1.4 USE OF LIGHTNING DATA FOR SPACE SHUTTLE AND SOYUZ RE-ENTRY AND LANDING FORECASTS AT JOHNSON SPACE CENTER

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1. OPERATIONAL LIGHTNING FORECASTS AND CONCERNS

The National Weather Service (NWS) Spaceflight Meteorology Group (SMG) provides operational and staff meteorology support to NASA's human spaceflight program at Johnson Space Center (JSC) (Brody et al, 1997). Lightning is a concern in the operation of the Space Shuttle during landing, for personnel and facility protection at JSC, and during landing of the Soyuz capsule used for emergency and planned crew transport from the International Space Station (Oram, 2002). The weather-related flight rules describe the acceptable conditions for landing the Orbiter (NASA/JSC, 2004). The intent of the lightning-related flight rules is to avoid either a naturally occurring lightning strike or a triggered lightning event as occurred during the Apollo 12 (Godfrey et al, 1970) and the Atlas-Centaur-67 (Christian et al, 1989) launches. The lightning related flight rules are adaptations of the Lightning Launch Committ Criteria (LCC) developed by the Lightning Advisory Panel (Krider et al,.1999). The adaptations are due to the Flight Rules covering both observed and forecast conditions as compared to the LCC which are primarily observed conditions. SMG also issues local lightning advisories for JSC to protect workers and vital computer resources controlling the space vehicles from injury or damage. Finally, JSC Flight Directors requested thunderstorm forecasts for each potential landing opportunity for the Soyuz capsule although the Soyuz is apparently less weather sensitive than the Shuttle. The Soyuz landing sites are located throughout the world. Table 1 summarizes the key lightning-related forecast criteria for SMG while Figure 1 shows the locations of all areas for which SMG must try to monitor lightning activity and forecast thunderstorms.

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2. LIGHTNING DATA SOURCES AT SMG

The world-wide nature of the forecasts issued by SMG requires a wide variety of lightning data sources. Many of the lightning data sources available at SMG are integrated into either the Advanced Weather Information Processing System (AWIPS) or the Meteorological Interactive Data Display System (MIDDS). In addition, the Internet has provided access to other sources of lightning information. While the Internet data sources are not integrated into the current display systems, the free access to the data allows the forecaster to evaluate the utility of the new or experimental systems before entering into the procurement process. Table 2 lists the Lightning observing systems used at SMG and key characteristics of each system.

2.1 Synoptic/Mesoscale Lightning Observing Systems

Lightning observing systems can be broken down into meteorological scales using the range and detection accuracy. The wide-area coverage provided by the synoptic scale systems such as the National Lightning Detection Network (NLDN) provides the forecaster information on lightning associated with synoptic scale features such as cold fronts. In addition, the location accuracy of these systems is sufficient to provide mesoscale information. For example, the parent cloud that produced the lightning can be identified in some instances.

The primary synoptic scale lightning detection system used at SMG for the continental United States is the NLDN. NLDN data cover the three Continental US Space Shuttle landing locations as well as the Space Shuttle Emergency Landing Sites and Soyuz landing sites in North America. The data are available for forecaster use in both AWIPS and MIDDS. Cummins et al (1998) discuss the technical characteristics of the NLDN.

SMG relies on the Spanish National Institute of Meteorology (INM) Cloud-to-Ground Lightning Data to detect lightning near the Spanish TAL sites at Zarogoza and Moron. The INM data are requested through the Internet from a McIDAS data server in Spain. Due to the commonality of display systems, SMG can display the data in MIDDS. The INM system is a magnetic direction finding system developed by Lightning Location and Protection, Inc (now part of Vaisala) that detects cloud-to-ground lightning in Spain, Portugal, and France.

In addition to the INM system, the United Kingdom Meteorological Office operates a sferics detection network (Lee, 1986). The lightning location data are distributed as text bulletins (SFUK30 and SFUK31) through the Global Telecommunication System. These bulletins provide a summary of the number of flashes detected in 1/2 degree latitude by 1/2 degree longitude blocks within a 30-minute period. The encoding of the sferics data into the text bulletins limits the application of the data to large scale identification of the location of lightning. SMG software decodes and displays the data in the MIDDS. This data will be added to AWIPS in the near future.

