USE OF THE WSR-88D FOR SPACE SHUTTLE WEATHER SUPPORT DURING THE STS-57 AND STS-51 MISSIONS

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Abstract

The National Weather Service (NWS) Spaceflight Meteorology Group (SMG), in support of the National Aeronautics and Space Administration (NASA) Space Shuttle Program at the Johnson Space Center, has been an associated user of the Doppler radar (WSR-88D) at the NWS Office in Melbourne, Florida since the summer of 1992. One of the SMG's primary functions is to prepare specific forecasts throughout all shuttle missions for the Shuttle Landing Facility (SLF) located at the Kennedy Space Center (KSC), Florida. SMG forecasters have found that using the Melbourne WSR-88D data, which fully covers the SLF, has proven to be a most valuable part of the forecast process. During the summer of 1993, the Space Transportation System (STS) 57 and STS-51 missions were prime examples of how the SMG employs the WSR-88D Principle User Processor (PUP) in such operations.

During June 1993, weather at and around the SLF caused a one-day delay of the STS-57 launch and postponed the end-of-mission landing for two days. Different approaches to the use of the WSR-88D data were called for in each case due to the varying weather regimes. In September 1993, the STS-51 mission was able to launch on schedule because precise tracking of "outflow" convergence boundaries was possible using the WSR-88D PUP. The STS-51 landing forecast for the SLF was complicated by the loss of Geostationary Operational Environmental Satellite (GOES) imagery due to the autumnal eclipse. Convergence, observed in the synoptic scale surface data, was pinpointed and tracked using the WSR-88D PUP and the KSC mesoscale wind network. The landing was delayed for one day because of the potential for shower development. The following day, the first-ever night Space Shuttle landing at the SLF occurred. On this day, the WSR-88D PUP was used to track and help forecast the dissipation of thunderstorm activity that approached the SLF from the north.

This paper describes these weather events and how the WSR-88D PUP was used to make real-time weather "calls" involved with Space Shuttle launch and landing operations.

1. Introduction

The primary task of the Spaceflight Meteorology Group (SMG) is to provide worldwide site specific weather forecasts for Space Shuttle landings (Brody 1993). SMG meteorologists are under extreme pressure to provide these forecasts from which decisions to launch or land the Shuttle are made. Highly restrictive and complicated flight rules make an already difficult forecast sometimes exceed the state-of-the-art. Recent deployments of WSR-88D radars by the National Weather Service (Klazure and Imy 1993) near landing sites are providing valuable assistance in forecasting for the Shuttle Program. During two recent Shuttle missions, designated Space Transportation System (STS)-57 and STS-51, SMG meteorologists were able to provide the required accurate forecasts in part due to the WSR-88D's ability to detect and track phenomena that previously could not be done by conventional radar systems.

2. Background

Weather is of utmost importance during the launch and landing phases of all Shuttle missions. Weather, both observed and forecasted, has caused delays in more than half of all 68 Shuttle missions to date. The U.S. Air Force's 45th Weather Squadron at Cape Canaveral Air Force Station provides weather support for all phases of ground operations including the Shuttle's launch, while SMG provides all weather support to mission operations once the vehicle has lifted off. Specifically, SMG prepares forecasts for the following:

—Return to Launch Site (RTLS)—KSC
—Transoceanic Abort Landing (TAL) sites—three locations in Spain and Western Africa.
—Abort Once Around (AOA) sites—KSC, Edwards AFB, CA and White Sands, NM.
—Third orbit Primary Landing Sites (3rd rev PLS)—KSC, Edwards AFB, CA and White Sands, NM.
—Daily On-orbit Primary Landing Sites (PLS)—KSC, Edwards AFB, CA and White Sands, NM.
—Numerous emergency landing sites around the world (when needed)
—The primary and alternate End of Mission (EOM) sites—KSC, Edwards AFB, CA and White Sands, NM.

The shuttle has an extensive list of flight rules which cover weather conditions both observed and forecasted. The flight rules are complex and address numerous parameters. The basic "weather" minimums for a landing are:

—Cloud ceiling ≥ 8000 feet.
—Visibility ≥ 5 nautical miles.
—Winds ≤ 25 knots.
—Cross-wind component ≤ 15 knots.
—No precipitation or thunderstorm anvil debris clouds within a 30 nautical mile radius of the site.

These are highly restrictive rules with numerous variations depending on the type of landing situation. While flight rules

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are explicit, they can be difficult to interpret. For example, computing cross winds is not a straightforward process (Tongue and Hogan 1993). Judgment by both meteorologists and the NASA flight control team is often called upon.

Violation of flight rules associated with abort landing sites have on numerous occasions caused mission managers to delay a launch. This is because during every launch the potential for an emergency RTLS or TAL landing exists. The weather must be within flight rule limits at these sites prior to actual launch, or the launch will be delayed.

RTLS flight rules require no thunderstorms within 20 nautical miles (nm) of the Shuttle Landing Facility (SLF) and this rule extends out to 30 nm to the east depending on cloud top heights. Rain showers are not permitted within an oval like area that extends out to 20 nm from the SLF. Figure 1 is a graphical depiction of the complicated RTLS precipitation flight rules.

3. The End-of-Mission Landing Site

The primary EOM landing site is currently designated as the SLF at the Kennedy Space Center (KSC) on the central east coast of Florida. Landing at the SLF results in saving at least a week's worth of processing time for the vehicle since it does not require transport from the alternate landing site at Edwards Air Force Base (AFB) in California. The overall monetary savings are significant, generally in excess of one million dollars.

The problem with landing at the SLF is that the nature of sub-tropical weather is often difficult to predict. Landing times, dictated by launch times, are often in the early morning. Drastic changes in conditions brought upon by mesoscale and microscale meteorological phenomena that are beyond the start-of-the-art to predict, can and do occur. The potential for a "sunrise surprise" fog or low cloud event exists when the decision to land occurs in the dark, but landing occurs at or just after sunrise. Factors that hamper the ability to forecast for the SLF include:

—Lack of high resolution satellite imagery at night.
—Meteorological processes associated with land/sea interfaces.
—Limited surrounding observation sites.

The WSR-88D in Melbourne has been a great assistance in overcoming the difficult forecast situations for Shuttle operations. The STS-57 and STS-51 missions are examples of how the WSR-88D helped provide the data to allow for safe Shuttle operations that included landings at the SLF.

