Space Shuttle Landing System Certification

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ABSTRACT

The Office of Aviation System Standards (AVN) has assumed flight inspection responsibilities for the space shuttle precision landing navigational aid under a recent agreement with the National Aeronautics and Space Administration (NASA).

This paper will discuss the background of the space shuttle landing system, locations and navigational aids, history of flight inspection by NASA, and the development of the capability to assume flight inspection of the precision navigational aid, named the Microwave Scanning Beam Landing System.

INTRODUCTION

For the NASA space shuttle, also referred to as the Space Transport System (STS), or orbiter, flight rules require all designated landing sites be inspected and certified every two years by actual flight-testing using shuttle receivers mounted in test aircraft. As necessitated by mission requirements, there are several facilities in the continental United States (CONUS), and several overseas facilities where MSBLS was installed to accommodate shuttle landings. The CONUS sites include Kennedy Space Center, near Titusville, Florida, White Sands Space Harbor, near Alamogordo, New Mexico, and Dryden Flight Research Center, near Edwards, California. These are the primary landing sites. Should an emergency develop, especially on launch, before orbit was obtained, the overseas locations serve as alternate landing sites. These sites include locations in Spain and Morocco.

As the shuttle approaches the landing site from a relatively high angle of approximately 22°, the entire service volume of the MSBLS is much larger than the actual used portion. The landing corridor is a cross-sector of the azimuth/elevation guidance proportional with the descent path of the shuttle. The horizontal boundary of the corridor lies within 2.5° of true runway heading, while the vertical boundaries are defined in two sectors.

Sector one is defined as from 12,000 feet above ground level (AGL) to 2,000 feet AGL. This sector considers a heavyweight shuttle executing a 15.5° glide slope to an aiming point 9,000 feet before runway threshold and a lightweight shuttle executing a 21.5° glide slope to an aiming point 5,000 feet before runway threshold.

Sector two is defined as from 2,000 feet AGL to 200 feet AGL. It consists of a 15.5° glide slope to an aiming point 9,000 feet before runway threshold and an 11.3° degree glide slope to an aiming point of runway threshold.

The NASA Microwave Scanning Beam Landing System (MSBLS) Flight Inspection and Certification System consisted of a comprehensive electronic system of computers, navigation receivers, and interface units between different data sources. The electronic components were rack-mounted on multiple cargo pallets placed in a C-130 or a C-135 aircraft. The pallets contained navigation receivers, data processing computer equipment, interface adapters, uninterruptible power supplies, remote display of real-time test data, and a display for the pilots that provided aircraft position relative to the required flight path. The data control and processing units consisted of high performance workstations that controlled and acquired navigation data from MSBLS, GPS, and TACAN receivers. Computers received position data from respective receivers and converted and compared the current GPS aircraft position to MSBLS and TACAN provided position information. A graphical presentation of differences between the GPS versus MSBLS and GPS versus TACAN data was displayed and recorded for data reduction purposes. The real-time processing of GPS and MSBLS position data allowed any required adjustment and alignment of the MSBLS to be performed during flight checks.

MSBLS is used during the terminal area energy management, the approach and landing flight phases, and return to launch-site aborts. The orbiter is equipped with three independent MSBLS sets, each consisting of a Ku-band receiver/transmitter and decoder. Data computation capabilities determine elevation angle, azimuth angle, and orbiter range with respect to the MSBLS station. The MSBLS provides highly accurate three-dimensional navigation position information to the orbiter to compute vector components for steering commands that maintain the orbiter on its proper flight trajectory.

HISTORY AND OPERATION OF MSBLS

HISTORY

The MSBLS is a predecessor of the Microwave Landing System (MLS). Originally developed as a United States (US) Navy automatic carrier landing system, the US Navy and Swedish forces presently use it for precise landing guidance.

OPERATION OF MSBLS

MSBLS Ground System MSBLS is a Ku-band (15.4 to 15.7 GHz) precision approach and landing system which provides slant range, azimuth, and elevation data to the orbiter from approximately 18,000 feet and 15 nm through touchdown.

