107.

NASA rolled STS-107 to the launch pad on December 9, 2002. On January 17, 2003, STS-107 launched successfully into orbit, but experienced a catastrophic failure during reentry to Earth on February 1, 2003. All seven crewmembers and STS-107 were lost.

This paper presents the process for consolidating archived weather data for the STS-107 accident investigation and includes the challenges created by an 8-day data gap at Spaceport Florida, which includes the U.S. Air Force Cape Canaveral Air Force Station and NASA's Kennedy Space Center (KSC). This paper will not cover the use of the data by the accident board and other investigating teams, but rather stresses the importance of properly archiving weather data for the most effective and efficient analyses.

2. BACKGROUND

The 45th Weather Squadron (45 WS), within the 45th Space Wing, is the U.S. Air Force unit providing comprehensive weather services to America's space program at Spaceport Florida (Boyd et al., 1993). Weather has a large impact on many aspects of space launch, including: launch operations, ground processing operations in preparation for launch, post-launch operations, various special missions, and routine 24/7 weather watch and warning responsibilities. The meteorological sensors used by 45 WS are perhaps the most unique and dense network of weather sensors in operational meteorology (Harms et al., 2003). These sensors are needed because of the unique weather requirements for space launch and the frequent hazardous mesoscale weather in east central Florida.

The 45 WS provides pre-launch, launch, and post-launch weather support to NASA's Space Shuttle program. This support includes launch processing such as orbiter rollover from the Orbital Processing Facility to the Vehicle Assembly Building, rollout of the Shuttle vehicle to the launch pad, launch operations including vehicle preparation and solid rocket booster recovery operations, and post-landing operations. Weather advisories, watches, and warnings are provided 24 hours a day for lightning, strong winds, severe weather, cold temperatures, and hail of any size. Another unique mission is the Space Shuttle Ferry Flight, which is considered aviation's most weather-sensitive flight operation (Priselac et al., 1997).

The Space Shuttle also has Flight Rules that apply only to that program and cover the time between clearing the launch tower and wheels stopping on landing. These Flight Rules are evaluated and forecast by the National Weather Service Spaceflight Meteorology Group (SMG), located at Johnson Space Center in Houston, Texas (Brody, 1997). SMG provides weather support for Shuttle landings including weather on launch day for Transoceanic Abort Landing sites, Continental U.S. (CONUS) landing sites, and the KSC Shuttle Landing Facility (SLF); and weather on day of landing for KSC, Northrop Field, and Edwards Air Force Base, the primary CONUS landing sites. The 45 WS and SMG work cooperatively on launch and landing days to ensure consistency between forecasts for KSC.

3. LOCAL WEATHER DATA

The 45 WS collects data from a large network of local weather sensors to conduct their weather support mission (Harms et al., 1998). Figure 1 displays the geographical distribution of most of these weather sensors, and Table 1 lists most of the weather systems. The Range Technical Services Contractor, Computer Science-Raytheon (CSR), archives this data (CSR, 2003), and Marshall Spaceflight Center (MSFC) Environments Group also archives KSC data. Additionally, InDyne Inc., contracted by NASA, archives Spaceport Florida meteorological data in support of the

Corresponding Author: Katherine Winters, 45 WS/DOR, 1201 Edward H. White II St., MS 7302, Patrick AFB, FL 32925-3238, katherine.winters@patrick.af.mil

Tropical Rainfall Measurement Mission, and provides the data via the World Wide Web.