4. STS-57 Mission

The Space Shuttle Endeavor launched from KSC on 21 June 1993 at 1307 UTC after a one-day delay due to weather. Endeavor landed at the SLF at 1253 UTC on 1 July 1993 after a nine-day, 23-hour and 15-minute mission of satellite rendezvous and retrieval, scientific research and experimentation, and a two-day landing delay due to weather.

a. Launch

1) Launch attempt—20 June 1993

The first STS-57 launch attempt was on the morning of 20 June 1993. The mean low-level flow was southeasterly with high pressure dominating the weather over Florida. Showers persisted over the water and moved northwestward during the launch count. Figure 2 shows the Composite Reflectivity (CR) and Echo Tops (ET) products for the expected launch and RTLS time. Reflectivity values of 45 dBz and echo tops to

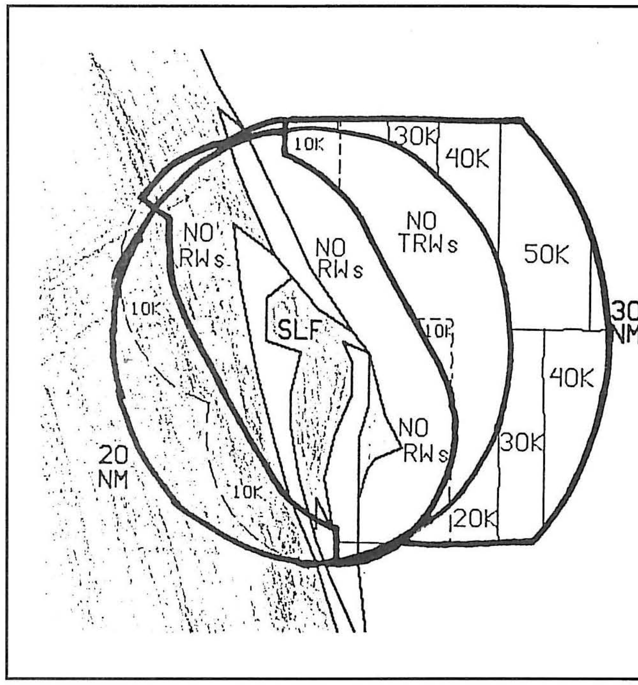

Fig. 1. Diagram of the Shuttle RTLS precipitation and thunderstorm flight rules. Tops must not exceed the height indicated in thousands of feet for those regions specified. 20 and 30 nm radius circles are noted.

20,000 feet are present within the 30 nm circle. Low ceilings and rain showers at the SLF, as well as ceilings and crosswinds at the TAL sites, caused a 24-hour delay.

2) Launch—21 June 1993

Weather again threatened the launch on 21 June. A southeasterly low-level flow helped cause persistent, isolated rain showers over the Atlantic southeast of the SLF beyond the 30 nm circle. The scheduled launch time was approximately 30 minutes earlier than the day before. Skies were clear initially, but cumulus clouds began to develop as the launch time approached. Echo Tops products and Reflectivity Cross-Section products were used in conjunction with the Shuttle Training Aircraft (STA) pilot reports to determine the extent of development and movement of this activity. Reflectivity values of 30 dBz and echo tops below 15,000 feet were seen over the water. Although some development was evident, showers remained below the flight rule constraint at decision time. Endeavor lifted off the pad without a second to spare. Showers occurred at the SLF within the hour following RTLS time. The STA pilot, astronaut "Hoot" Gibson, stated that as he flew the approach to the SLF at the RTLS time, the developing clouds would have made it a difficult landing. Figure 3 is the CR product for 1309 UTC, which depicts the isolated shower activity within the 30 nm circle at launch time.

b. Landing

From the outset, the flight control team and NASA mission managers wanted to land Endeavor at the SLF. This would save significant processing time and expense in preparation for Endeavor's next mission—the repair of the Hubble Space Telescope.

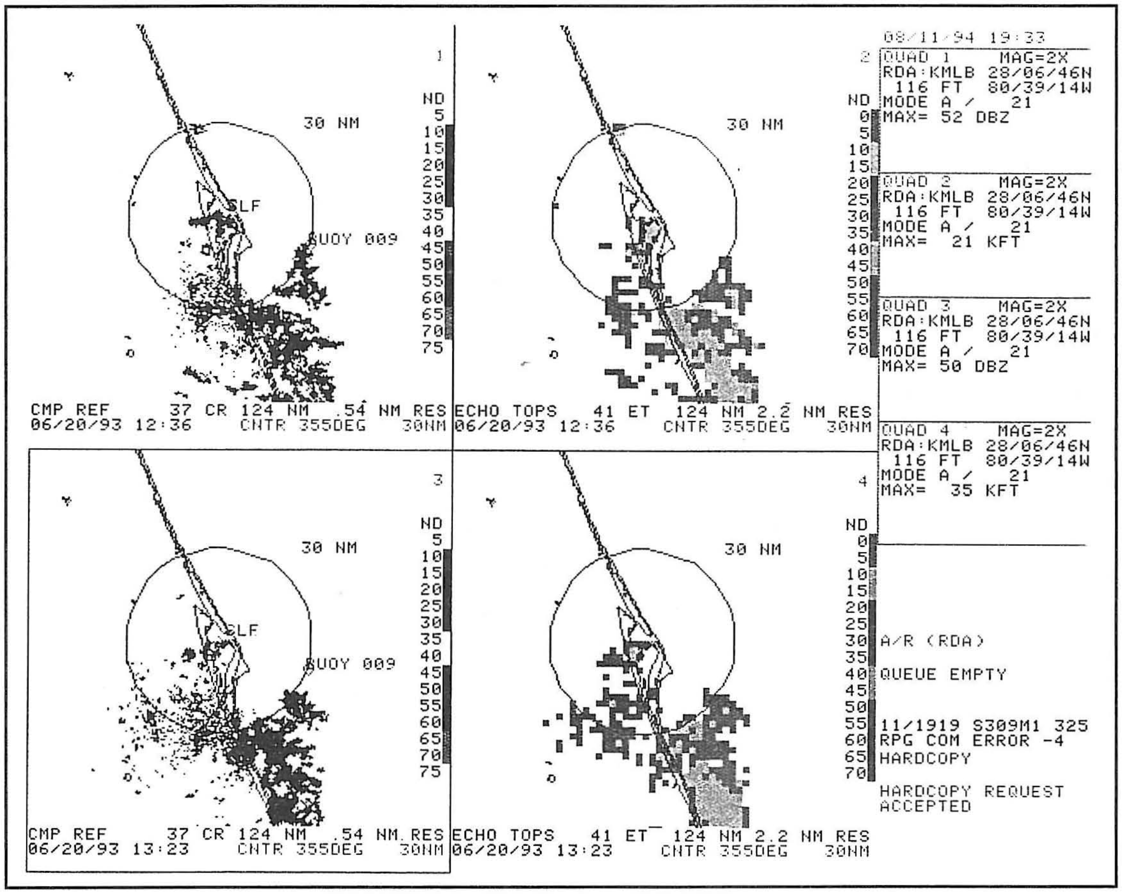

Fig. 2. WSR-88D CR and ET products from 1236 UTC and 1323 UTC corresponding to the expected launch and RTLS times for 20 June 1993. Reflectivity values of 45 dBz and echo tops to 20,000 feet are evident within 30 nm of the SLF.