Unlike a conventional microwave landing system, the MSBLS does not provide a published procedural azimuth track at a fixed angle of descent. It provides the shuttle's Guidance, Navigation, and Control (GN&C) computer continuous azimuth, elevation, and range signal offsets relative to the appropriate MSBLS antenna phase center. The GN&C computer, in turn, steers the shuttle on a programmed approach and landing profile containing multiple azimuth tracks and elevation angles.

MSBLS distance measuring equipment (DME) signals, due to the 15.4 – 15.7 GHz transmit frequency, cannot be received using conventional DME receivers.

Each runway at an STS landing site has two MSBLS siting possibilities: MSBLS Ground Station (MSBLS-GS) or MSBLS Junior (MSBLS-JR) configurations.

The MSBLS-GS configuration provides azimuth and DME through landing rollout, and elevation to touchdown. Two equipment shelters are included; one for azimuth/ distance, the other for elevation. Both shelters contain primary and standby equipment and antennas (strings).

(a) Azimuth/ DME and elevation shelters are both located 300 feet offset right or left from runway centerline (500 feet at military installations).

(b) The azimuth/ DME shelter is located 1,300 feet beyond the rollout end of the runway. *Newer MSBLS-GS installations may have the azimuth sited 1,500 feet prior to the rollout end of the runway.*

(c) The elevation shelter is located 3,360 feet from runway threshold. *Newer installations may have the elevation sited 1,500 feet from threshold.*

The collocated MSBLS-JR configuration provides azimuth/ DME and elevation guidance up to runway threshold, but cannot support rollout guidance. Single transmitter/antenna azimuth and elevation facilities are included in a single equipment shelter. *MSBLS-JRSW configuration includes two MSBLS-JR sites installed side-by-side.*

(a) Runway offsets remain the same as the MSBLS-GS configuration

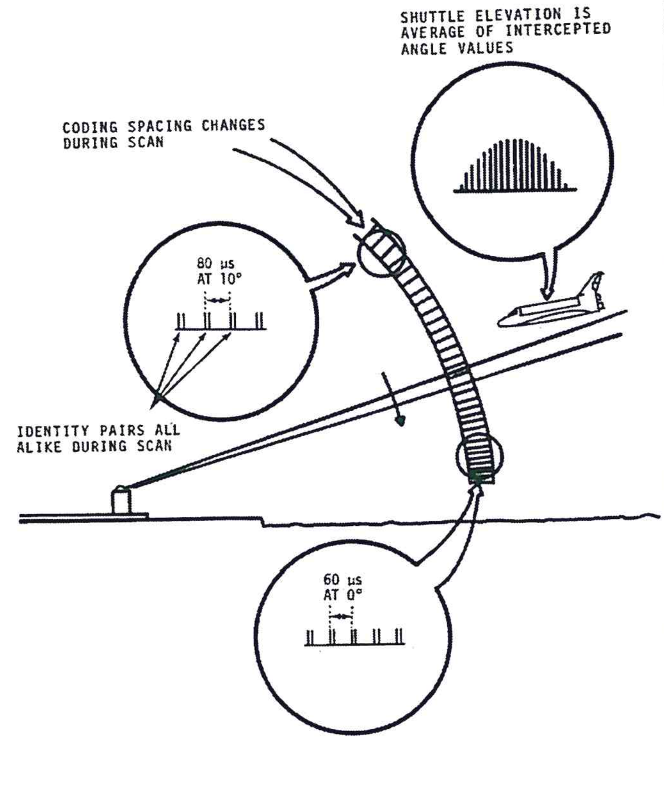
(b) Shelter to threshold distance is a standard 1,500 feet

Azimuth and elevation data are broadcast by rapidly oscillating antennas that produce narrow, fan-shaped radio beams, which are pulse-pair encoded with the ground antenna's present pointing angle. The MSBLS provides steering commands to the STS via a highly accurate three-dimensional navigation position to maintain the orbiter on its proper flight trajectory until over the runway approach threshold, at an altitude of approximately 100 feet.