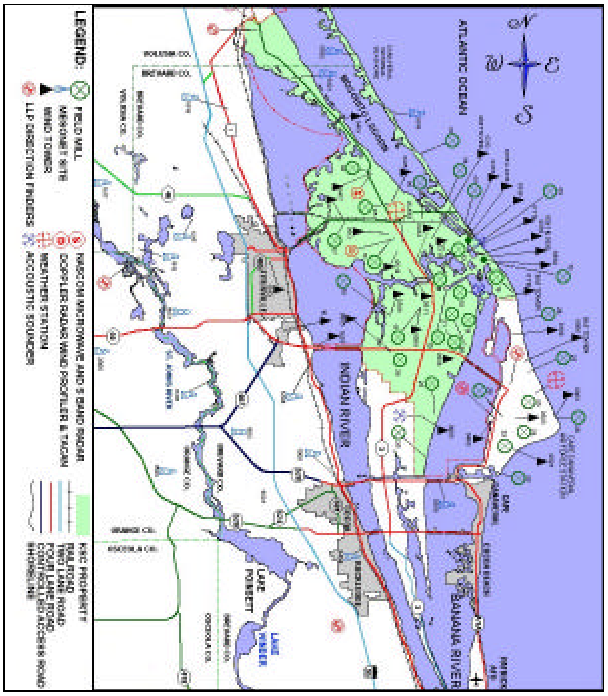

Figure 1. Locations of most Spaceport Florida weather sensors.

4. EXAMPLE OF USE OF ARCHIVED DATA: STS-107 ACCIDENT

On February 1, 2003, STS-107 was lost during re-entry. Upon notification of the accident, the 45 WS immediately began their “Catastrophic Failure” checklist, which included saving all Spaceport Florida meteorological data. Launch data was also collected. This massive volume of data was consolidated and quarantined for the accident board. The data was also duplicated to allow data analysis without contaminating the quarantined data. In the days following the accident, the 45 WS, KSC Weather Office, MSFC Natural Environments Group, and SMG began reviewing pre-launch and launch data for the entire time the vehicle was exposed (MSFC Environments Group, 2003).

As a result of the accident, NASA began a major investigation to examine the data across all disciplines and determine if any data was unusual, or ’out-of-family‘, compared to the other missions. Debris collection for STS-107 also began immediately and provided clues to investigators concerning the cause of the accident.

Since SMG provides weather support for flight and landing, they began a detailed analysis of the re-entry environment. Results of the analyses are available at Oram and Garner (2003).

TABLE 1. Local weather sensors archived at Spaceport Florida (Roeder et al., 2003).

Sensor	**No.**	**Frequency of Archive***	**Comments**
Weather Towers (includes towers at Shuttle Launch Pads)	44	5-minute and 1-minute	30 x 40 Km Area, 2 to 150 m, Wind, Temperature, Humidity
915 MHz DRWP/RASS	5	15-minute	Wind (0.12-3 Km), 5 Min Virtual Temperature (0.12-2.5 Km), 15 Min
Mini-Sodars	8	15-minute	Wind (15m-150 m, every 5 m), 1 min
Rain Gauges (tipping bucket)	33	Time recorded every .01 in.	Most collocated at field mill sites (see LPLWS)
Automated Meteo. Profiling System (AMPS) (Low-Res)	1	All	GPS-tracked RAOB (asynoptic times)
Automated Meteo. Profiling System (High-Res)	1	All	GPS-tracked Jimsphere (high precision wind balloon, countdowns only)
50 MHz DRWP	1	5-minute	Winds (2.0-19.0 Km), 112 Gates (150 m spacing), 5 Min refresh rate
Lightning Detection And Ranging (LDAR)	7	1-minute	Detects all lightning types, Depicts 3-D structure
Launch Pad Lightning Warning System (LPLWS)	31	5-minute	Surface electric field @ 50 samples/sec; Detects all lightning types (poor location accuracy)
Cloud to Ground Lightning Surveillance System (CGLSS)	6	All strikes	Improved Accuracy with Combined Technology sensors (includes time of arrival and direction finding sensors)

* Archive frequency may be less than operational reporting frequency

Weather was also a factor in other aspects of the STS-107 accident investigation. Meteorologists from the 45th Space Wing and SMG refined the debris fallout path by analyzing mosaiced weather radar data at the National Severe Storms Laboratory and NEXRAD Operational Support Facility, and collecting weather observations around the reentry path across the CONUS. The 45 WS also collected pertinent numerical model data, obtained projections of where reentry tiles may have drifted in the Atlantic Ocean on launch day and in the Pacific Ocean on landing day, and advised on the possible role of upper atmospheric electricity as a contributor to the accident.