The synoptic scale lightning data in SMG's MIDDS and AWIPS do not provide coverage over some of the Space Shuttle and Soyuz landing areas in Asia, Europe, and the Southern Hemisphere. For these areas, synoptic and Aviation Surface Observations (METAR) provide the primary thunderstorm and lightning information. In addition, SMG uses developmental or experimental lightning data sources available via the Internet. Examples of data used by SMG are the European Cooperation for Lightning Data (EUCLID) at http://www.euclid.org/ and the Low Frequency Electromagnetic Research Ltd (LF*EM) World-Wide Lightning Location (WWLL) Network at http://flash.ess.washington.edu. These Internet data sources provide near-real time information that helps forecasters better analyze the phenomena occurring in these regions of the world and descriminate between to thunderstorms and rain or rain showers.

Although not received in real-time, SMG can readily plot data from the Vaisala long range lightning detection network. The long range network uses Very-Low Frequency (VLF) sensors to locate lightning over the oceans. SMG is currently evaluating the requirement for this type of data. At this time, transient luminescent events are not considered to be a hazard to the Orbiter during landing. However, SMG may need systems that can locate lightning associated with sprites, jets, elves if NASA determines these phenomena are associated with hazards to the vehicle.

2.2 Mesoscale and Stormscale Observing Systems

Recent advances in technology have led to the installation of several systems that detect both intracloud and cloud-to-ground lightning. These systems provide accurate locations of Very-High Frequency (VHF) radiation sources associated with lightning. The location accuracy of these systems allows the forecaster to clearly identify the clouds associated with lightning. Electric field measuring systems have limited range but provide mesoscale information on the development of charge within clouds.

Since about 1987, SMG has had access via the MIDDS to the 45th Space Wing Cloud-to-Ground Lightning Sensor System (CGLSS) and the Launch Pad Lightning Warning System (LPLWS) field mill network (Harms et al, 1998). The CGLSS is a magnetic direction finding (MDF) system similar to the NLDN, but only using MDF sensors located around Kennedy Space Center and the Cape Canaveral Air Force Station. The MDF sensors are "tuned" to try to detect lower amplitude flashes. The data complement the NLDN data for evaluating Flight Rules at KSC. The LPLWS provides 1-minute average electric field values for each field mill in the network. The electric field changes measured by the LPLWS field mills are also used to produce an estimated charge center associated with a lightning flash. While the LPLWS provides valuable information on the atmosphere's electric field at the surface, the location accuracy of the data are not sufficient to infer information about the charges associated with particular clouds.

The Kennedy Space Center (KSC) Lightning Detection and Ranging (LDAR) detects VHF sources from both CG and intracloud lightning surrounding KSC, the primary landing site for the Space Shuttle. SMG currently receives a 3-dimensional grid product that displays a VHF source density over a 1-minute period. The grid boxes are 0.5 km within 50 km of KSC and 2 km between 50 and 100 km range from KSC. The real-time display of the LDAR data is a stand alone system. Local software has been written to display both the LDAR grids and archived data in the MIDDS. Although the grid total lightning data from the KSC LDAR system has proved useful, the developmental nature of the software created maintainability and reliability problems with receipt of the data. SMG is therefore upgrading their capability to receive the individual VHF source information that is currently used at the 45th

Weather Squadron. This data will be available before the Shuttle's scheduled return to flight in 2005.

By the end of 2005, total lightning detection systems will be installed at White Sands Missile Range (WSMR), New Mexico and Houston, Texas. A Lightning Mapping Array (LMA) developed by New Mexico Tech is being installed at the White Sands Missile Range. SMG is working with White Sands Missile Range to receive access to the data. In support of the Houston Environmental Aerosol Thunderstorm (HEAT) Project, a Vaisala LDAR II system is being installed around Johnson Space Center. One of the antennas will be located at JSC and the data will be available for local resource protection in the SMG forecast office. SMG is building on the work by NASA's Short-term Prediction and Research Transition (SPORT) Center and the NWS Huntsville Weather Forecast Office to integrate the LMA data into AWIPS (Goodman et al, 2004).