Basic MSBLS Operation The three MSBLS components operate on a common channel during the STS landing phase. The MSBLS transmits a DME "solicit" pulse. The onboard MSBLS receiver responds with a DME interrogation pulse. The ground equipment responds by transmitting a return pulse. A decoder in the onboard MSBLS decodes the pulses to determine range, azimuth, and elevation. Range is a function of the elapsed time between interrogation pulse transmission and signal return. Azimuth pulses are returned in pairs. The spacing between the two pulses in a pair identifies the pair as azimuth and indicates which side of the runway the orbiter is on. Spacing between pulse pairs defines the angular position from runway centerline. The spacing between the two pulses in a pair identifies the pair as elevation, and the spacing between two pulse pairs defines the angular position of the orbiter above the runway. Figure 1 shows the pulse-coding concept.

The azimuth antenna produces a narrow, planar-shaped vertical beam that scans horizontally through the approach volume, 0° to 23° high and 13.5° right and left of runway centerline. This beam is encoded with the antenna's azimuth angle from 0° at center of scan. The azimuth information is encoded on the scanning azimuth beam by varying the spacing between pulse pairs. The pulse-spacing code is 60 microseconds at 0° plus two microseconds per degree from 0°. The spacing between pulses in a pair tells the airborne user that azimuth information is being transmitted and whether the angle is in the fly-left portion of coverage (10 microseconds between pulses in a pair) or the fly-right portion of the coverage (14 microseconds between pulses in a pair).

The elevation beam produces a similar, planar-shaped horizontal beam that is scanned vertically 1.3° to 29° high, 25° right and left of runway centerline. The elevation beam is encoded with the antenna's elevation angle from the horizon. The identity spacing (between pulses in a pair) for elevation is 12 microseconds. The code is, once again, 60 microseconds for 0° plus 2 microseconds per degree from 0°.

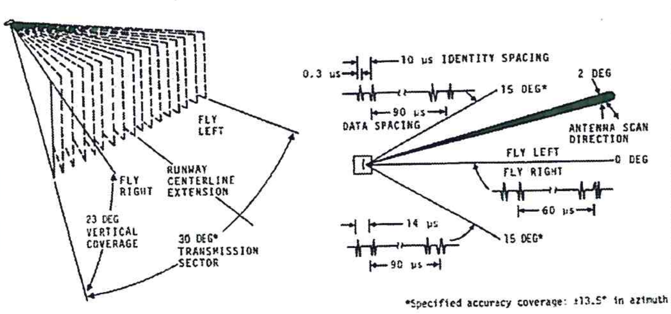


Pulse-position coding of elevation beam.

Figure 1. MSBLS Pulse Coding Approach

As the two directional antennas alternately scan through the approach volume, the antennas on the approaching orbiter vehicle intercept these ground-originated signals when the spacecraft is within the beam of the ground station antennas. The detection circuits within the navigation set accept only those pulse pairs that are above a threshold amplitude level. By placing limits on the number of data spaces (between 8 and 127), errors due to beam shaping and multi-path reflections are minimized. The navigation set decodes the intercepted signals and averages the pulse-pair spacing to obtain the elevation angle of the orbiter. A similar function is performed for the azimuth angle.

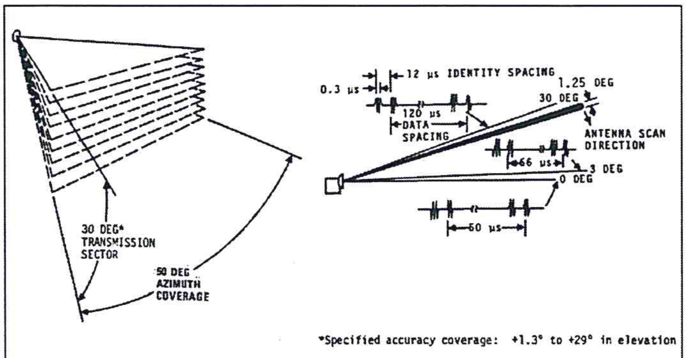
The azimuth and elevation antennas are electronically synchronized so that only one antenna is radiating at any particular time. The azimuth and elevation antennas are oscillated in a sinusoidal fashion. The azimuth antenna oscillates ± 44° about azimuth center, parallel to the runway, but only transmits ± 15° in the same area. Azimuth coverage is shown in Figure 2.



