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Development of the Spirit III Telescope: from Design through Test

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ABSTRACT

This paper documents the development of the SPIRIT III telescope from the design through its test activities at SSG, Inc. The SPIRIT III Instrument is the primary infrared instrument on the Mid-Course Space Experiment (MSX). The telescope is an all reflective optical system consisting of twelve mirrors. It represents the largest high straylight rejection, cryogenic telescope built by SSG to date. The nominal collecting aperture is 14 inches. It was designed and built to integrate with a multi-color radiometer and a Michelson interferometer built by the Space Dynamics Laboratory at Utah State University. Key performance features are discussed and measured test data is presented. These include: an internal scan mirror assembly, low scatter mirrors and baffle assemblies, cryogenic optical performance and contamination control. The structural/thermal trade-off issues of a satellite-based cryogenic instrument are presented along with a review of the test techniques and test equipment utilized at SSG to qualify the SPIRIT III telescope.

1. OPTICAL DESIGN

The SPIRIT III telescope configuration is shown in block diagram form in Figure 1.0. The telescope consists of three optics modules - an afocal high straylight rejection optics module, the radiometer optics module, and the

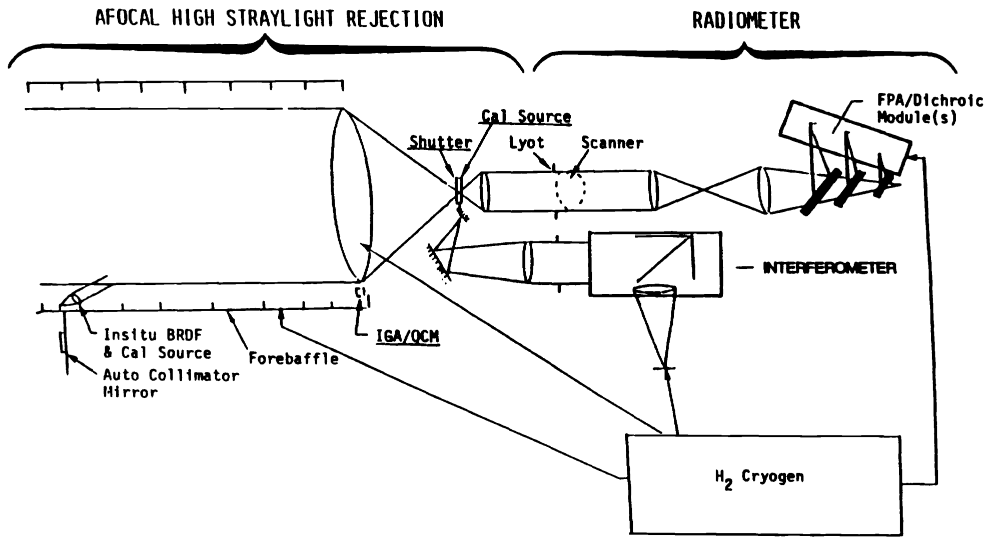

Figure 1.0. Spirit III telescope block diagram

interferometer optics module. The afocal optics operate at 4:1 magnification and image the 14.5 inch diameter entrance aperture to the Lyot stop which is located on the scan mirror assembly. The entrance aperture is located in the baffle assembly approximately 32 inches from the primary mirror. The afocal optics are: a concave off-axis parabolic primary, a convex off-axis hyperbolic secondary, a concave off-axis parabolic tertiary, and a fold flat. The first field stop is located between the secondary and tertiary. It is at this first field stop where the telescope splits the energy between the radiometer and the interferometer channels. The first field stop contains two rectangular apertures. The radiometer aperture is 3.0 x 1.0 degrees and allows the 0.3 x 1.0 degree IFOV of the radiometer to be scanned by 3 degrees in object space. The interferometer field is 0.86 x 0.7 degrees. The combination of low scatter finishes on the primary and secondary mirrors, the baffle assembly, the entrance aperture, Lyot stop, and field stops produce the required high straylight rejection performance of the SPIRIT III telescope. These issues are discussed in section 4.3 of this paper. Figure 2.0 shows the location of the optical elements in the system.