3. USE OF LIGHTNING DATA AT SMG

Lightning data are used for the following purposes:

- Evaluating Flight Rules for observed violations
- Forecasting thunderstorm and triggered lightning potential for flight rule evaluation and resource protection
- Development and implementation of new thunderstorm forecasting techniques
- Forecast Verification

Synoptic scale lightning detection systems such as the NLDN, the INM CG system, and the UK sferics system are critical to the evaluation of the Space Shuttle Flight Rules for launch and landing. In the event of an emergency during launch, the Shuttle requires a Transoceanic Abort Landing (TAL) site with acceptable weather conditions. SMG must evaluate the observed conditions and forecast that acceptable weather conditions will occur at the expected abort landing time. Figure 2 contains examples of the display of lightning data used to evaluate the flight rules at Transoceanic Abort Landing sites during a Shuttle launch. Figure 2a shows the lightning detected by the INM network including one strike within the area protected for launch. Figure 2b shows the UK sferics data for the same time period. It has been SMG's experience that the sferics data location is fairly accurate when compared to the INM CG data (which is assumed to be more accurate). The value of the sferics data is that the detection area is larger and provides complementary data to the INM data.

Note that although the sferics did not indicate any lightning within the protected zone, the interpretation of the data from both systems would have been "No-Go" due to the presence of a thunderstorm as indicated by the non-transparent cloud connected from the lightning location to the protected zone. SMG needs lightning detection systems that can locate total lightning up to 300 to 450 nautical miles from a landing location in order to determine the presence of lightning in thunderstorm anvils. These anvils can be advected long distances by the jet stream. The difficulties of analyzing and forecasting thunderstorm anvil clouds (attached and detached) have been described by Garner, et al (1996). The primary limitation of the synoptic scale lightning detection systems is the inability to detect intracloud lightning.

Mesoscale and storm scale detection systems are also important. The evaluation of the flight rules is not limited to the occurrence of CG lightning. Mesocale detection systems such as LDAR and LMA provide detailed information on total lightning activity at the Shuttle landing sites and JSC. In addition, the LPLWS field mills provide an indication of the development of charge within the cloud and help identify the potential for either natural or triggered lightning occurrence. On 9 Nov 2004, a weak cold front passed through Kennedy Space Center. Cloud top temperatures were as low as -5 to -10 degrees Celsius indicating the clouds likely contained both ice and water. Although no lightning were observed with the showers, the clouds appeared to be electrified. 1-minute average electric fields of -250 V/m to +1200 V/m were measured as the showers passed through the area (a fair weather field would be +150 V/m using the LPLWS convention). Figure 3 shows the "Hazards Display" and associated 0.5 degree elevation angle base reflectivity data from the Melbourne WSR-88D. The SMG "Hazards Display" integrates the display of the LPLWS field mill values for the 31 sensors, weather symbols from the METAR observations, and lightning locations from the CGLSS system. The "Hazards Display" helps promote situational awareness for the forecaster during launch and landing operations and helps improve understanding of cloud electrification processes when used in simulation and training. The primary limitation of the mesoscale sensors is the limited range.

Although lightning observations are important to evaluate the current status of flight rule violations, Space Shuttle launch and landing decisions are also based on the forecast conditions. The launch decision occurs 35-45 minutes prior to the abort landing times while the landing decision occurs about 60-90 minutes prior to the planned landing time. Thunderstorm nowcasts depend on the ability to observe and diagnose the causes of the current conditions and to project the evolution of those conditions into the future. Forecasters must anticipate the development of new thunderstorms and electrified clouds. Part of this process involves extrapolating and trending of thunderstorms through the integration of lightning data with other observing systems such as radar and satellite. Numerical models, local forecasting techniques, and forecaster experience provide additional tools to predict the landing weather. SMG is currently implementing mesoscale forecast models with explicit cloud physics to help with the thunderstorm forecasts in the 0- to 6-hour period. Some of the challenges unique to SMG forecasts include the prediction of the location and dissipation of electrified anvil clouds, dissipation and movement of clouds formed from cumulonimbus, and convective initiation associated with the development of electrified cumulus and thunderstorms.

The SMG Techniques Development Unit is charged with the responsibility of developing new forecasting techniques and transitioning forecasting techniques from research organizations into operations. The development of improved thunderstorm forecast techniques relies on the availability of quality lightning data. SMG uses the WSR-88D radar-based rules to make short term predictions of lightning (Garner et al, 2002). These rules are derived from studies by Gremillion and Orville (1998), Dye et al (1989), and others. Research studies of necessity are limited in scope, usually either in the time period studied, the location studied, or both. The practical implementation of the studies involves applying the guidelines in real-time operations and refining the guidelines based on forecaster experience. The research guidelines cannot be critically evaluated and refined without quality lightning data in the forecast office. For example, it has been SMG's experience that approximately five minutes lead time is lost when applying guidelines developed by Gremillion and Orville when the forecasts are verified with LDAR and NLDN data rather than only NLDN, as was done in the original study.