Azimuth coverage and pulse coding.

Figure 2. MSBLS Azimuth Coverage

The elevation antenna oscillates ± 24° about a 15° rest angle, but transmits only within the sector from 0 to 30° of elevation, above the horizontal, as shown in Figure 3.



Elevation coverage and pulse coding.

Figure 3. MSBLS Elevation Coverage

In the time period that precedes the azimuth transmission and follows the elevation transmissions, distance information is transmitted. Once every 200 milliseconds, a set of azimuth, elevation, and distance information is transmitted by the ground station and processed by the airborne navigation receiver.

Azimuth and DME assemblies are co-located on the ground and time-share a transmitter. The AZ/ DME "GS" ground station is located near the stop-end of the runway to provide centerline guidance and distance information through touchdown and rollout. The elevation station is located near the expected touchdown point to provide touchdown guidance.

The MSBLS has a dual-redundant uninterruptible power supply (UPS). The UPS contains batteries that allow 15 minutes of operation after loss of facility power.

The azimuth and elevation "angle" field monitors are special purpose receiver/ decoders looking for a particular azimuth/ elevation signal. The monitor receives the coded RF signal, converts it to a digital form, and accumulates its deviation from the signal it expects to receive. The DME field monitor interrogates the DME ground station as the orbiter would when it desires distance data. The MSBLS DME provides slant range to facility distance measurements with errors less than 100 feet.

NASA INSPECTION OF MSBLS

NASA developed a pallet-based flight inspection system for inspecting MSBLS, and used it on C-130 and KC-135 aircraft. Installation and removal were required each time inspections were preformed. The larger aircraft worked well, as they could also carry ground navigation aids personnel and a large amount of support equipment. Laser tracker, Radio Telemetering Theodolite (RTT), Global Positioning System (GPS), and eventually, Differential GPS were used as truth systems for MSBLS flight inspection. It was found that the MSBLS beams would bend toward the earth, and this had to be included in the calculations in order to properly inspect and adjust the facilities. On the aircraft, a radome was installed on the bottom of the fuselage, and within the radome were horn antennas, and a waveguide switch. NASA had a rear-facing horn, in addition to a forward-facing and 2 side facing horns. This allowed approach, orbits, or arc profiles, and even outbound profiles to be performed.

The MSBLS receiver utilizes the military standard (MIL-STD) 1553 data encoding scheme for output of data and for control, and tuning of the receiver. NASA's flight inspection system utilized this MIL-STD 1553 data directly, and processed errors from the output words as compared to the truth system.

FAA FLIGHT INSPECTION PROCEDURES

Flying an aircraft at the high angles of shuttle approaches to the runway is not feasible. As a result, numerous level radial runs, arcs, and approaches are flown.

Radials of 0° (centerline), ±3°, ±6°, and ± 9° are flown at an altitude of 8000 feet, and from a distance of 20 nautical miles (NM) from the facility to 3 NM from the facility.

Clockwise (CW) and counterclockwise (CCW) orbits or arcs are flown, at an altitude of 8000 feet, a distance of 15 NM, and ±15 degrees azimuth. Approach profiles include 1.5°, 2°, 3° and 4°, with a landing rollout on one of the approaches.

Azimuth, elevation, and DME coverage and accuracy are evaluated concurrently for each maneuver.

a. Approaches. Multiple approaches are flown to runway centerline (RWY CL) and the MSBLS azimuth antenna centerline (MSBLS CL) between 1.5° and 4° elevation angles, to sample MSBLS position accuracy in the vertical plane. The flight inspection profile is terminated when the aircraft transitions out of the usable horizontal coverage of the System Under Test (SUT) identified as ±13.5° from the azimuth antenna and ±20° from the elevation antenna.

