A second generation Multi-Angle Imaging SpectroRadiometer (MISR-2)

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***Abstract*—The Multi-angle Imaging SpectroRadiometer (MISR) has been in Earth orbit since December 1999 on NASA's Terra spacecraft. This instrument provides new ways of looking at the Earth's atmosphere, clouds, and surface for the purpose of understanding the Earth's ecology, environment, and climate. To facilitate the potential future continuation of MISR's multi-angle observations, a study was undertaken in 1999 and 2000 under the Instrument Incubator Program (IIP) of NASA Code Y's Earth Science Technology Office (ESTO) to investigate and demonstrate the feasibility of a successor to MISR that will have greatly reduced size and mass. The kernel of the program was the design, construction, and testing of a highly miniaturized camera, one of the nine that would probably be used on a future spaceborne MISR-like instrument. This demonstrated that the size and mass reduction of the optical system and camera electronics are possible and that filters can be assembled to meet the miniaturized packaging requirements. An innovative, reflective optics design was used, enabling the wavelength range to be extended into the shortwave infrared. This was the smallest all-reflective camera ever produced by the contractor. A study was undertaken to determine the feasibility of implementing nine (multi-angle) cameras within a single structure. This resulted in several possible configurations. It would also be possible to incorporate one of the cameras into an airborne instrument.**

Keywords: Earth Science, SpectroRadiometer, MISR

I. Introduction

The Multi-Angle Imaging SpectroRadiometer-2 (MISR-2) Instrument Incubator Program (IIP) has demonstrated component-level technologies that produce a significant reduction in spacecraft resource requirements (size and mass) while reducing costs of a future multi-angle imaging space-based instrument. The MISR-2 IIP built and tested a complete signal acquisition chain from photons to digital data of one of nine cameras required for a future instrument. The IIP also demonstrated a 3× mass reduction and a 6× volume reduction compared to the current MISR instrument.

The MISR instrument was launched into polar Earth orbit aboard the Terra spacecraft on December 18, 1999. Terra is in a 16-day-repeat, 705-km, Sun-synchronous orbit and has a nominal 10:30 a.m. equator crossing time on the descending node. MISR provides multiple-angle, continuous imagery of the Earth in reflected sunlight. MISR uses nine separate charge coupled device (CCD)-based pushbroom cameras to observe the Earth at nine discrete angles: one at nadir, plus eight other symmetrically placed cameras that provide fore-aft observations with view angles at the Earth's surface of 26.1°, 45.6°, 60.0°, and 70.5° relative to the local vertical. Imagery in four spectral bands (blue, green, red, and near-infrared) is provided at each angle, yielding a total of 36 image channels (9 angles × 4 bands). MISR measurements are designed to improve our understanding of the Earth's ecology, environment, and climate.

II. Scientific Objectives

A detailed understanding of how sunlight is scattered in different directions is necessary to determine how changes in the amounts, types, and distribution of clouds, airborne particulates, and surface cover affect our climate. The need for calibrated multi-angle and multi-spectral imaging at kilometer and sub-kilometer spatial resolution is dictated by the physics of radiative transfer in the coupled atmosphere-surface system. Aerosol and cirrus signals are accentuated at the oblique viewing angles, and coverage in scattering angle provides constraints on particle composition, size, and shape. MISR's multi-angle strategy enables atmospherically corrected directional surface reflectances to be retrieved with accuracies warranting the use of physically based vegetation canopy models. Because clouds, aerosols, and the surface do not reflect sunlight equally in all directions, multi-angle measurements are necessary for accurate estimation of albedos. Angular scattering "signatures", along with stereo-photogrammetric and textural measures, are diagnostic of three-dimensional geometric structure. MISR's multi-angle approach allows retrieval of an array of cloud, aerosol, and land surface parameters that relate to specific issues in these areas and the terrestrial climate system in general.

III. MISR-2 IIP Objectives

The MISR-2 Instrument Incubator Program (IIP) allowed demonstration of critical subsystem hardware that could be adopted for a future MISR-2 flight instrument. This demonstration hardware validates our system level projections for size and mass by proving that one of the nine MISR-2 cameras can be built to the specified size and mass

with the required performance. The following objectives were set for the IIP:

1) Demonstrate a significant **size and mass reduction in the optical system: Demonstrated.** A JPL design was produced by IIP partner SSG Inc. and tested by SSG and JPL. Results show full compliance to size and mass and performance requirements.

2) Demonstrate a significant **size and mass reduction of the camera electronics: Demonstrated.** JPL built and tested a working version of one of the 9 MISR-2 Camera Support Electronics (CSE) boards. This board incorporated in-line packaging techniques and demonstrated a 75% reduction in board volume.

3) Demonstrate that **filters can be cut and bonded to meet the MISR-2 packaging requirements: Demonstrated.** Filter substrates were diced and bonded by IIP partner Barr Associates to meet the MISR-2 requirements of 80-μm center-to-center spacings, which is a 2× reduction from the MISR dimensions.