Finally, forecast verification is important for identifying possible areas for forecast process improvement. Lightning detection systems have proven to be the most reliable method for determining the occurrence of thunderstorms. Oram (2002) discusses some of the challenges and impacts of attempting to verifying the Soyuz forecasts for Russia and Kazahkstan due to the lack of lightning detection networks covering this area and the limited number of surface observing sites providing aviation (METAR) and synoptic observations. Cloud-to-ground lightning detection systems cover the most critical Space Shuttle landing locations used for End-of-Mission, RTLS abort, and TAL aborts. Current efforts at integrating total lightning detection systems covering KSC and WSMR will help mitigate the lack of total lightning information, but the new data may also point out limitations of the current forecasting techniques.

4. USE OF LIGHTNING DATA IN *Columbia* ACCIDENT INVESTIGATION

Lightning data were an important addition to other meteorological data used to help characterize the environment *Columbia* flew through prior to break-up of the vehicle. Figure 4 contains a satellite image and analysis of the weather conditions over which STS-107 Columbia flew during re-entry from 13:45 to 14:05 UTC on February 1, 2003. At approximately 13:45:44 UTC and an altitude of 105 km (345,000 ft), the orbiter passed over the southern end of a cold front near 160W. Cloud top temperatures estimated from the GOES-10 infrared satellite image were as cold as –70C. An experimental long-range lightning location system operated by Vaisala, Inc. detected a lightning flash near 32.7N 162.5W at 13:31:13 UTC. It is possible, perhaps likely, that thunderstorms were located in this area as the orbiter flew over the cold front. However, the Orbiter did not experience any unusual indications while flying over this area. The orbiter then passed without incident over a weaker convective band near 37N 149W at about 13:48:17 UTC while at an altitude of 85 km (280,000 ft). High pressure and low stratocumulus clouds covered the ocean area between the weak convective band and the California coast.

At approximately 13:53:30 UTC, *Columbia* crossed the California coastline at an altitude of 70 km (230,000 ft). A cold front extended from Montana through northern California. Rain showers and low ceilings covered northern California. Central California (including the San Francisco Bay Area) had fog and low stratus clouds with ceilings around 1000 feet, and thin high cirrus clouds. High thin cirrus clouds covered most of the sky in southern California. No cloud-to-ground lightning was detected by the National Lightning Detection Network over the eastern Pacific Ocean or the continental US near the ground track.

A photograph of a purple "bolt" either near or attached to the Orbiter was provided to Johnson Space Center by an amateur astronomer from near San Francisco. The picture was taken as *Columbia* flew over California. Both NLDN and Long Range lightning data were provided to the Space / Atmospheric Environment Scientist Panel, a special panel of scientists and engineers appointed to examine the potential causes of the bolt. The lightning data from these systems as well as other sferic detection systems were important to the panel's conclusion that neither Transient Luminous Events (sprites, jets, or elves) nor sprites induced by thunderstorms at the geomagnetic conjugate point were the cause of the images. In fact, the panel concluded the purple bolt was due to an impulsive event to the camera itself (Space/Atmosphere Environment Scientist Panel, 2003).

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Table 1. Summary of SMG Lightning Forecast and Observation Concerns.

(L) No lightning within 6 statute miles of Johnson Space Center
(S) No thunderstorms or lightning within 30 nautical miles of a landing site (End-of-mission)
(S) No thunderstorms or lightning within 20 nautical miles of the Return-to-Launch Site (RTLS) and Transoceanic Abort Landing (TAL) sites (Launch)
(S) No thunderstorms at an Emergency Landing site (Launch and On-orbit)
(S) No detached non-transparent thunderstorm anvils (cirrus spissatus cumulonimbogenitus) less than 3 hours from detachment within specified distances of landing sites
(S) No cumulus associated with fires in the flight path
(S) No cumuliform clouds that are potentially electrified within 10 nautical miles of the flight path
(I) No thunderstorms or lightning within 100 km of Soyuz emergency landing location
"L" indicates a local advisory requirement, "S" indicates a Space Shuttle requirement, and "I" indicates an International Space Station Soyuz forecast requirement