During commissioning-type inspections of each MSBLS-GS string, the aircraft continues on the extended glide path angle on one of the RWY CL approaches to the touchdown point. The landing roll is continued the length of the runway to measure azimuth accuracy and coverage. On commissioning-type inspections of collocated MSBLS-JR and MSBLS-JRSW configurations (each string), flight check continues on the extended glide path angle on one of the RWY CL approaches to the touchdown point.

On all other inspections, one RWY CL approach on each MSBLS string is checked, crossing runway threshold at approximately 50 feet. The aircraft conducts a low approach at 50 feet down the length of the runway or beyond the horizontal coverage of the SUT, whichever occurs first. The MSBLS CL 4.0° approach is evaluated to a point abeam runway threshold at approximately 50 feet. The remaining approaches terminate at runway threshold.

b. Lateral Arcs. Arcs are used to evaluate the lateral limits of the azimuth, elevation, and DME facilities within horizontal MSBLS coverage.

MSBLS accuracy and coverage are evaluated to 13.5° both sides of MSBLS CL. Flight check provides the NASA NAVAIDS engineer with real-time elevation "roll" results. Any elevation error imbalance over the course of the arc could be caused by a tilt in the scanning elevation antenna.

c. Radials. Level runs provide a cross-section analysis of the MSBLS-GS (see Figure 4) and MSBLS-JR/ JRSW (see Figure 5) guidance within vertical coverage at pre-selected azimuth settings.

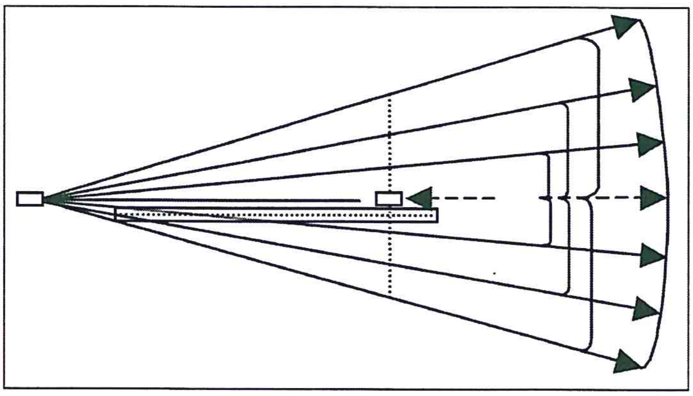


Figure 4. MSBLS GS Radial Profiles

MSBLS accuracy and coverage is evaluated between vertical angles of 1.3° to 23.0°, at pre-selected azimuth angles. The NASA NAVAID engineer is provided with real-time azimuth "roll" results for the 8,000 feet AGL

MSBLS CL run. Any noticeable azimuth error imbalance along the radial could be caused by a tilt in the scanning azimuth antenna.

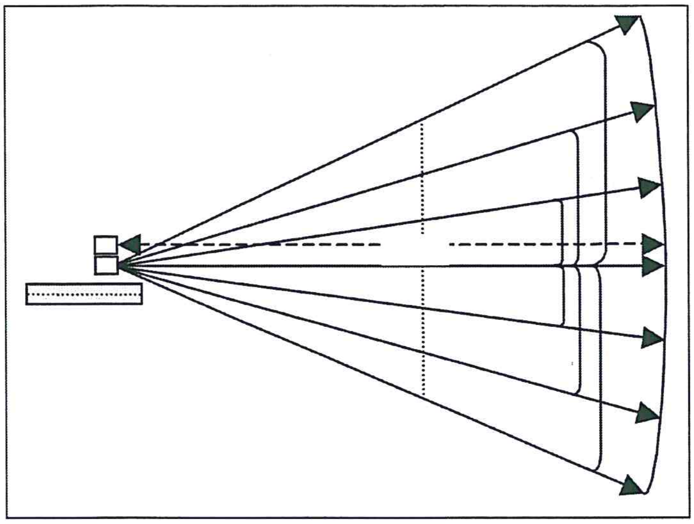


Figure 5. MSBLS JR Radial Profiles

d. DME. MSBLS DME is checked on all runs and evaluated for accuracy and coverage throughout the service volumes.