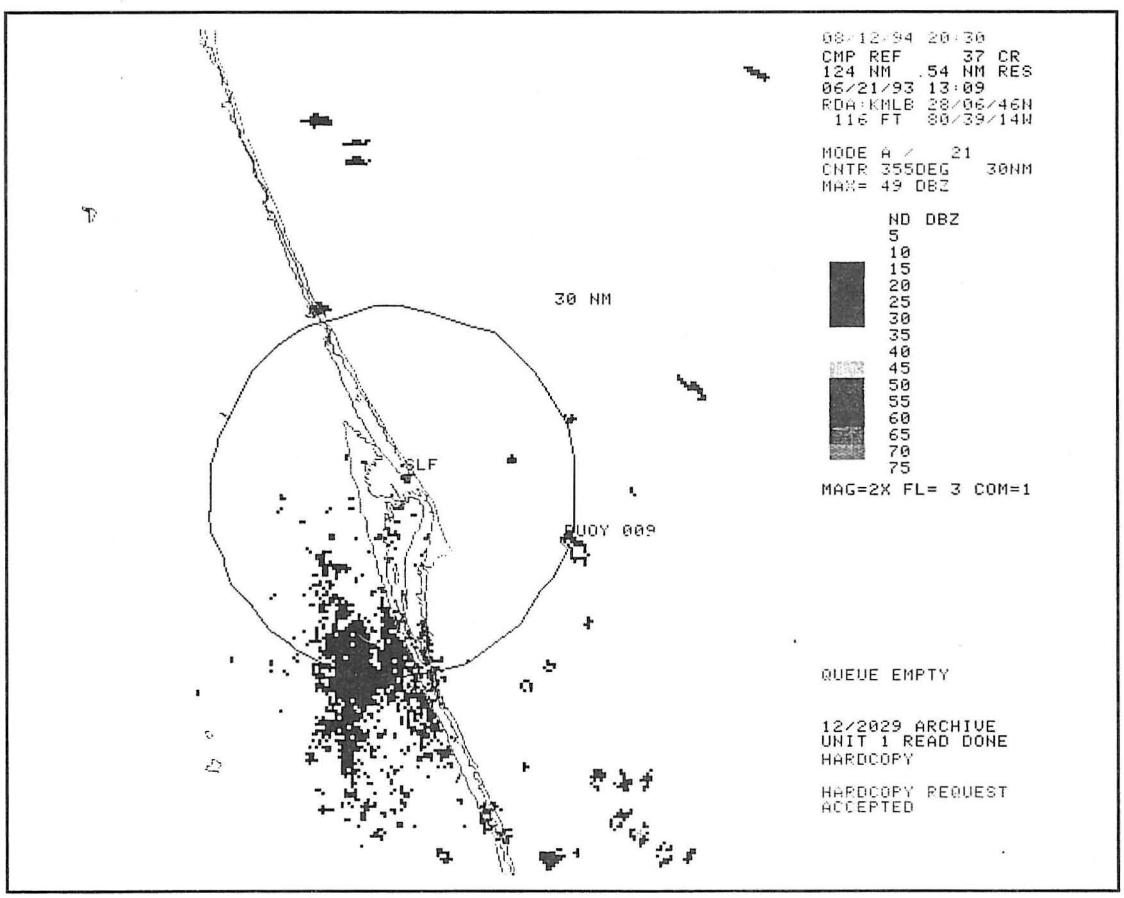

Fig. 3. WSR-88D CR product for 1309 UTC 21 June 1993 (STS-57 launch time). Isolated showers remained offshore and below flight rule constraints.

1) Landing attempts—29 June 1993

Weather at Edwards AFB, the alternate/backup landing site, remained "GO" throughout the mission. Mission managers felt that as long as the "good weather" continued at Edwards AFB, the team would make every attempt to land the Shuttle at the SLF as planned.

The initial landing day at KSC looked promising even though there was a threat of rain showers. Reflectivity cross-sections were used to interrogate upstream echoes. Surface observations were limited, but it was apparent that mid-level precipitation was increasing the low level moisture fields upstream from the SLF. Although no showers occurred, cloud development began early and increased to 3/10s coverage prior to making the "GO/NO GO" forecast for the initial landing opportunity. Figure 4 is a four-panel display of CR and ET products for the decision time and expected landing time. Isolated showers with tops to 15,000 feet were developing within the 30 nm circle north of the SLF as evidenced by the CR and ET products. Although cloud conditions remained SCATTERED in the low levels, the STA pilot recommended "NO GO" for landing due to low clouds obscuring the landing navigation aids aim-point. The forecast was amended to reflect the "NO GO" condition. Rain shower activity occurring within 30 nm precluded an attempt at the second landing opportunity at the SLF that day.

2) Landing attempts—30 June 1993

The following day, a line of thunderstorms moved through the SLF during the time that the landing opportunities occurred. SMG meteorologists tracked the movement through the area. Even though it was an obvious "NO GO" day, i.e., precipitation occurring within 30 NM, flight controllers pressed SMG to determine whether the line would clear the area in time for the second landing opportunity that day. Figure 5 is the four-panel display of the CR and ET products valid for the first landing opportunity and the decision time for the second landing opportunity. Composite Reflectivity values of 50–55 dBz and ET up to 45,000 feet are depicted. Composite Reflectivity returns from behind the initial line caused concern about using the second landing opportunity. Thus, the decision was made to wave-off for the second day in a row.

3) Landing—1 July 1993

Weather conditions improved somewhat on July 1st, but the initial forecast still reflected the threat of precipitation. Rain showers did develop over the western portion of Florida, but none were in the area of the SLF. The plan was to land at the SLF on the first opportunity. If weather prevented this, then Endeavor could land on the next orbit at either the SLF or at Edwards AFB. This strategy allowed for a final additional Edwards AFB opportunity should the earlier attempts for a KSC SLF landing prove unacceptable. Figure 6 shows the CR product for the de-orbit decision time with the thunderstorm and shower activity over western Florida.

The weather remained "GO" at the SLF for the first opportunity and Endeavor's main gear touched down at 1252 UTC. Not since 1986, prior to the Challenger accident, had there been a two-day weather wave-off for a Shuttle landing.