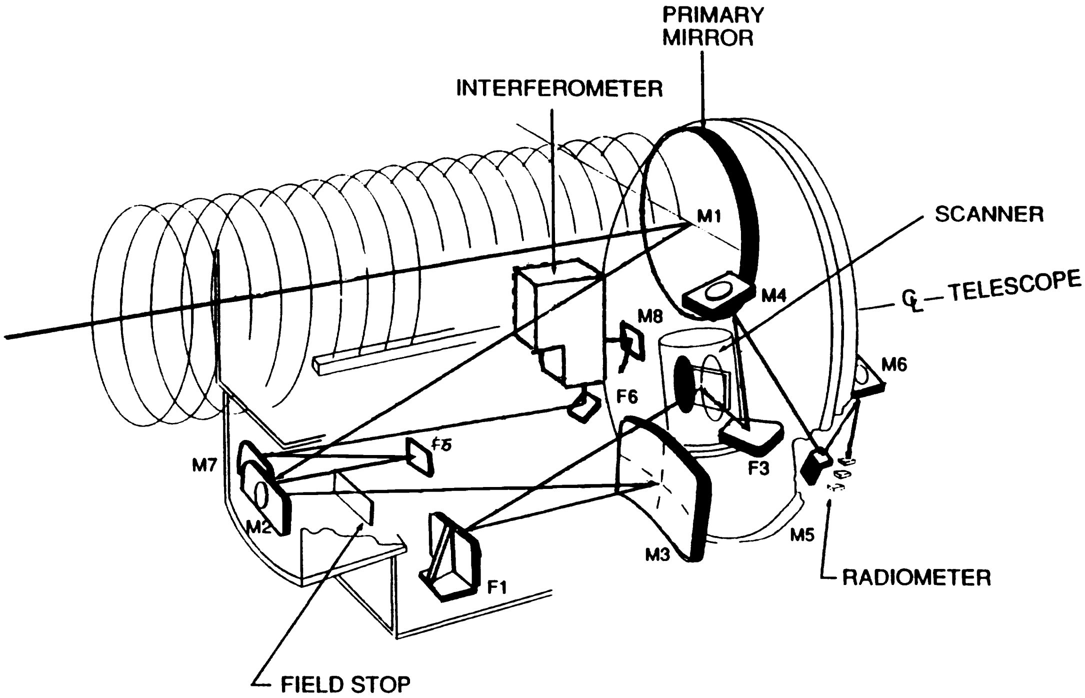

Figure 2.0. Spirit III optical layout

The radiometer optics consist of a three mirror reimager, the scan mirror assembly and a fold flat. The 3.5 inch diameter collimated output of the afocal front end feeds into the scan mirror assembly. The energy is directed by the fold flat to the first mirror in the reimager. This element is a concave ellipse which focuses the energy through the second field stop (0.3 x 1.0 deg aperture). The remaining two optical elements - a convex sphere and a concave sphere reimage the energy onto the focal planes. The radiometer focal planes consist of three focal plane/dichroic modules which were built by Space Dynamics Laboratory at Utah State University (SDL\USU).

The interferometer optics split off at the first field stop as previously mentioned. These optics provide a 1.6 inch diameter collimated beam to the Space Dynamics Laboratory Michelson interferometer.

2. MECHANICAL DESIGN

The mechanical design of the SPIRIT III telescope was based on the design concepts and techniques developed for the SPIRIT II telescope and other previous SSG cryogenic high straylight rejection telescopes.[1] Figure 3.0 shows a photograph of the completed telescope prior to shipment to the Space Dynamics Laboratory. To achieve an athermal telescope, the entire structure, mirror substrates and their mounts are made from 6061 aluminum. The main structural assembly consists of the telescope main plate and the optics housing. The main plate of the telescope, shown on the right side of Figure 2.0, is the key interface point of the telescope to the SDL\USU radiometer and the Lockheed cryostat. The main plate is 34 inches in diameter and the baffle assembly extends 50 inches off the main plate. The optics housing consists of many precision machined aluminum plates that along with the main plate were dip brazed together to form one rigid "optical bench". The dip brazing process produces an assembly that has the structural characteristics of a single part. It also results in an assembly that has excellent heat transfer properties which minimizes thermal gradients in the telescope at its operating temperature of 20K. SSG has utilized dip brazing on at least ten previous telescope systems including the CLAES telescope which in currently in orbit aboard the Upper Atmospheric Research Satellite (UARS).[2] The optics housing and its covers contain the mounts for all the mirrors and the interfaces for the SDL\USU shutter assembly and interferometer.