FLIGHT INSPECTION ANALYSIS

Maximum MSBLS azimuth and elevation system error tolerance is 0.05° within azimuth angles ±10° of MSBLS CL, and shall be allowed to increase linearly to ±0.10° at azimuth angles ±13.5° from MSBLS CL.

a. The azimuth/elevation error measured by flight check on each run is acceptable if the mean alignment is less than ±0.015° and 68% of the data samples collected fall within ± 0.05° of the zero baseline. This analysis applies separately to the overall measurement area and the orbiter corridor.

b. Standard deviation indicates the dispersal of data sample errors from the mean alignment. The NASA NAVAIDS engineer is advised if this value exceeds ± 0.05°.

c. DME must meet tolerances within the MSBLS service volume.

d. Expected azimuth and elevation "roll" error is 0.10° or less.

Tolerances

Mean azimuth and elevation alignment error shall not exceed 0.015° of the composite bias with respect to the airborne truth system. Composite bias is defined as the accumulative mean MSBLS error of *all combined* flight profiles. Azimuth and elevation errors are computed separately for tolerance application. Mean DME error shall not exceed 100 feet with respect to the airborne truth system.

Weather Limitations

MSBLS flight inspection is normally limited to fair weather conditions. At the discretion of the NASA NAVAIDS engineer, the flight inspection will be terminated if precipitation on the ground adversely affects the MSBLS signal propagation.

Reports

Flight inspection reports accurately reflect the operating parameters of the MSBLS. They are the means to certify the operational status of the facility and the quality of signals-in-space. Reports generated by the Automated Flight Inspection System (AFIS) shall be utilized to report MSBLS flight inspection results. Interim flight inspection reports are provided to on-site NASA personnel on request. Final flight inspection reports and recordings will be distributed and archived IAW FAA Orders 8240.36 and 1350.15. The automated MSBLS Flight Inspection Report page is provided as the final flight inspection report for each MSBLS string.

Flight Certification

The FAA is now responsible for commissioning, periodic, and special MSBLS flight inspections, as defined in FAA Order 8200.1, current edition, and applicable NASA directives.

Commissioning: Comprehensive testing to determine the capability of the MSBLS, as installed at a particular location, to support the STS mission. Flight tests to demonstrate system capabilities over a large volume of coverage are performed, and tests to measure site peculiar characteristics may be conducted. A commissioning flight inspection is performed for an initial installation before the system is committed to operational support.

Periodic: Scheduled comprehensive flight inspections sufficient to demonstrate that the MSBLS continues to meet *commissioning standards* and support its operational requirements. The minimum frequency of periodic inspections shall be two years, and the inspection will be considered completed within the periodic interval, if accomplished from 60 days before until 60 days after the due date. More frequent inspections may be made when deemed necessary or as requested by NASA.

Special: Inspections performed outside the normal periodic interval. They may be used to define/ evaluate performance characteristics of systems, subsystems, or individual facilities. NASA shall be responsible for coordinating the flight inspection checks that are to be accomplished with the FAA, based on NASA requirements and type of maintenance performed on the equipment.

SYSTEM IMPLEMENTATION

The existing AVN flight inspection Challenger CL-601 aircraft was chosen to implement the MSBLS flight inspection system into, due to the overseas requirement, and ability of the CL-601 to efficiently fly long distances to reach the locations. NASA-provided MSBLS receiver and interrogator, DGPS receiver, DGPS data link receiver, a data converter, a timing pulse converter, and associated antennas were installed on the CL-601. Existing AFIS software was modified to process MSBLS data. The existing AFIS computer utilizes ARINC 429, in addition to discrete and analog inputs and outputs. It does not have an existing MIL-STD 1553 capability. The data converter was specified, procured and installed to convert the MIL-STD 1553 data to ARINC 429 format.