4.1 DATA REQUESTS

While the 45 WS, KSC, and MSFC were reviewing weather data from pre-launch and launch operations, many requests were received from media investigative reporters through public affairs and the Columbia Accident Investigation Board. The requests ranged from simple (weather at launch time) to more thorough (analysis of hourly weather data during the 40 days STS-107 was at the launch pad). The KSC Weather Office, 45 WS, SMG, and MSFC Environments personnel quickly realized the need to coordinate data requests, paying close attention to how data was applied to each scenario. The meteorologists involved in responding to the requests kept in mind the many ways data could be misused if temporal and spatial differences weren't understood, as well as sensor errors and resolution, and combinations of parameters. For every request, the team interviewed the customer about the application to ensure they received the best answer for the problem under study. Thus, the team worked as consultants as well as data providers.

The ability to stratify archived data many different ways was essential. An example was the precipitation analysis for the time STS-107 was on the launch pad. Since foam separated from the External Tank of the Shuttle and impacted the Orbiter, and this foam area is exposed during the time the vehicle is at the launch pad, the significant amount of rainfall on the External Tank was a concern. Meteorologists involved in the precipitation analysis realized exposure of various portions of the Shuttle could vary widely depending on the protection provided by the Rotating Service Structure, a steel structure on the launch pad that covers and provides protected access to the orbiter. Consequently, the impact of a rain event on a specific area of the Shuttle could vary significantly as a function of rainfall intensity, wind direction, and wind speed. The time period and intensities in which the rainfall occurred were also considered. The precipitation analysis for STS-107 is covered in more detail in paragraph 4.3.

4.2 DATA COLLECTION ISSUES

While consolidating data to satisfy requests or perform analyses, several difficulties arose. First, during the time STS-107 was on the launch pad, there was a scheduled 9-day power outage at the Range Operations Control Center where weather data for Spaceport Florida is quality controlled and archived. CSR was able to maintain the real-time weather data during this time, but there was not enough power to also maintain the data archive. This caused a 9-day gap in the data during the 40 days STS-107 was on the launch pad (Figure 2).

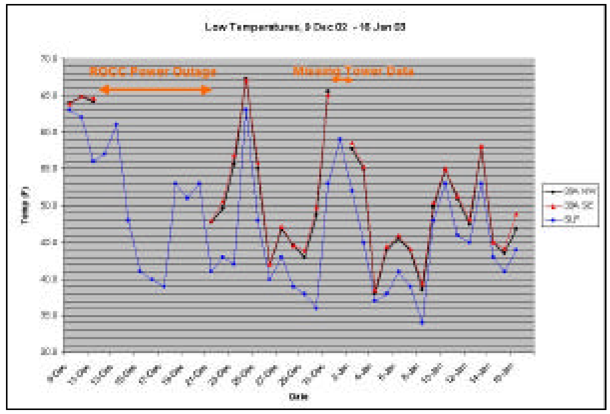

Figure 2. Graph of low temperatures while STS-107 was on the launch pad. Data from the SLF was included to compensate for data lost during the power outage, but temperatures at the launch pad can differ significantly between the two locations.

To supplement the data, the KSC Wave Analysis Lab provided hard-copy graphs of the data, which the 45 WS transposed into hourly data for wind direction, average wind, peak wind, high and low temperatures, and average temperatures. The process of transposing the data by hand into hourly data required several additional days. Figure 3 displays an example of this effort for just a few hours of data. Possible interpretation errors were also identified and included with the data.

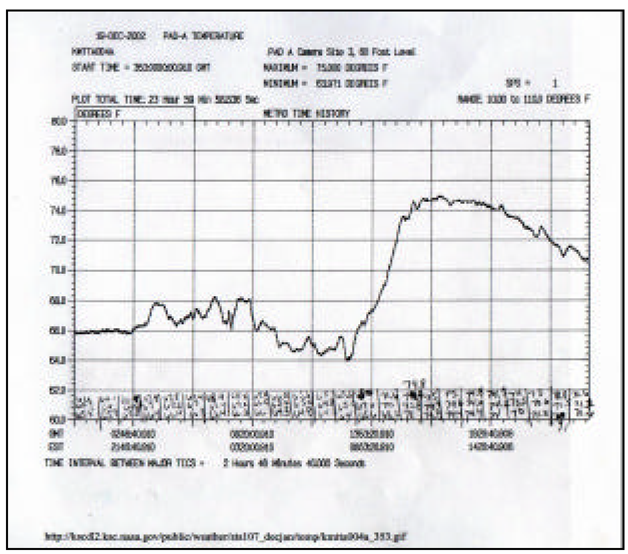

Figure 3. Graph from KSC Wave Analysis used to supplement missing data during power outage.