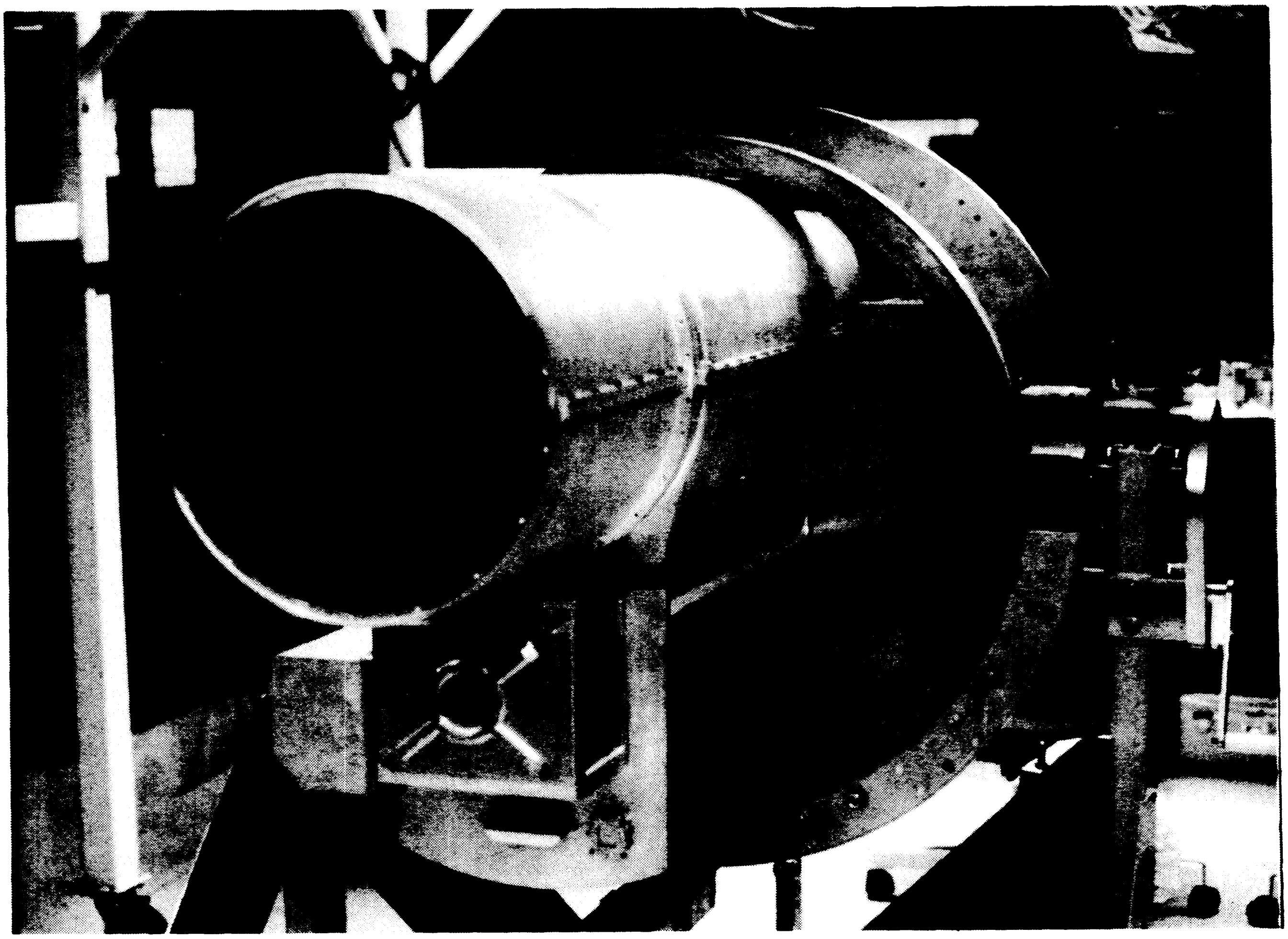

Figure 3.0. Completed telescope

The telescope structural design was driven by the environmental test levels required by the MSX program. The random vibration levels produced the highest stresses into the telescope. SSG successfully tested the completed telescope in a qualification and acceptance level random vibration testing. The thermal design requirements had the following nominal temperature limits.

- Optics & Structure: Less than 20K
- Baffle Assembly: Less than 70K
- Focal Plane Assemblies: 10K

To achieve these design requirements, SSG and SDL\USU utilized several thermal design techniques. The baffle assembly is thermally isolated from the telescope structure. This aluminum assembly is supported off the main plate by a G-10 isolator. The details of the baffle isolator are described below. The SDL\USU radiometer FPA assembly is also thermally isolated from the telescope structure through three G-10 pedestals. In addition, the thermal design has the telescope structure and optics, the baffle, the radiometer, and the interferometer separately heat sunk to the Lockheed cryogen.

The baffle isolator is an interesting example of the trade-offs required to meet the structural and thermal requirements of a satellite-based cryogenic instrument. The mission lifetime and the high random vibration levels were working against each other on this isolator. The telescope design required this isolator, shown in Figure 4.0, to support the entire baffle assembly. The baffle was not allowed to contact the telescope structure at any other point in order to minimize the thermal loads into the optical bench and therefore the cryogen assembly. An additional complication for this isolator was imposed during the conceptual design phase of the program. In order to maximize the collecting area of the telescope within the limits of the envelope the baffle isolator became "non-circular". The final design had two flat sections connecting the semi-circular halves of the isolator. SSG worked with a local vendor to produce the isolator to meet all the structural and thermal requirements. The G-10 was wound onto a precision mandrel to a create a uniform part of approximately 0.5 inches in thickness. The mandrel was machined to meet the tight mechanical tolerances of the ID of the isolator. It is 16.5 inches in diameter with two 1.4 inch long flat sections at the top and bottom. The length of the completed assembly is 6.5 inches. The G-10 was then machined to a wall thickness of 0.040 inches with three circumferential ribs and four lateral ribs. The lateral ribs were located at the flats to strengthen the part in these high stress areas. Many iterations of the structural, mechanical, and thermal analyses were expended to achieve the final design of this critical component. Several isolators were fabricated and tested to insure the success of the telescope. The prototype unit was tested in static compression and tension tests to verify the design analyses. The flight unit baffle isolator passed the telescope random vibration tests during the acceptance testing at SSG.

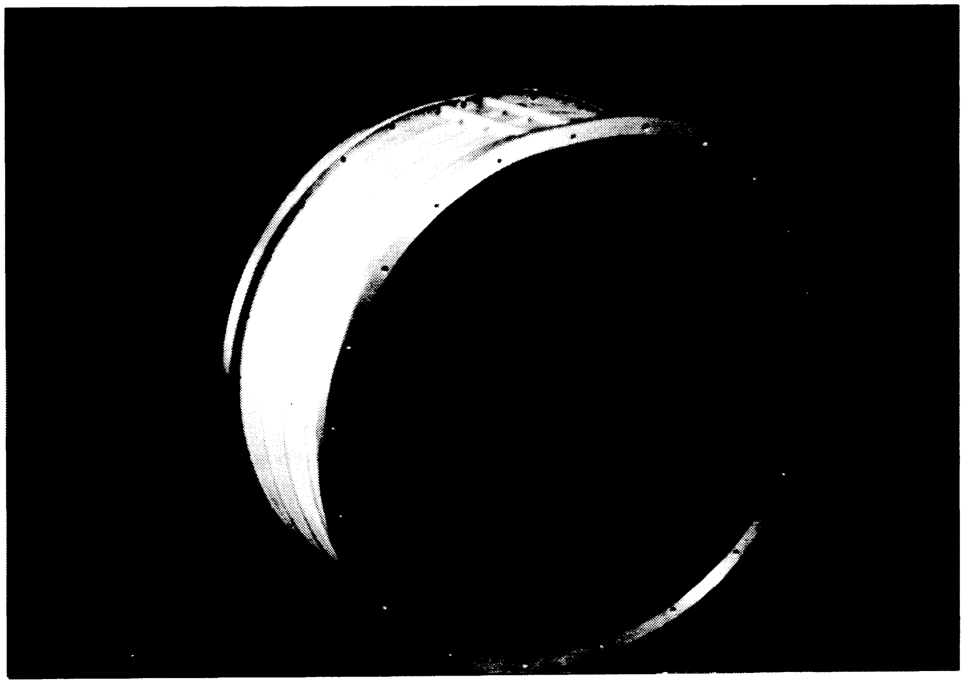

Figure 4.0. Baffle isolator

3. SCAN MIRROR ASSEMBLY AND ELECTRONICS

As previously mentioned, the SPIRIT III scan mirror assembly operates in collimated light at the output of the 4:1 afocal optics. The nominal beam size is 3.5 inches in diameter and is limited by the Lyot stop which is located on the scan housing. Figure 5.0 shows the completed flight scan mirror assembly. The scan housing and the scan mirror are made from 6061 aluminum to be consistent with the athermal design of the telescope. The scan mirror is a lightweighted, machined aluminum optical element that was diamond turned to its final optical figure. The physical size of this mirror is 6.0 x 4.5 inches with a face thickness of 0.3 inches. The scan mirror was cryogenically tested as a component and maintained a one wave peak-valley surface figure (@ 0.633 μm) at 94K.