Technical Implementation

The MIL-STD 1553 nature of the MSBLS receiver required the specification of a data converter which would convert both the receiver output data from 1553 format to ARINC 429 format, and would also convert ARINC 429 command and control data into MIL-STD 1553 format command and control data.

As this was not a simple conversion, in either direction, a specification was written, and bids were solicited for purchase of a compliant converter. Bids were submitted from several companies, from several different countries, and a technical evaluation of the bids was performed. The selected company produced the converter in strict adherence to the specification, and the converter performed as intended.

In order to perform accurate error calculations on MSBLS data as compared to truth system data, a method of synchronizing was required. The MSBLS receiver time tags each azimuth, elevation and distance data word. The time tags are actually a differential time, in milliseconds, from an externally applied 1 Hz pulse source. The AFIS computer also receives this 1 Hz synchronization pulse. The DGPS receiver outputs a 1 Hz pulse, and also time tags the DGPS position, velocity and time data with an offset from the 1 Hz pulse. This DGPS 1 Hz pulse was used as an input to a timing pulse converter. The timing pulse converter transmits a buffered pulse to the MSBLS receiver, and an ARINC 743 differential pulse to the AFIS computer.

The MSBLS horn antennas were mounted behind the nose radome. Figure 4 shows the antennas behind a raised radome. The maximum path loss from the receiver to the outside air was specified to be 7 decibels (db) by NASA, so the length of radio frequency (RF) cables, losses through switches, adapters, and radome attenuation were factors that had to be considered. Testing was done on the radome, at the 15-16 GHz frequencies, and at the locations that the horn antennas would receive signals through. Using RF cables rather than waveguide greatly simplified the mechanical installation. With the relatively short cable lengths, the loss was kept under 7db.

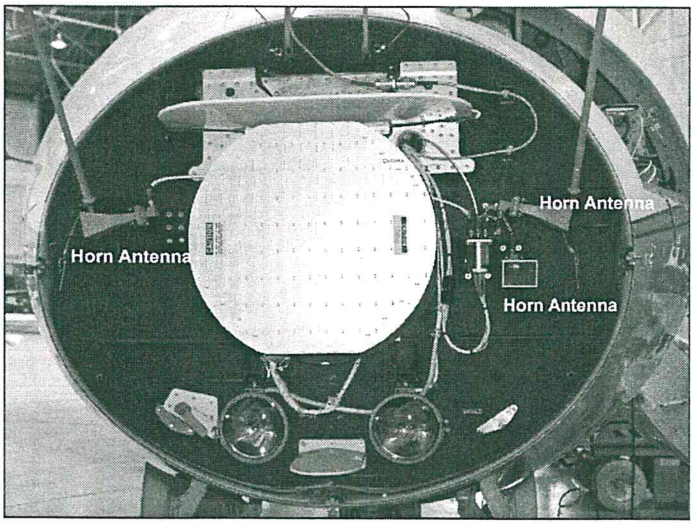


Figure 6. MSBLS Horn Antennas

After flight testing, it was found that the forward facing horn antenna was more susceptible to a noisy RF environment, possibly due to reflections in the radome. A conformal antenna, similar to the type the shuttle uses, was then installed aft of the radome. This antenna proved to be better on approach runs. During this flight testing, a multi-path problem was experienced, which caused errors on elevation and distance to deviate noticeably. This was a brief occurrence, and though it was eventually judged to be a tolerable condition for the facility, it caused in-depth investigation, as NASA flight testing had not shown this anomaly.

CONCLUSION

The MSBLS flight inspection responsibility has been transferred from NASA to the FAA. The implementation of the capability involved the normal flight inspection challenges: implementing a truth system, choosing flight inspection profiles, acquiring the signal in space, processing, analysis, and reporting. Unique aspects of the MSBLS include the frequency range of the signal in space, the tolerances, the MIL-STD-1553 data format, and the time tagging of data.