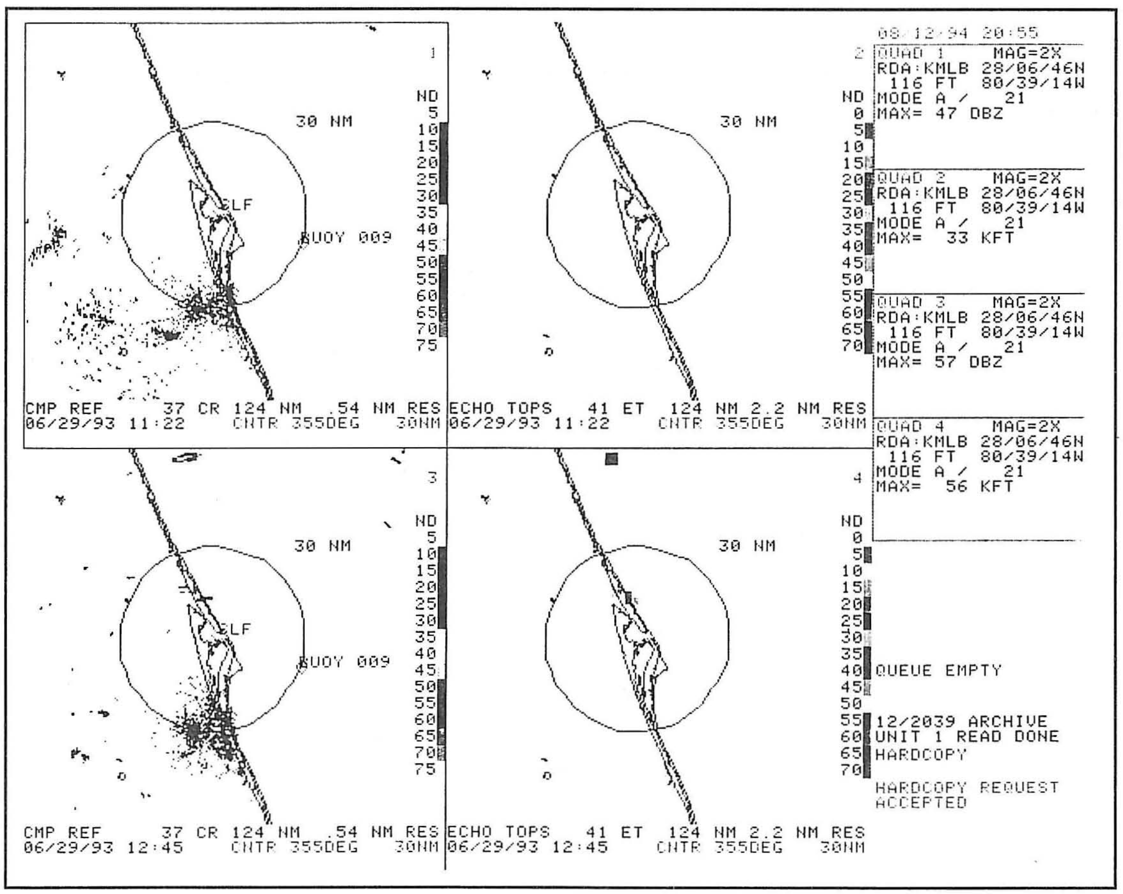

Fig. 4. WSR-88D four-panel display of CR and ET products for the 29 June 1993 de-orbit decision time (1122 UTC) and the expected landing time (1245 UTC).

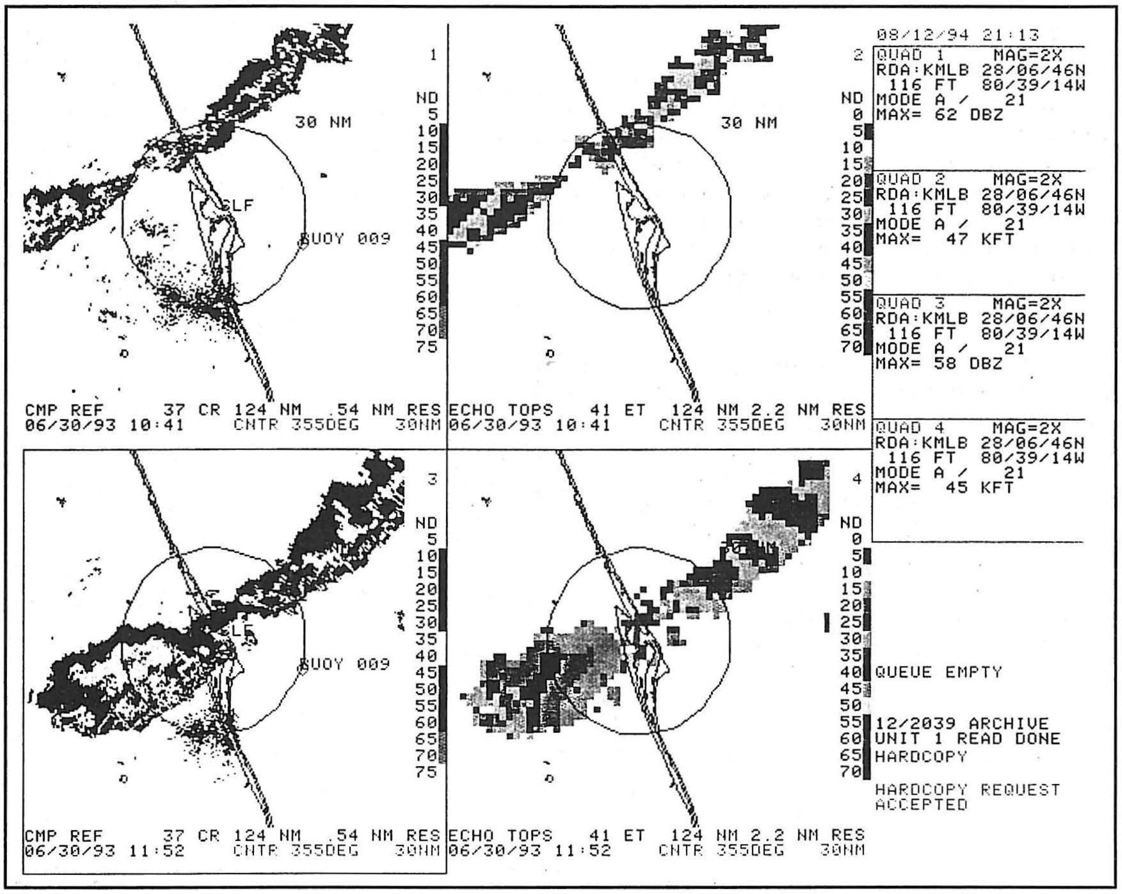

Fig. 5. WSR-88D four-panel CR and ET product for 30 June 1993 first (1041 UTC) and second (1152 UTC) de-orbit decision times.