Figure 5.0. Spirit III scan mirror assembly

Inconel flex pivots are used to support the mirror assembly in the scan housing. Inconel was selected over stainless steel to improve the margin of safety during the specified dynamic launch loads with the scanner at 20K. Stainless steel changes from an austenitic to a martinsitic material at cryogenic temperatures and can be damaged or fail when subjected to random vibration or shock loads due to its embrittlement. The program required the scan mirror assembly to survive the launch loads with no power applied to cage the mirror. A combination of design features were used to meet this requirement. These included: a lightweighted scan mirror, the inconel flex pivots, balancing of the mirror/yoke assembly, and the use of shunt resistors across the motor leads help keep the mirror in the center of its range during the launch.

To improve the reliability of the scan mirror assembly, redundant motors and servo controls with two different and independent position sensors were incorporated into SPIRIT III. SSG also designed and fabricated the flight scanner electronics. These boards contained radiation tolerant S-class electronics parts and interfaced with the SDL/USU electronics assemblies. The primary servo is an inductosyn and the secondary is a capacitive device. The motors are rotary voice coil motors with a moving coil rotor and a SmCo stator.

The scan mirror assembly measured performance data is summarized in Table 1.0. The values are given in object space of the telescope which varies from scan space by a factor of four (the afocal magnification). The completed flight scanner was vibration tested as an assembly and survived the expected launch loads. The performance parameters were verified at 20K in a cryogenic chamber at SSG. A scanner diagnostic test station was developed at SSG to test the scanner's performance to a high level of precision.

Table 1.0 Scan Mirror Assembly Optical Requirements (Object Space)

Modes (extent):	4 ($\pm$ 0.38; $\pm$ 0.75; $\pm$ 1.5 deg.; and home at 0 deg.
Scan rate:	0.46 deg/sec
Scan efficiency:	90%
Readout accuracy	$\pm$ 20 μrad
In-scan jitter:	4 μrad RMS
Linearity:	Primary servo: 94%, Secondary servo: 97%
Design life:	3 years

4. TESTING

4.1 Optical and Environmental Testing

The fabrication and testing program for the SPIRIT III telescope is shown in Figure 6.0. The ambient temperature and cryogenic testing of the scan mirror assembly was completed prior to integrating it into the telescope for the acceptance testing of the telescope system.

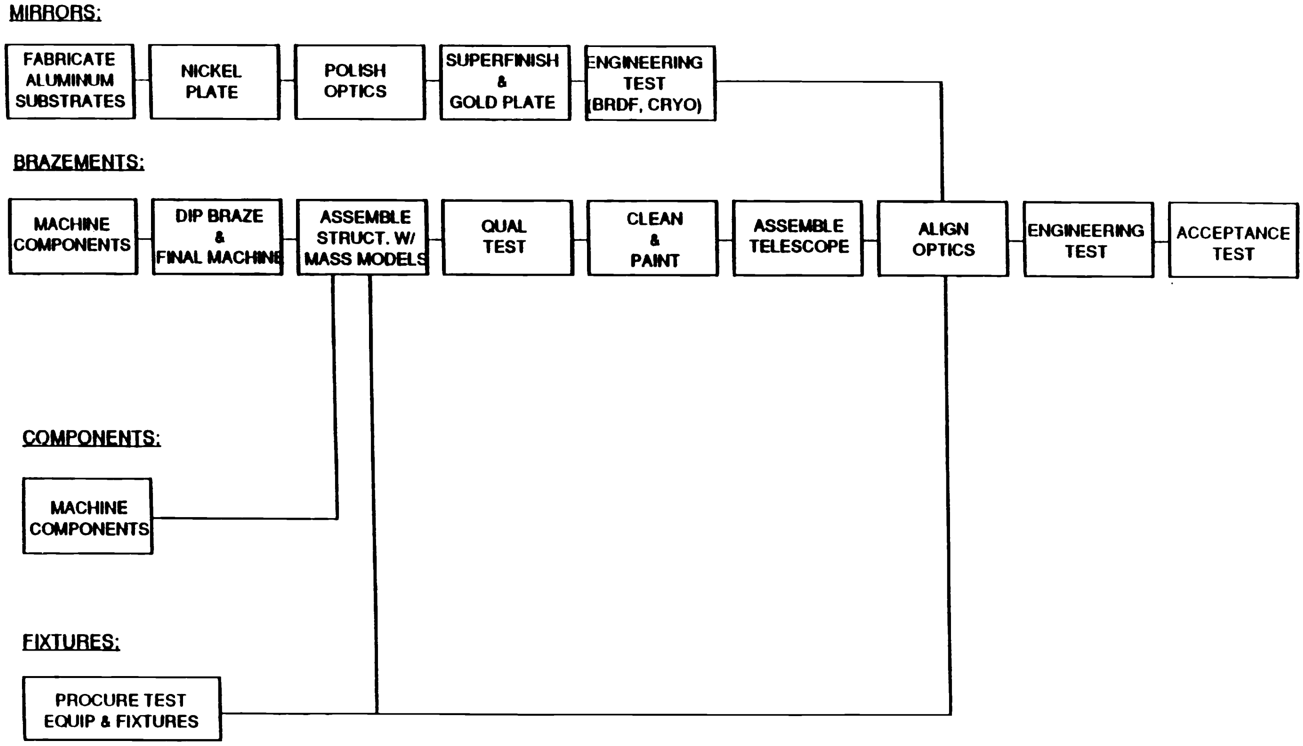

Figure 6.0. Fabrication and testing flow diagram

The acceptance testing of the telescope can be divided into four sections - ambient temperature optical testing, environmental (random vibration & sine dwell) testing, cryogenic optical testing, and straylight testing. The results of the ambient optical testing are summarized in Table 2.0. The environmental testing was performed at NTS/Acton Test Laboratory in August 1991. Cryogenic optical testing and straylight testing characterize key performance features of the SPIRIT III telescope. These topics are described in section 4.2 and 4.3 of this paper.