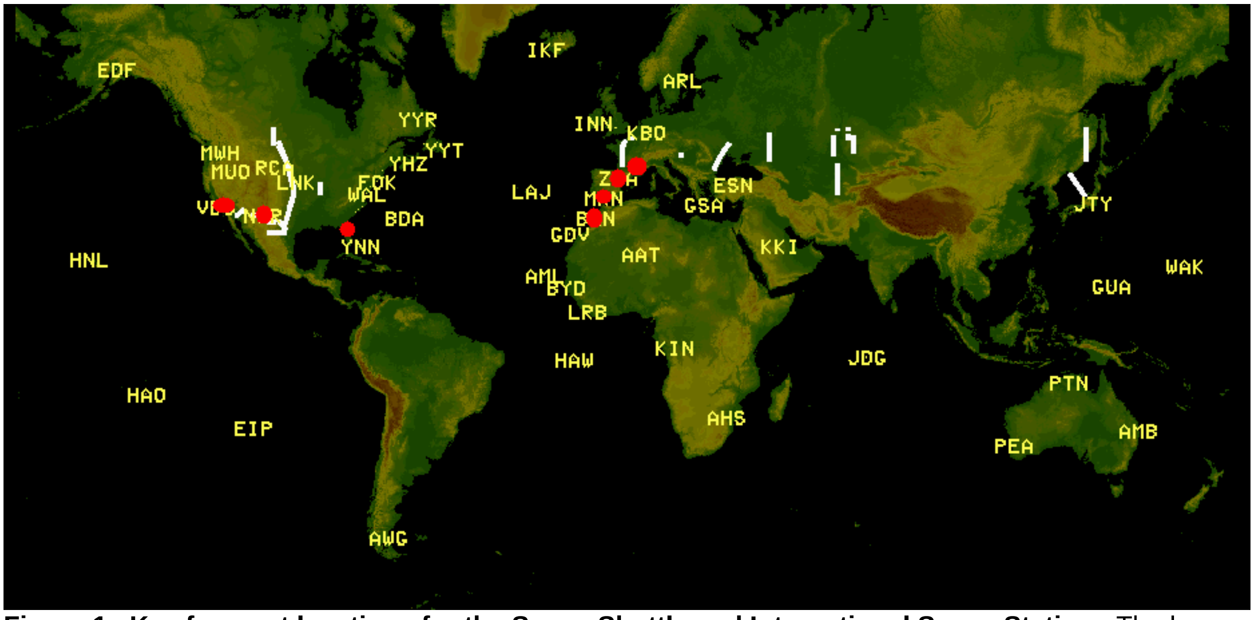

Figure 1. Key forecast locations for the Space Shuttle and International Space Station. The large red dots are Space Shuttle Primary and Transoceanic Abort Landing (TAL) sites in the United States, Europe, and Africa. The yellow 3-letter identifiers are a subset of the current 60 Space Shuttle Emergency Landing Sites. The solid white lines are emergency landing areas for the Soyuz vehicle used for planned and emergency crew transport from the International Space Station.

Table 2. Lightning Observing Systems in use, or planned for use, at SMG.

System	Area Covered	Date Available	Phenomena Detected	Range	Location Accuracy	Display System
CGLSS	Central Florida	1987	CG lightning	100 km	0.5 km	MIDDS
LPLWS	KSC	1987	Electric Field and Electric Field Change	20 km	2-20 km for charge center	MIDDS
NLDN	CONUS	1999	CG lightning	5000 km	0.5 km	MIDDS and AWIPS
INM	Iberian Peninsula and France	2000	CG lightning	2500 km	1-10 km	MIDDS
UK Sferics	Europe and Atlantic	2000	CG lightning	10000 km	50 km	MIDDS
LDAR Grid Data	KSC	2001	Total lightning	100 km	0.5-1.0 km	Standalone and MIDDS
EUCLID	Europe	2001	CG lightning	2500 km	1-10 km	Internet
WWLN	World	2003	CG lightning	World	???	Internet
LMA		2004	Total lightning		0.1 km	Internet
LMA	WSMR	2005	Total lightning		0.1 km	Standalone and AWIPS
LDAR II	Houston	2005	Total lightning	500 KM	0.1 KM	Standalone and AWIPS
4DLSS (LDAR II)	KSC	2005-2006	Total lightning	100 KM	0.1 KM	Standalone and AWIPS