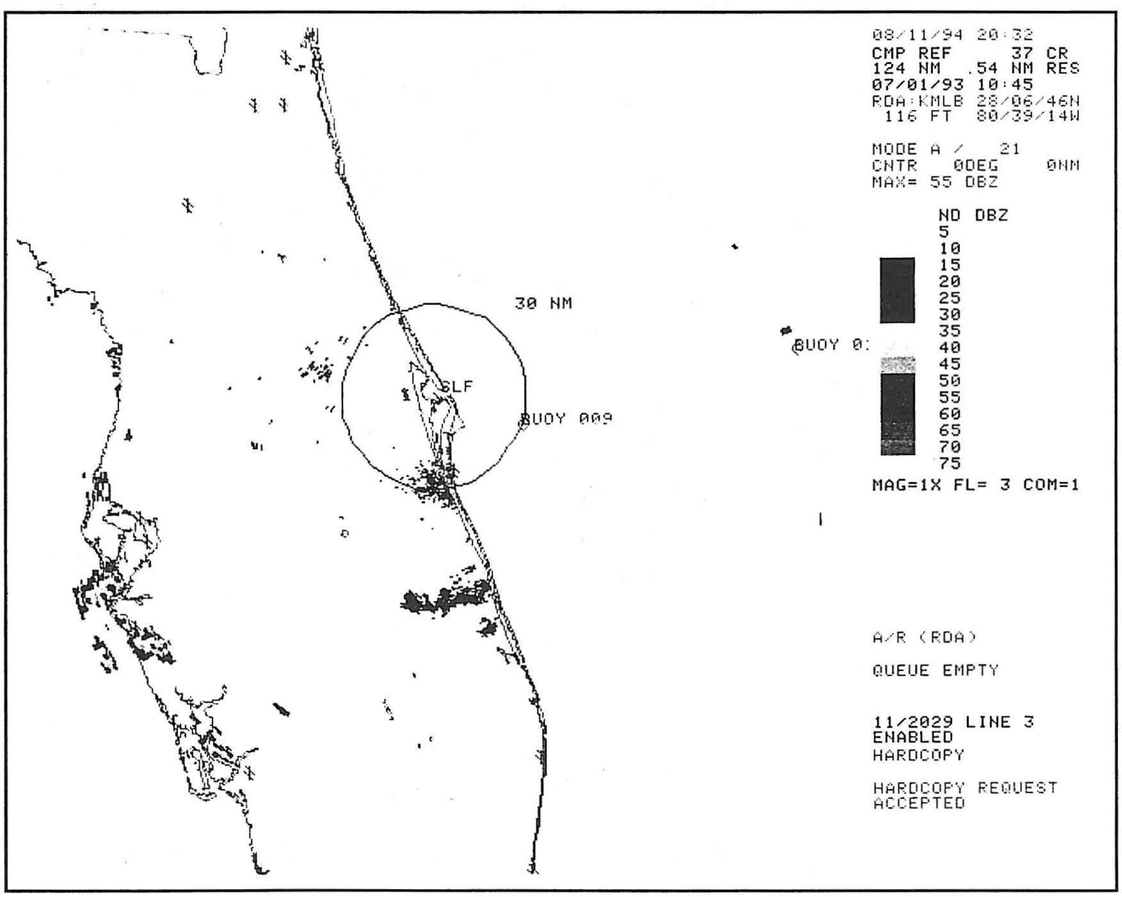

Fig. 6. WSR-88D CR product for de-orbit decision time (1045 UTC) prior to landing—1 July 1993. Only "clutter" is observed within the 30 nm circle.

5. STS-51 Mission

The STS-51 mission was originally scheduled for launch on 17 July 1993, but hardware failures caused a cancellation in the final few minutes of the countdown. Additional launch dates were set and two more attempts were made before the actual launch occurred on 12 September 1993. The ten-day mission deployed an advanced communications satellite and a scientific data collection platform, which was also retrieved. The mission ended with the first-ever night landing at the SLF.

a. Launch

The primary weather concern for the early morning launch on 12 September 1993 was precipitation. A weak frontal zone was located in the area. The mean flow below 10,000 feet was less than 10 knots from the northeast. Shower and thunderstorm activity were confined to the Gulf Stream waters east of the SLF. Over the Florida Peninsula, low stratus and fog were reported but this did not extend into the vicinity of the SLF.

As the scheduled launch time (1145 UTC) approached, the chance for showers within 20 nm remained in the forecast for the RTLS. One intensifying rain shower was encroaching on the 20 nm radius circle. By 1123 UTC, the WSR-88D storm tracking algorithm had identified a "storm" with a 50 dBz core 22 nm to the northeast of the SLF (Fig. 7). The cell had formed along an outflow boundary from thunderstorm activity further to the east. The boundary itself was just within 20 nm. Reflectivity cross-sections through the storm indicated that the precipitation top was near 24,000 feet. Visual reports from NASA's STA indicated that the storm was dissipating.

Based upon the STA report and precise tracking of the precipitation by the WSR-88D, a forecast for rain showers within 20 nm, but outside flight rule constraints was issued 17 minutes prior to launch. The shower dissipated following launch. The shower's remains and the outflow boundary with 25 dBz reflectivity were observed 15–17 nm northeast of the SLF 25 minutes following the launch of STS-51, the valid time of the RTLS forecast.

b. Landing

Landing proved another challenge—a night landing at the SLF. Night SLF landings had been attempted on two previous missions only to be "waved-off" to Edwards AFB due to weather. During the STS-51 landing, satellite data would be limited. The semi-annual eclipse of the geostationary satellites caused a two and a half hour break in satellite imagery. Additionally, the NOAA polar-orbiting satellite would not pass close enough to Florida to provide usable high resolution infrared imagery. While both the METEOSAT-3 and GOES were utilized, there was a period when no satellite imagery was available. Lastly, the lack of any moonlight made it difficult for the STA pilot to scout for weather. The Melbourne WSR-88DD proved a most valuable asset.

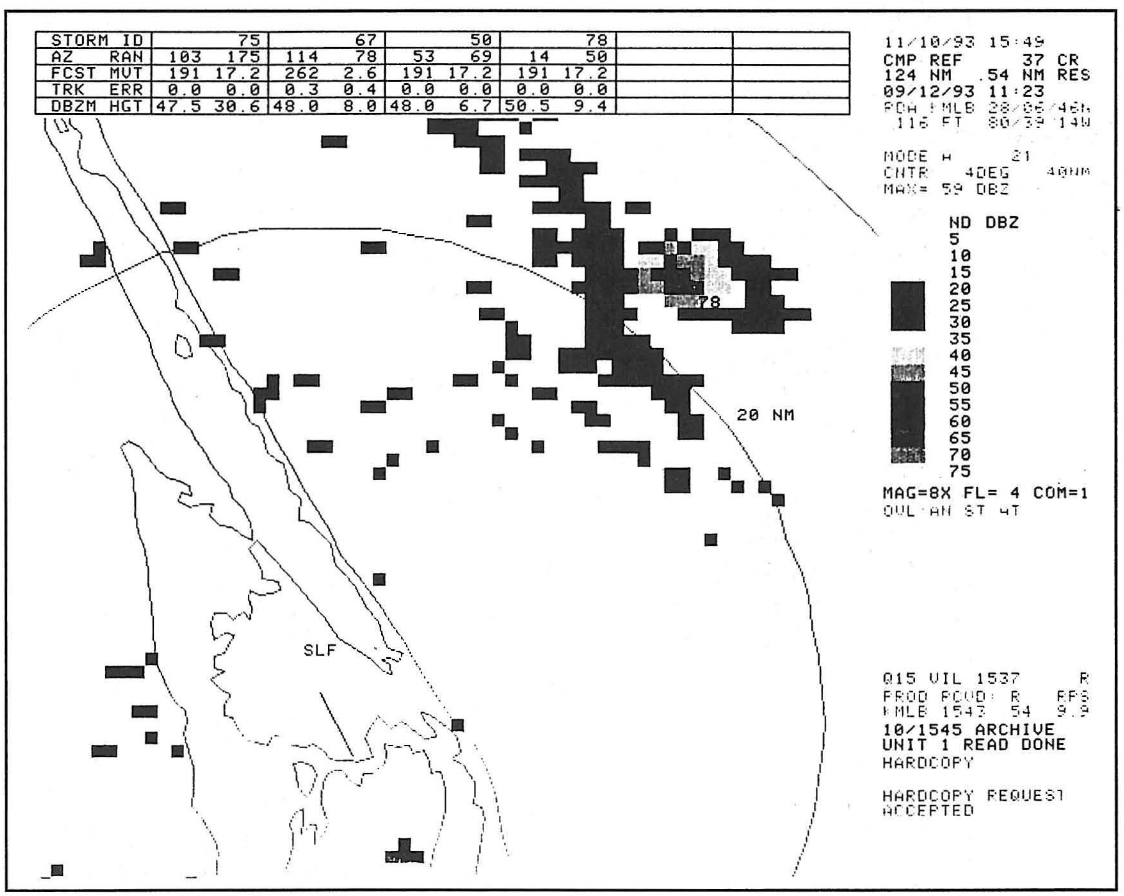

Fig. 7. WSR-88D CR product from 1123 UTC 12 September 1993. Reflectivity values less than 20 dBz have been filtered. A 20 nm radius circle around the SLF is overlaid on the product. Storm ID 78 located northeast of the SLF shows maximum reflectivity of 50 dBz.