Table 2.0 Telescope Acceptance Test Data

Parameter	Measured Test Results
Focal length	52.4 inches
F-Number	F/3.72
Radiometer FOV	No scan: 0.3 x 1.0 degrees Scan: 3.0 x 1.0 degrees
Interferometer FOV	0.86 x 0.7 degrees
Point Source Rejection Ratio (PSRR)	$\leq$ 1E^{-10} for a μsteradian detector at 2.5 degrees off-axis angle with a $1/\Theta^2$ rolloff - see section 4.3
Resolution - radiometer	74% energy per pixel @ 12 microns with the telescope at LHe temperature - see section 4.2
Resolution - interferometer	0.9 mrad spot size
Distortion	0.2 pixel over 4 TDI (max)

4.2 Cryogenic Optical Testing

Two cryogenic test configurations of the SPIRIT III telescope will be discussed in this section. The first test is that of the primary mirror as an element, and second is the system level cryogenic optical test of the radiometer channel (afocal and radiometer optics modules) of the SPIRIT III telescope. Similar test techniques have been utilized at SSG to test previous systems and the details of these tests can be found in reference 3.

The primary mirror (M1) of SPIRIT III is an off-axis parabola that is nominally 16 inches in diameter. The off-axis distance (from vertex to center of the mirror) is 16 inches and the focal length 41.546 inch. The F-number of the M1 off-axis section is F/2.5.

The mirror was installed into a 36 inch diameter cryogenic dewar. The dewar has two optically correct windows on the dewar wall that are in the optical path of the M1 mirror. A LUPI was placed at the focus of the M1 and aligned to the mirror (aligned meaning correct pointing and position from the mirror). The laser energy diverges from the LUPI and passes through a 4 inch diameter window. Energy then diverges further to the M1 mirror which is suspended from the cooling flange of the dewar. A collimated bundle of energy passes from M1 through a 16 inch diameter window and ultimately to a 20 inch autocollimating flat. The flat retro-reflects the energy back through the system to the LUPI. Figure 7.0 illustrates the test configuration.

M1 mirror performance at 100K was 1.103 waves peak to valley and 0.193 waves RMS. Figure 8.0 shows the interferogram and WYKO computer analysis for M1 performance at 100K. The change in position of focus of the M1 mirror due to change in temperature (300K to 80K) was experimentally measured to be 0.180 inches on average over two cold tests. The calculated position shift due to temperature was 0.1791 inches which yields a 0.0009 inch discrepancy between experimental and theoretical values which is well within experimental error.

Cryogenic system level performance testing for the radiometer channel of the SPIRIT III telescope was performed in a custom made cryogenic vacuum dewar as shown in Figure 9.0. A 16 inch diameter window allowed an end to end full aperture interferometric test of the radiometer channel of the telescope. Energy filled the aperture of the system in the on-axis position and a diamond turned bare aluminum convex sphere was aligned at the final image of the system. The convex sphere is the retro-reflector for the system creating a double pass optical test (test results are presented in single pass).