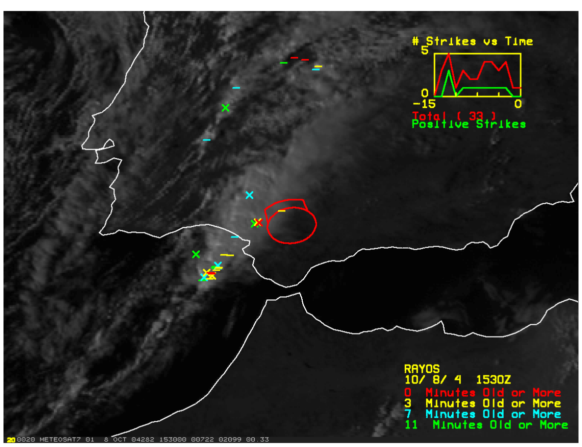

Figure 2a. INM CG Lightning locations for 1500 to 1530 UTC on 8 Oct 2004 shown as "+" for positive CG lightning and "-" for negative CG. The background is the Meteosat visible image from 1530 UTC.

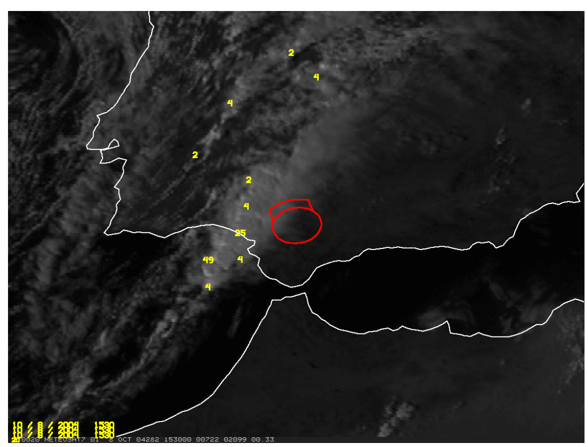

Figure 2b. Same at Figure 2a except the sferics data for 1500 to 1530 UTC are shown as number of flashes located in the 1/2 degree by 1/2 degree box.

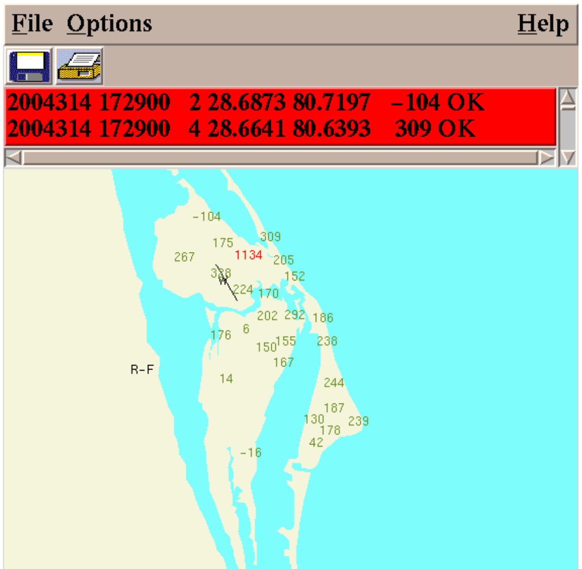

Figure 3a. SMG Display of Launch Pad Lightning Warning System (LPLWS) Field Mill data for 1729 UTC on 9 Nov 2004 . The display shows the geographic area surround the Shuttle Landing Facility (the black line near the center of the display). The LPLWS system uses the convention of positive values being in the fair weather direction. The text listing is highlighted in yellow for absolute values of the electric field mill greater than 500 V/m and red for absolute values of electric field greater than 1000 V/m.