1) Landing attempts—21 September 1993

STS-51 was scheduled to land at the SLF on 21 September at 0932 UTC. If successful, it would be the first nighttime landing at the SLF. The challenge was to predict the development of showers. The WSR-88D CR product from 0537 UTC reveals only a single isolated shower 20 nm west northwest of the SLF (Fig. 8). When reflectivity values as low as 5 dBz were included in the reflectivity products and a time lapse sequence was viewed, "lines" of low reflectivity values were evident. These lines, oriented northwest to southeast and propagating slowly to the north, were a result of thunderstorm outflows to the southeast of the SLF. Interestingly, the base velocity data did not show these features due to very weak nor non-existing convergence. The storm relative mean radial velocity map (SRM) products also did not identify the cloud lines, but did identify a very pronounced land breeze boundary along the coast. The relative velocity computation and the smaller contouring interval of the SRM product allowed for the detection of this boundary. While not initially appearing too significant, the cloud lines became the focus for new rain shower development. The 0555 UTC CR product (Fig. 9) shows this new shower development with 50 dBz maximum just southeast of the SLF. The lines were tracked for several hours with new rain shower development along the coast in the vicinity of the SLF. Consequently, the decision was made not to attempt the 0932 UTC landing. Discovery's Astronauts did not "suit-up" and the payload bay doors remained open. Rain showers continued to violate the flight rule for landing at the deorbit decision time.

The last attempt for the day was at 1103 UTC. Showers were on the decrease from earlier in the night and the cloud boundaries were less evident on the WSR-88D. The SRM products showed that the land breeze boundary had progressed east over the barrier islands. Low level convergence was also observed in the mesoscale wind tower network that surrounds the SLF. Due to the convergence in the wind field and the boundaries detected using the WSR-88D, the forecast for rain showers to remain within 30 nm of the SLF was provided to mission management. Landing was postponed until the following day.

2) Landing attempts—22 September 1993

The first inspection of the weather situation showed a strong squall line of thunderstorms progressing south down the Florida Peninsula ahead of a cold front. At 0304 UTC, the CR product (Fig. 10) showed extensive precipitation activity to the southwest through north of the SLF. All of the activity was moving south at 10 knots and was on a diurnal downward trend. The focus of attention then turned to the cirrus anvils that would be within 30 nm of the SLF. Flight rules state that anvil cirrus must be detached and thin for more than 3 hours to assure safety to the orbiter returning from space.

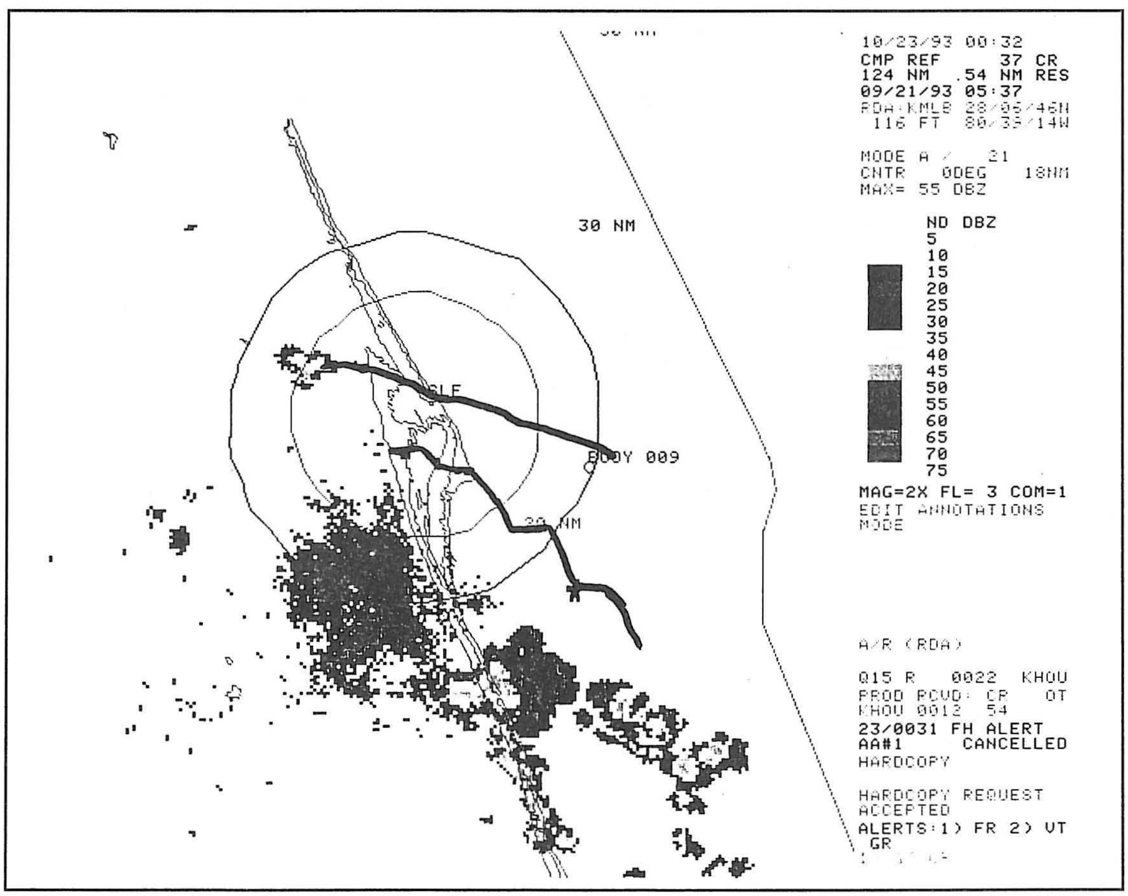

Fig. 8. WSR-88D CR product from 0537 UTC 21 September 1993. Reflectivity values less than 15 dBz have been removed. 20 and 30 nm range rings surround the SLF. The dark lines indicate "lines" detected in the lower reflectivity values.