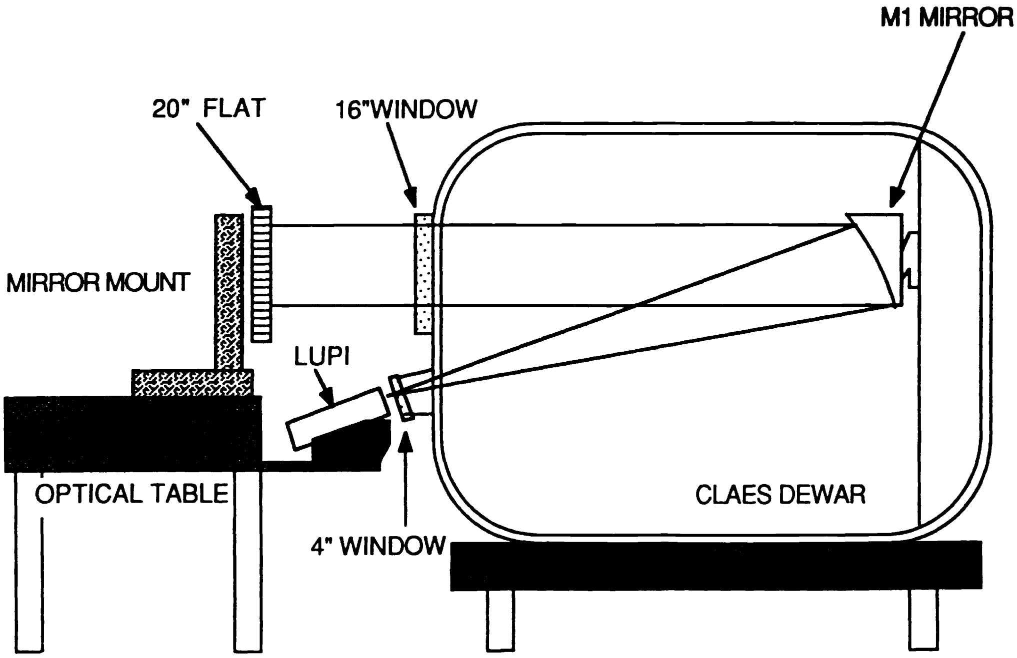

Figure 7.0. M1 test configuration

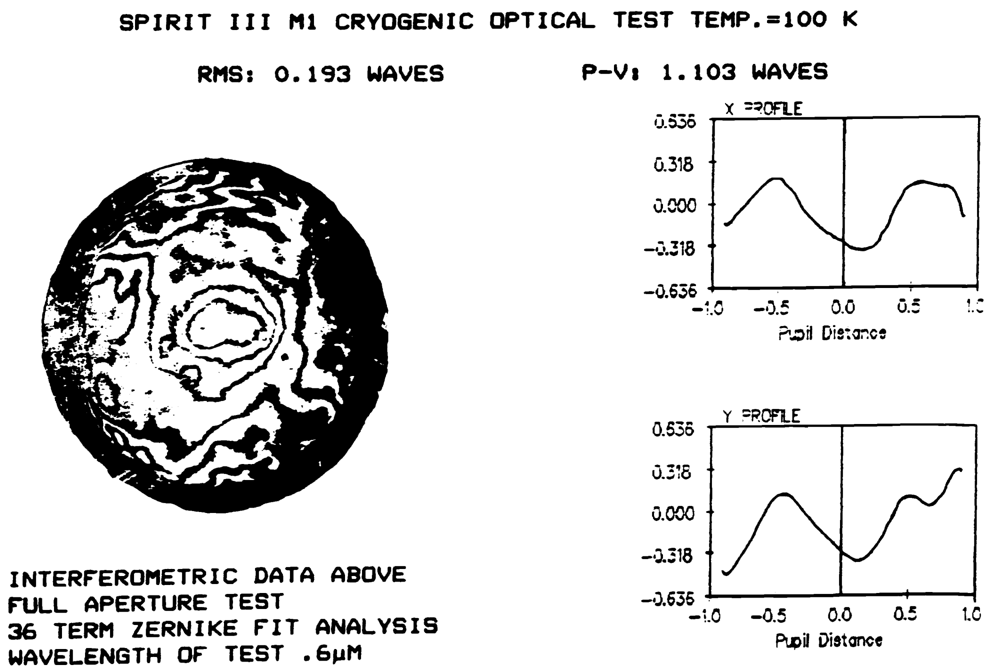

Figure 8.0. Measured interferogram of the M1 and 100K

Collimated energy enters normal to the window on the dewar wall and follows the nine (9) element optical path to the retro-sphere. The retro-sphere returns the 0.633 μm energy back through the system and collimator and to the LUPI (which is the source for the collimator). It is important to note that the scan mirror assembly was calibrated and electrically driven to the same point from test to test, warm or cold.

System level performance of the telescope was determined by collecting interferometric data at two temperatures. Interferograms were digitized on an electro-magnetic tablet, and converted into RMS and Peak to

Figure Valley (P-V) wavefront error using a 36 term Zernike polynomial fitting of the data. To determine percent ensquared energy of the SPIRIT III system the coefficients of the 36 term Zernike polynomial were entered into CODE V. CODE V, in conjunction with the SPIRIT III optical design and other parameters, generated the percent ensquared energy per pixel.

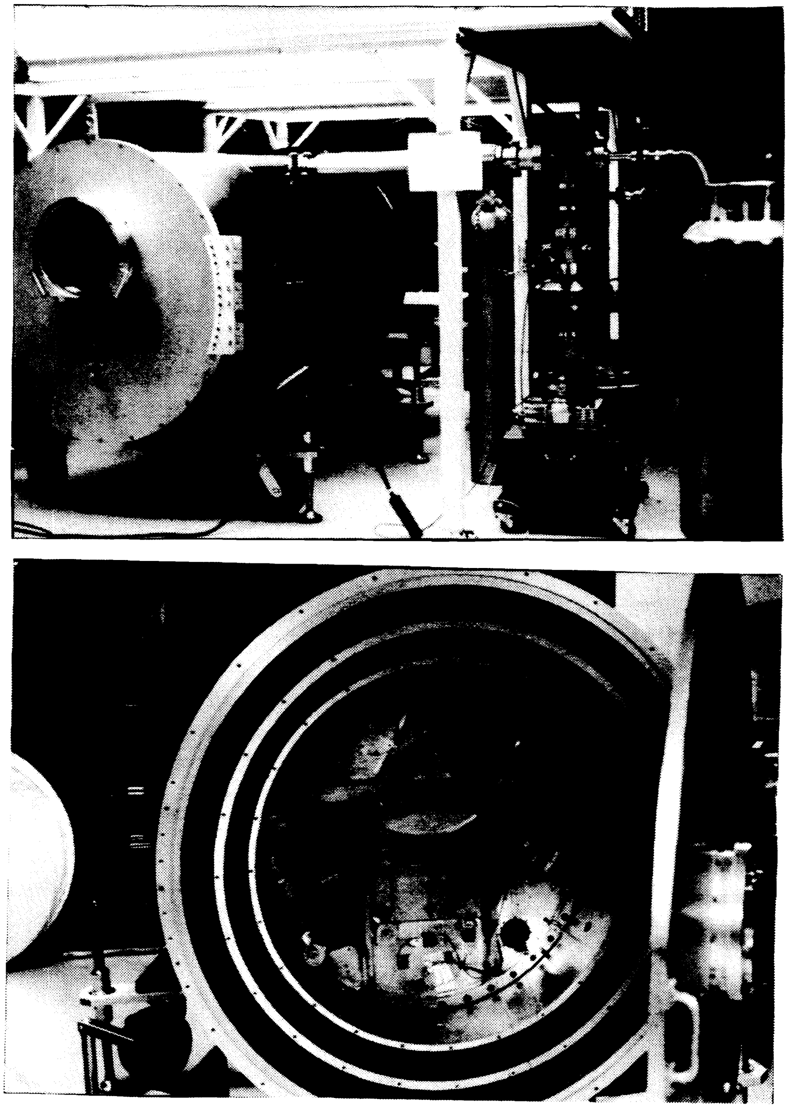

Figure 9.0. System level cryogenic test

The first cryogenic test evaluation of the system at 80K and 10K showed the following performance:

Temperature in K	P-V @ .6 μm	RMS @ .6 μm	RMS @ 12 μM	CODE V % ENSQUARED
80	13.826	2.729	.144	62%
10	13.756	2.724	.144	64%

It was determined that some residual aberration could be removed from the system with a defocus. CODE V analysis verified that a defocus of the retro-sphere by 0.017 inch, making the system focal length shorter, would improve system performance to above the specified 70% ensquared energy. The retro-sphere was physically shifted by the predicted defocus of 0.017 inch and the system was retested. After this cryogenic defocus the second cryogenic test yielded the following system performance:

Temperature in K	P-V @ .6 μm	RMS @ .6 μm	RMS @ 12 μm	CODE V % Ensquared
80	11.405	1.964	.104	74%

The final result of 74% energy per pixel meets the requirement of the all reflective telescope of 70% energy per pixel @ 12 μm.