Another challenge occurred when analyzing precipitation data. No launch pad precipitation measurements existed before 1991, so comparing precipitation amounts for STS-107 to other missions posed a problem. The closest precipitation sensor was at the SLF, which is 4NM west of the launch pad. During the winter season when synoptic weather systems are the source of precipitation, this distance would most likely be reasonable for determining the amount of precipitation on the vehicle at the launch pad. However, in the summertime regime, significant differences could occur due to small-scale convective rains and the east-west rainfall gradients caused by the east coast sea breeze and its interaction with local river breezes, the west coast sea breeze, and outflow boundaries. Still, the data during these months could represent the fact that precipitation occurred at the launch pad on a day the precipitation occurred at the SLF (Lambert, 2003). The bottom line is that the closest geographically displaced data may not be the most representative; thus, archiving all data is important to be able to use the most representative to best satisfy study requirements.

Finally, the large volume of data collected was difficult to manage. Analyzing 5-minute data for the entire 40 days the vehicle was at the launch pad was a difficult task, and then further, accessing data from previous missions back to 1981 was overwhelming. The volume of data was difficult to manage and transfer, and the 45 WS software was limited in handling this data. Thus, the Applied Meteorology Unit (Ernst and Merceret, 1995) was tasked to use their statistical analysis software that can process large amounts of data, to perform the precipitation analysis.

4.3 RESULTS

A review of all the weather data from pre-launch and launch times only flagged one item that was unusual, yet still well within the engineered weather constraints: rainfall amount on the vehicle. A total of 12.8 inches of precipitation occurred from rollover through the time the vehicle was launched. This amount was considerable for the time of year, but was it significant compared to other missions? Although there is no particular weather constraint for rainfall while the vehicle is at the launch pad, the fact that there was a significant amount of rain and the unusual event of the foam loss (an exposed portion of the vehicle while at the pad) approximately 82 seconds after launch, personnel from the 45 WS and KSC Weather Office realized the need to examine the precipitation further and determine if the occurrence for STS-107 was 'out-of-family.' Total launch pad rainfall amounts were compared to all other Shuttle missions. The Applied Meteorology Unit performed the analyses.

For STS-107, the bulk of the rainfall fell over 2 of the 40 days the vehicle was on the launch pad. For each and every Shuttle mission's exposure, the total rainfall, the maximum daily rainfall, and the average daily rainfall was analyzed. For each analysis, STS-107 was within the top 10 of 113 missions (Lambert, 2003).

5. RECOMMENDATIONS

Performing the precipitation analysis highlighted an issue that became true across many disciplines within the Space Shuttle program, the need to analyze past data and compare it to the current mission. This is done in some areas. For example, in February 2002, STS-109 was delayed due to forecast cold temperatures which, although within constraints, were still 'out-of-family'. For future missions, the 45 WS and KSC Weather Office recommend creating a data set of wind, rain, temperature, and other operationally significant weather parameters during Shuttle exposures to easily, objectively, and formally identify 'out-of-family' items before launch and flag any concerns to Shuttle managers.

This reinforces the need and importance of archiving data. To analyze data in response to external requests or for internal review, the data must be available in a usable format, must remain as closely as possible in that format throughout the archive, and must be quality controlled. System upgrades and new instrumentation will no doubt occur, but when incorporated, the archive data must continue to be quality controlled, and the data format from the previous system to the new system should be standard. This includes either reformatting the data prior to the date of the implementation of the new system, or the previously archived data should be reformatted to match the new archive data format. The changes to the systems also need to be documented as meta-data. Additionally, experts on the vagaries of the local weather sensors and the local weather patterns must be involved to ensure high quality analysis. Statistical analysis software for easily analyzing the archive data should be readily available.