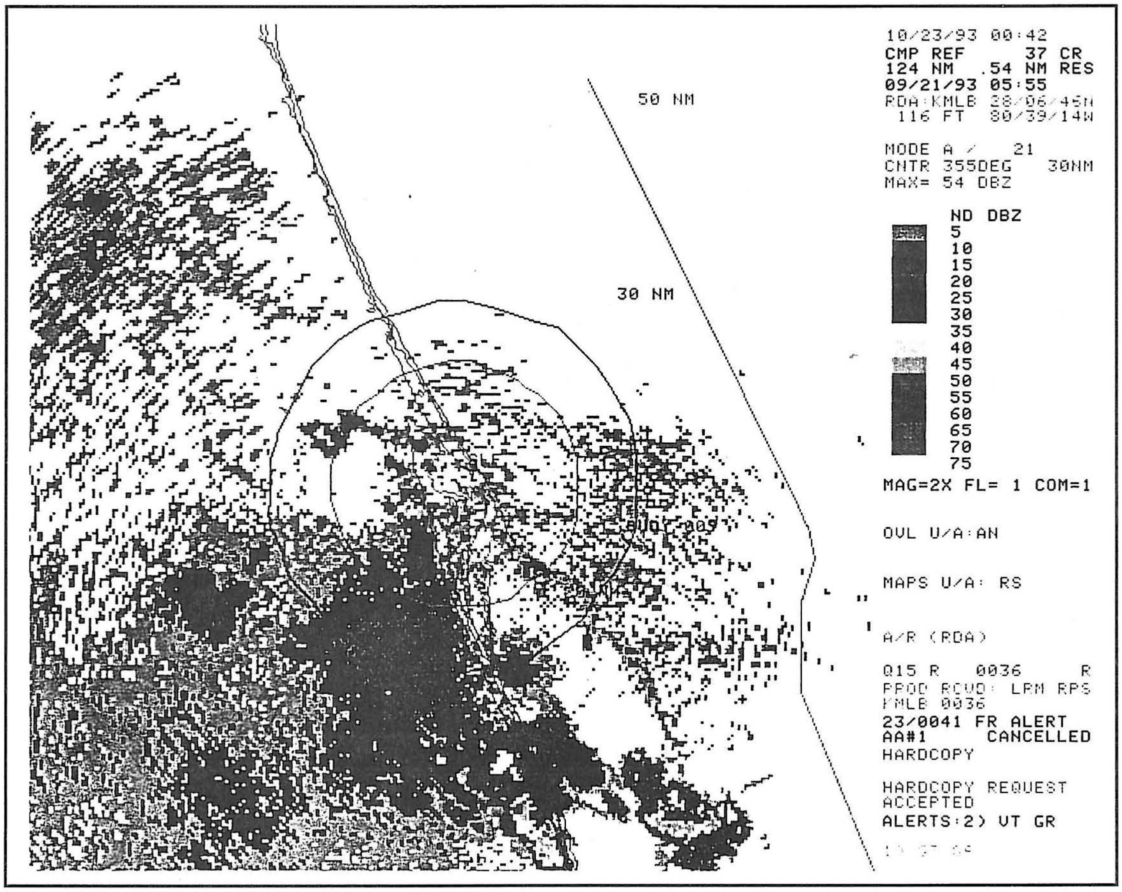

Fig. 9. WSR-88D CR product from 0555 UTC 21 September 1993. 20 and 30 nm range rings surround the SLF.

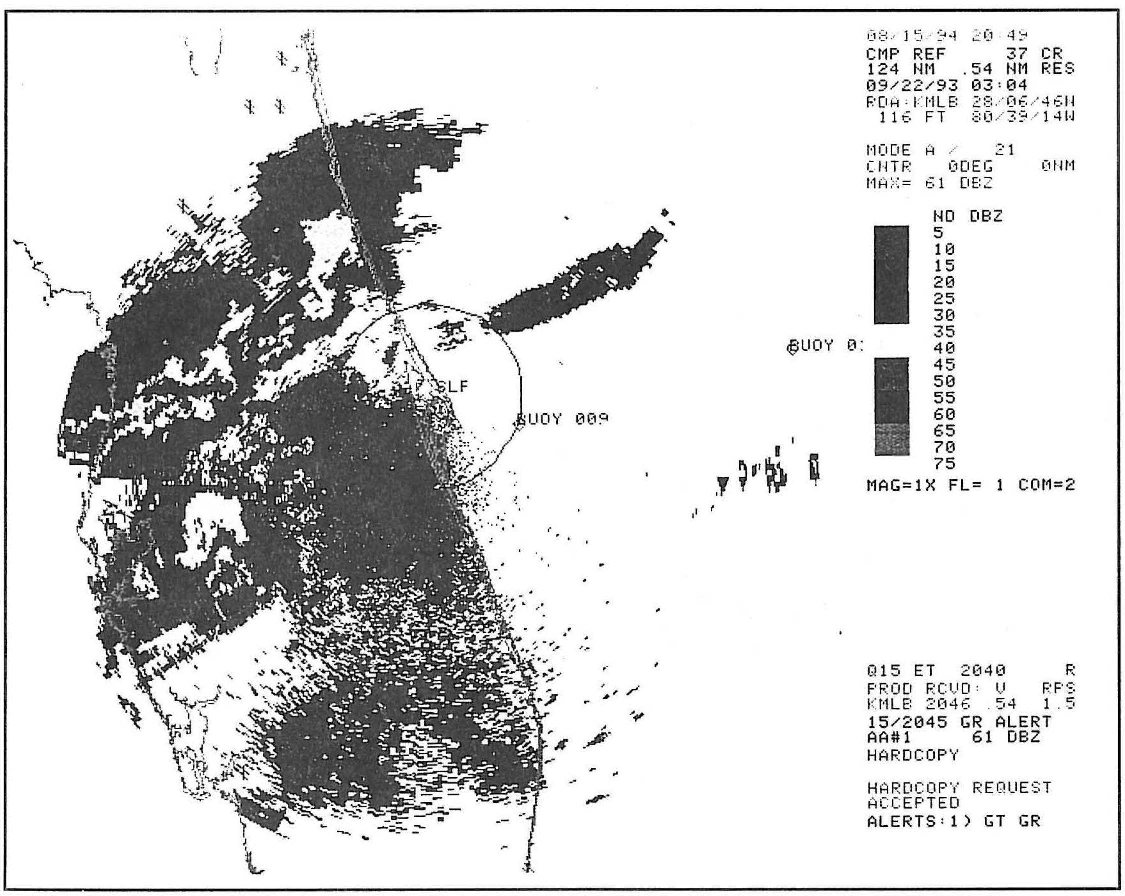

Fig. 10. WSR-88D CR product from 0304 UTC 22 September 1993. A 30 nm radius circle surrounds the SLF.

The reflectivity returns to the northeast of the SLF were suspicious. The elongated, streak-like appearance of the "echoes" strongly resembled chaff that is commonly observed over northern and central Florida. Reflectivity cross-sections (Fig. 11), showed the activity was low level, but ascending to the northeast. NASA had requested a suppression of all military chaff releases in the area, thus there was concern that the area could actually be precipitation. The other hypothesis was that the activity was smoke plumes from ships. When weather reconnaissance aircraft investigated the area, no precipitation was reported. Reconnaissance did note that there was an extensive fleet of (more than 50) "boats" in the area. The concern turned back to tracking thunderstorms and their anvil cirrus shields.

Reflectivity cross-sections combined with surface observations indicated the precipitation to the northwest through north was stratiform and falling from a 12,000 foot overcast cloud deck. By 0759 UTC, all precipitation had ended and only weak, but extensive, anomalous propagation returns were observed (Fig. 12) and the Space Shuttle Discovery made the first-ever night Shuttle landing at the SLF.

6. Conclusions

The WSR-88D provides meteorologists with observing and analysis tools far beyond that of conventional radars. The ability to track weak, but significant, reflectivity features allows identification of mesoscale boundaries that can result in precipitation and flight rule violations. WSR-88D velocity products can identify convergent boundaries that may not be detectable in reflectivity data. The ET and Reflectivity Cross-Section products help identify developing convection.

The use of WSR-88D reflectivity and velocity products together is needed to fully evaluate any given situation. In addition, it is advisable to utilize the full extent of the data range. Filtering out lower reflectivity values can result in failure to detect precipitation generating features. Minor changes in the velocity field can indicate significant boundaries. Use of lower velocity increments and the SRM product can assist in detecting convergent boundaries.

Space Shuttle landings at the SLF require precise forecasts. The WSR-88D has proven to be an extremely valuable diagnostic tool. As discussed in these pages, it allowed SMG meteorologists to accurately predict safe weather conditions for the STS-57 and STS-51 missions.