4.3 Straylight Testing

The SPIRIT III telescope was designed and built as a high straylight rejection telescope. The principle testing required to characterize this performance was the BRDF (Bidirectional Reflectance Distribution Function) at the component level, and the PSRR (Point Source Rejection Ratio) at the system level. Brief explanations, and the results from these measurements are presented below.

BRDF is defined as the ratio of the reflected radiance to the incident irradiance on a surface. For a well baffled re-imaging telescope, a low scatter finish is required for the elements (M1 and M2 for SPIRIT III) preceding the first field stop. As the field stop limits the telescope FOV, the remainder of the mirrors in the system do not significantly effect the telescopes straylight rejection performance.

The BRDF measurements of M1 and M2 were difficult. M1 has surface area of ≈ 200 square inches, requiring multiple samples. M2 is a convex hyperboloid. Convex mirrors are difficult to test accurately because they

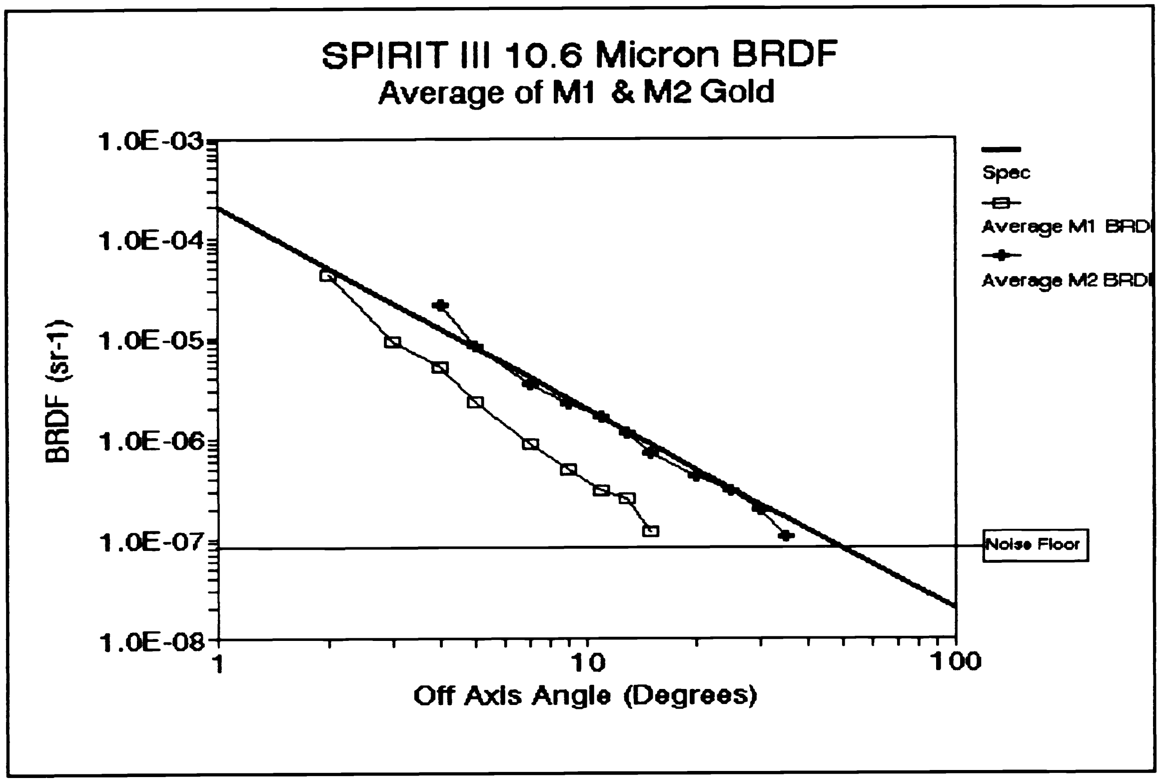

Figure 10.0. Measured BRDF of M1 and M2

do not focus the incident energy onto the detector. Measurements were made at 0.633 μm and 10.6 μm at SSG's standard BRDF test facility using a spinning Infragold reference. Figure 10.0 is a graph of the 10.6 μm BRDF of both M1 and M2. Both mirrors exhibited an average BRDF of less than 2 x 10^{-4} sr^{-1} @1° with a $1/\Theta^2$ rolloff.

The PSRR is defined as the ratio of the power on the detector when the telescope is viewing a point source away from its line of sight, versus the same point source within the detector boresight. PSRR is the final system level straylight test. This laboratory measurement sets the baseline for the performance of the pristine clean telescope assembly. The data from the PSRR test is used to model the expected on orbit NRER (Non-Rejected Earth Radiance) of the telescope. A comparison with the telescopes NRER in orbit will help determine the validity of models, as well as the current contamination level of the telescope.

The PSRR test process is presented below. The completed telescope assembly was placed in a clean room, and mounted on a fixture so that it could pivot about the entrance port. The fixture was also designed to allow the telescope to rotate for azimuth and elevation measurements. At the far end of a well baffled lab (≈ 70 feet away), a 24 inch diameter superfinished collimating mirror was fed by a 50 W CO_2 laser. The collimated beam was sent into the telescope overfilling the entrance aperture. A HgCdTe detector was placed at the image plane of the telescope. Alignment was performed with the use of attenuators in the CO_2 beam. Essentially, the power was measured on axis, and then the telescope was rotated off axis about the pivot point. The ratio of these measurements at each angle is the PSRR. Figure 11.0 is a graph of the average PSRR of the SPIRIT III telescope for the radiometer, in the direction of earth illumination.