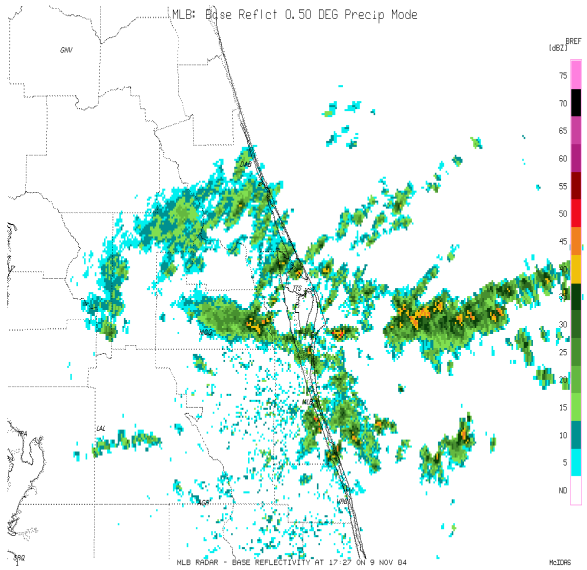

Figure 3b. Melbourne WSR-88 D 0.5 Degree Reflectivity Product for 1727 UTC on 9 Nov 2004.

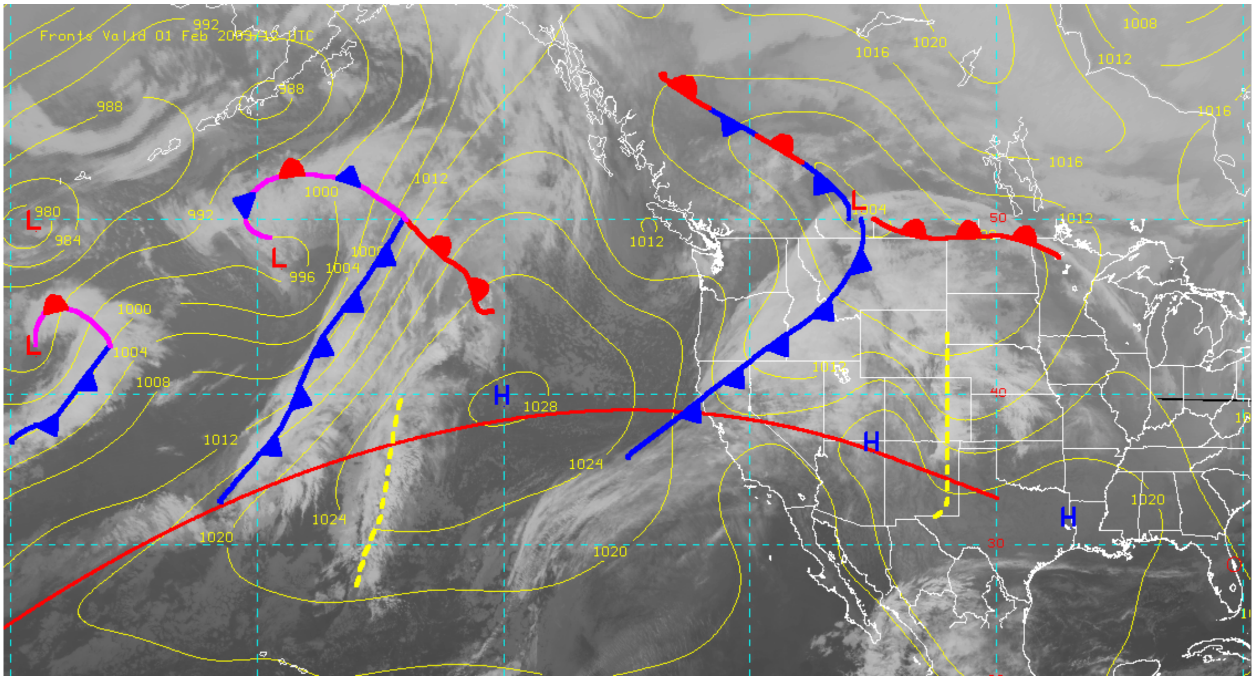

Figure 4. Satellite analysis of the weather conditions over which STS-107 Columbia flew during re-entry from 13:45 to 14:05 UTC on February 1, 2003. The image is a combination of the GOES-8 13:55 UTC and GOES-10 14:00 UTC infrared images. The red curve arcing from the left to right across the picture is the entry path recorded by the orbiter GPS system during re-entry. Kennedy Space Center, the designated landing location, is located in the center of the circle on the far right side of the image. The sea level pressure analysis from the National Center for Environmental Prediction (NCEP) 12Z Global Data Analysis System (GDAS) is plotted in yellow on the image.