Finally, power outages for routine, preventative maintenance in the Range Operations Control Center should not interrupt the data archive process.

6. SUMMARY

Although a review of the meteorological data for pre-launch and launch operations for STS-107 did not reveal any significant anomalies, the case further emphasized the need for archived meteorological data for space launch operations.

Archived meteorological data must be accessible; in a usable, standard format; and quality controlled to allow for efficient collection and analysis when required. Fusion of multiple, synergistic data sources should be accomplished for the best overall analysis and for internally self-consistent analysis. Experts in the local weather sensors and the local weather should participate in the analysis. Finally, for all launches, the archive should be used to create data sets for weather parameters, so a comparison of the current mission can be made to previous missions. This will allow the objective identification of weather conditions that a space launch vehicle has not experienced on previous missions. Even though these conditions may not violate current weather constraints, they may represent out-of-family conditions that warrant further review.

REFERENCES:

Boyd, B. F., J. T. Madura, and M. E. Adams, 1993: Meteorological Support to the United States Air Force and NASA at the Eastern Range and Kennedy Space Center, Paper 93-0753, *AIAA 31st Aerospace Sciences Meeting & Exhibit*, 11-14 Jan, pp 11

Brody, F. C., 1997: Operations of the National Weather Service Spaceflight Meteorology Group, *AIAA 35th Aerospace Sciences Meeting and Exhibit,* Paper 97-0181, 6-10 Jan 97, pp 8

CSR, 2003: Eastern Range Instrumentation Handbook, *prepared by Systems Analysis*, CSR, Patrick AFB, FL, CDRL A209, Contract F08650-00-C-0005, 15 Oct 2003

Ernst, E. and F. Merceret, 1995: The Applied Meteorology Unit: A Tri-Agency Applications Development Facility Supporting The Space Shuttle, *6th Conf. On Aviation Weather Systems*, 15-20 Jan 95, 266-269

Harms, D. E., B. F. Boyd, F. C. Flinn, J. T. Madura, T. L. Wilfong, and P. R. Conant, 2003: Weather Systems Upgrades to Support Space Launch at the Eastern Range and the Kennedy Space Center, *12th Symposium on Meteorological Observations and Instrumentation*, 9-13 Feb 03, pp 9

____, B. F. Boyd, R. M. Lucci, and M. W. Maier, 1998: Weather Systems Supporting Launch Operations at the Eastern Range. *AIAA 36th Aerospace Sciences Meeting and Exhibit*, Paper 98-0744, 12-15 Jan 98, pp 11

Lambert, W. C., 2003: Analysis of Rain Measurements in Support of the STS-107 Investigation, *Applied Meteorology Unit Memorandum for the 45 WS and KSC Weather Office*, Apr 03, pp 4

MSFC Environments Group, 2003: STS-107 Natural Environments Data, *Report for Space Shuttle Integration Office*, 16 May 03, pp 130

Oram, T. and T. Garner, 2003: Stratosphere and Mesosphere Analysis in Support of the Space Shuttle Columbia Investigation, *National Weather Association 28th Annual Meeting (abstract only)*, 18-23 Oct 03, pp 1

Priselac, E. D., J. E. Sardonia, and T. C. Adang, 1997: Operational Weather Support for NASA Space Shuttle Ferry Flights, Preprints 7th Conference On Aviation, Range, And Meteorology, Long Beach, CA. 2-7 Feb 97, 35-39

Roeder, W. P., D. L. Hajek, F. C. Flinn, G. A. Maul, and M. E. Fitzpatrick, 2003: Meteorological And Oceanic Instrumentation At Spaceport Florida-Opportunities For Coastal Research, *5th Conference on Coastal Atmospheric and Oceanic Prediction and Processes*, 6-8 Aug 03, Seattle, WA, 132-137

____, and D. E. Harms, 2000: Using Climatology to Improve Weather Forecasting for America's Space Program, *12th Conference On Applied Climatology*, 8-11 May 00, 66-69