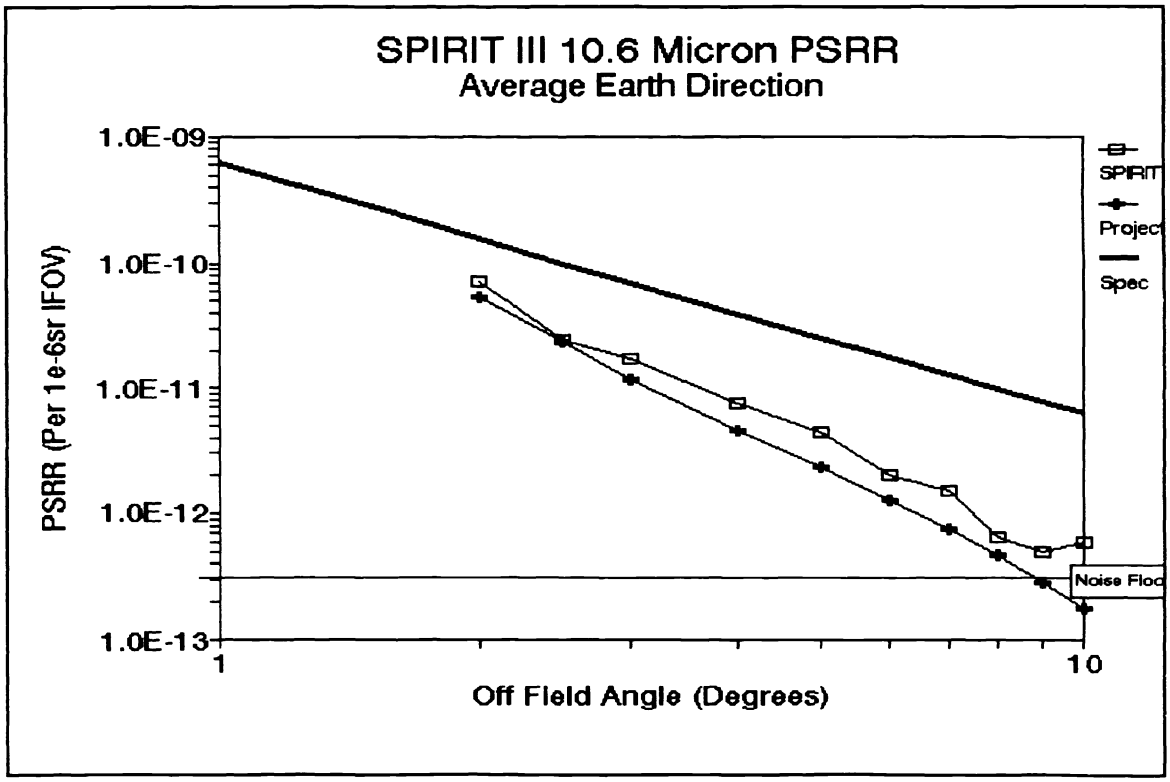

Figure 11.0. Measured telescope PSRR

An important result that can be seen on the graph is the agreement of the measured PSRR with modelled PSRR derived from the measured BRDFs' and other telescope parameters. The modelling proved to be important asset because the initial results did not fit with the model. This discrepancy led SSG to make a slight modification of the Lyot stop which improved the overall straylight performance. The final results agreed with the expected performance, within experimental error.

5. CONTAMINATION CONTROL

From the beginning of the program, it was determined that contamination control was the critical factor in maintaining the straylight performance of the system. Emphasis was placed on reducing molecular contamination, as well as particulates. Very high levels of cleanliness, on the order of level 200 or better, were required.[4]

This cleanliness also needed to be maintained over the 2-3 year mission life. Long term cryogenic BRDF measurements were made on 4 inch diameter test mirrors, proving the feasibility of maintaining BRDF levels of 2×10^{-4} sr^{-1} @ 1°, over 6 months at 20K, under ideal conditions. Other results, from portable BRDF measurements on the CIRRIS 1A and SPIRIT II telescopes during ground operations, showed some BRDF degradation over time. This degradation was easily cleaned using standard cleaning procedures, restoring the original BRDF values.

For the telescope, the process of minimizing contamination began with the selection of low outgassing materials which met the 1.0% TML and .1% CVCM guidelines using the ASTM E-595 test method. All components underwent a vacuum bakeout to further reduce outgassing. The bakeout was at 100° C, with a vacuum $< 5 \times 10^{-6}$ torr. The duration of the bakeout was determined by the reduction in RGA (residual gas analyzer) spectra peaks. This was usually met after 4 days at temperature. Llumalloy HST was chosen as the bagging material, and was used at all times during transport.

Oil free vacuum systems were used during cryogenic testing to eliminate any possibility of contamination. Heaters were mounted to the primary and secondary mirrors to insure that they were the last parts to go cold, and the first to warm up. These heaters will be used throughout ground operations. The telescope was built with pinned mirror assemblies, that allow mirror removal for cleaning, without the need for realignment.

A QCM (Quartz Crystal Microbalance) and an in-situ scatter monitor will be used in flight to quantify the contamination levels. The QCM Research Mark 16 was placed just below the primary mirror of the telescope. The main baffle design was modified to give the QCM a clear field of view out of the entrance aperture. The in-situ scatter monitor was installed in the main baffle. It is essentially a IR filament that illuminates a spherical reflector. The quasi-collimated beam is incident on the primary mirror, and reflected into a light trap that is mounted by the secondary mirror. A detector in the interferometer channel is used to measure the scattered light.

6. ACKNOWLEDGEMENTS

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