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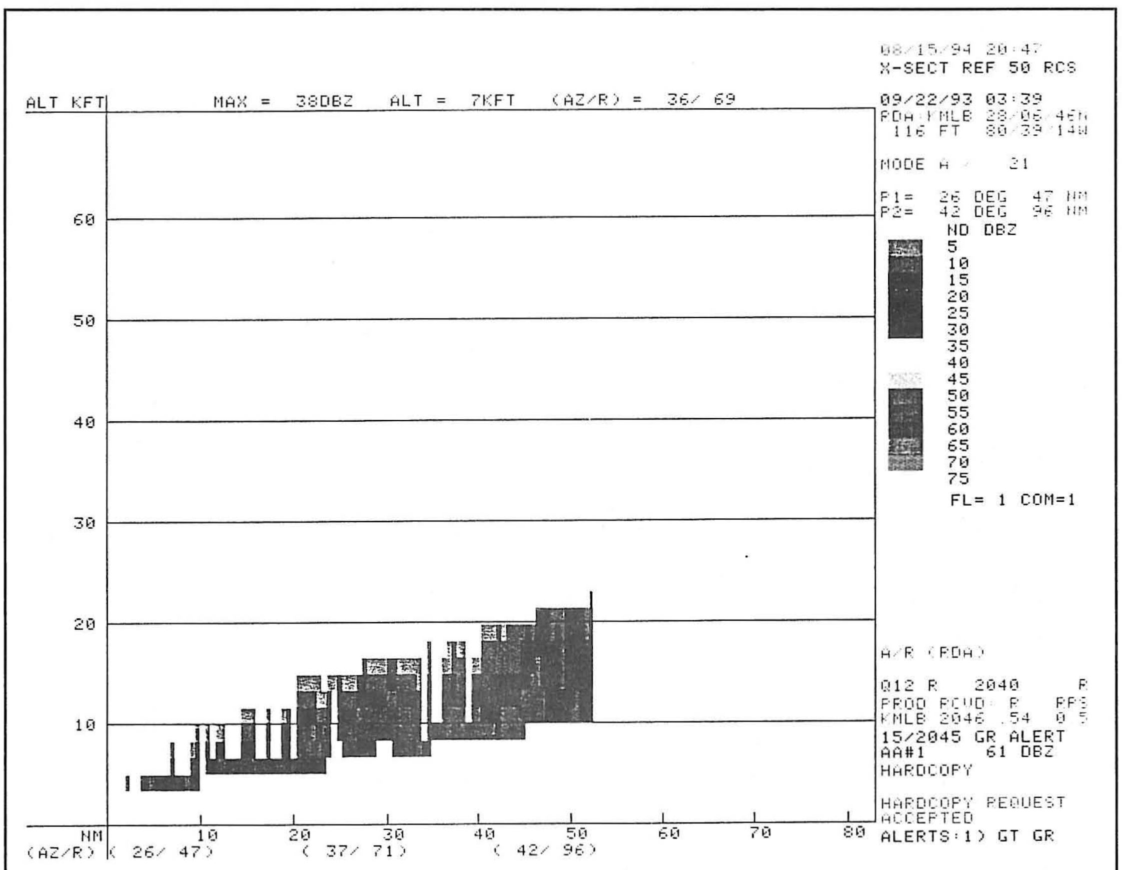

Fig. 11. Reflectivity cross section through ship smoke located to the northeast of the SLF.

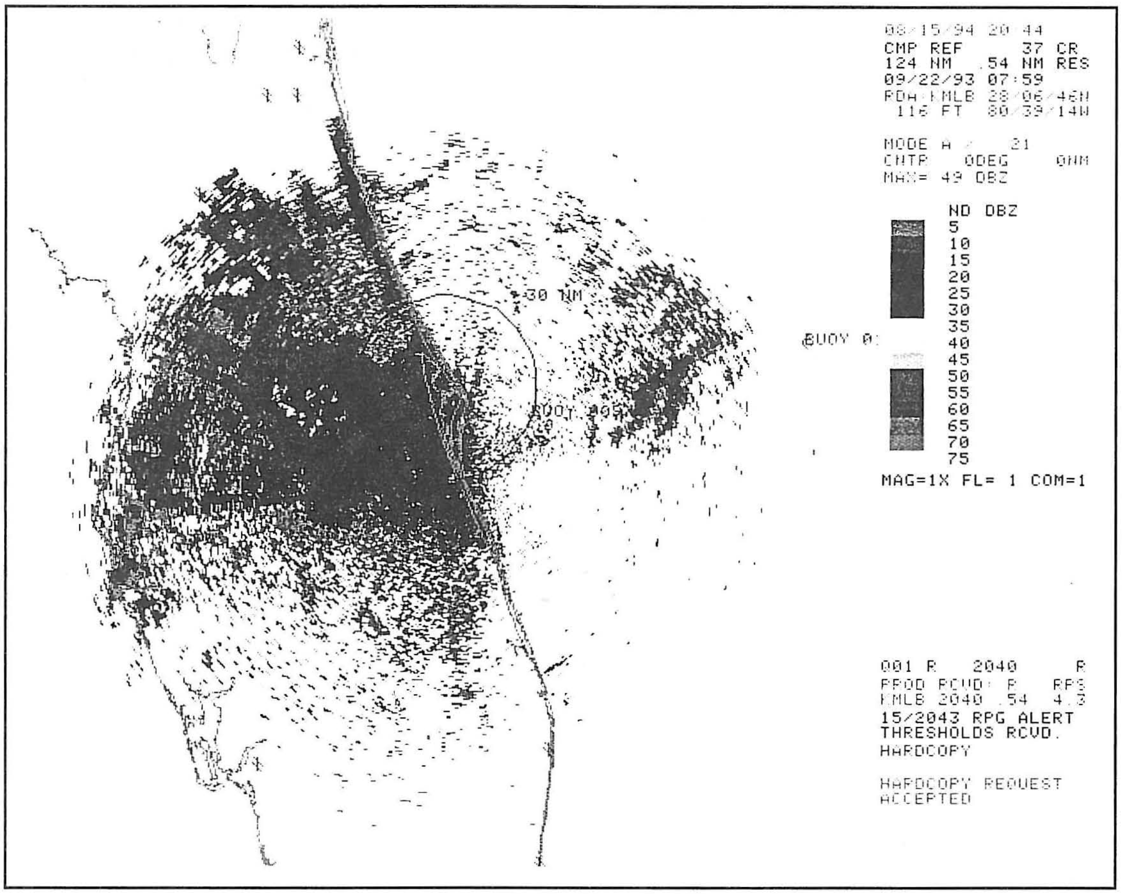

Fig. 12. WSR-88D CR product from 0759 UTC 22 September 1993.

57, STS-59 and STS-63. Prior to coming to the Johnson Space Center he was the Special Services Meteorologist, NWS Southern Region Headquarters. He was one of the original meteorologists to serve in the Fort Worth Center Weather Service Unit and he has served various forecast positions in the Fort Worth, San Antonio, and New Orleans Forecast Offices. He is a retired Colonel in the United States Air Force Reserves and has just completed twenty four years of service with the Texas Air National Guard. His last assignment was Air National Guard Assistant to the Deputy Chief of Staff—Operations and Plans, Directorate of Weather, Headquarters, United States Air Force. He received his B.S. degree in Mathematics from Baylor University in 1966 and his M.S. degree in Meteorology from Texas A & M University in 1972.

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