Another achievement that was not originally part of the MISR-2 IIP proposal was to demonstrate the ability of a MISR-2 to measure polarization. In the IIP we determined through analysis that the optical design has very low polarization if implemented with silver coated mirrors and will allow us to measure polarization by placement of polarizing filters on the focal plane assembly (FPA). Barr Associates also successfully performed the dicing operation, confirming that our concept can work.

IV. MISR-2 IIP Design Requirements

A future MISR-2 instrument requires basically all the capability of MISR with additional sensing capability in the short wavelength infrared (SWIR). Table 1 gives the requirements for the flight system and the IIP (Lab) Demonstration.

The MISR-2 flight system has six non-polarimetric spectral bands, including the four VNIR MISR bands, with two additional SWIR bands.

TABLE 1
MISR-2 Requirements

Item	MISR-2 Flight	MISR-2 IIP Demonstration
Spatial	0.354 mrad VNIR, 250 m 0.709 mrad SWIR, 500 m	0.354 mrad VNIR 0.545 mrad SWIR
Spectral	446 nm 558 nm 672 nm 866 nm 1375 nm 1640 nm	443 nm 1300 nm 1600 nm
Signal-to-Noise Ration	> 100 at 2% equivalent reflectance	>20 at 2% equivalent reflectance
Detectors	1 × 1504 VNIR 13 µm 1 × 752 SWIR 26 µm	1 × 2048 VNIR 13 µm 1 × 599 SWIR 20 µm 1
Optics Focal Length F-number	36.68 mm F/6.81	36.68 mm F/6.81

The laboratory system does not have all the channels that the flight camera has due to availability of focal plane assemblies. The requirement for the laboratory demonstration is that the optical system and electronics will be designed to meet the flight requirements of accommodating all 6 channels. This was achieved successfully.

The tasks specifically within this IIP are based upon fabrication and demonstration of the essential components of a single MISR-2 camera. The camera chosen for this is the nadir camera. To keep within the cost constraints of the IIP program, the task focused on demonstrating the optics and electronics while using commercially available detectors. These detectors were placed at the image plane of the camera. Adjustments on the detector mount were provided to adjust the detectors to the best imaging position. Additionally, the filter vendor was funded out of this IIP to demonstrate the required decrease in the size of filters. Finally, a polarimetric imaging capability was considered. This assessment indicates that this capability appears feasible; however, a technology demonstration would be very beneficial.

V. Optics

A. *Design and Development*

The first-order camera requirements are for a 4-mirror, all-reflective imager with the following characteristics:

a) Focal length shall be 36.68 mm
b) The focal ratio shall be f/6.81
c) The full field-of-view shall be 30°
d) MTF of > 50% at 20 cycles/mm in SWIR and > 60% at 39 cycles/mm in VNIR
e) The optical camera system shall fit within 6.6 cm × 6.3 cm × 7.5 cm volume

SSG was chosen for the camera fabrication as a vendor that is amenable to small developmental tasks and having a willingness to work to "goal"-types of specifications. The MISR-2 IIP camera is the smallest all-reflective camera system ever produced by SSG. Figure 1 shows the as-built camera lens. An initial optical design was given to SSG at the start of the camera fabrication activity.

Fig. 1. MISR-2 camera: the smallest ever produced by SSG.

Due to cost considerations, several compromises were made in the camera. First was the decision to use an all-aluminum implementation. Additionally, the diamond-turned mirrors were not heavily post-polished; therefore, scattered light performance, although acceptable, is not a good as can be produced. SSG was also able to adjust the design to provide more room to fit the detectors onto the camera. This was necessary because of our decision to use commercially available detectors in commercial packages. Overall, the performance of the MISR-2 IIP camera is adequate and provides a good demonstration of a small camera implementation.

B. As-built Performance

Interferometric testing was done with a ZYGO interferometer for field angles of 0°, ±7.5°, and ±15°. The results of RMS and peak-to-valley wavefront errors are shown in Table 2. (The graphic output showing the pupil map could not be printed for technical reasons).

It is important to note that each measurement was done with individual focusing; therefore, the data in Table 2 do not include field curvature.

The Modulation Transfer Function (MTF) and corresponding Point Spread Function (PSF) for each field point were evaluated using the interferometric data. For this purpose, interferometric data (as a set of Zernike coefficients) were used in the Code V model. The MTF for the center and end-of-field positions are shown in Figure 2. We see good image quality except near the end of the field of view. This is expected for the non-flight configuration and is due to limitations in alignment tooling and the mirror fabrication accuracies; both of these quality limitations were adopted to minimize development costs.

TABLE 2

RMS AND PEAK-TO-VALLEY WAVEFRONT ERRORS FOR DIFFERENT FIELD ANGLES

Field Angle	RMS. Waves	PV Errors, Waves
	0.213	1.163
−15°	0.203	1.085
	0.219	1.043
	0.177	0.766
−7.5°	0.181	0.805
	0.178	0.795
	0.084	0.464
0°	0.094	0.516
	0.083	0.560
	0.059	0.362
7.5°	0.058	0.335
	0.064	0.452
	0.122	0.665
15°	0.143	0.782
	0.147	0.790

C. Polarization Study

The purpose of the polarization analysis was to determine the polarization sensitivity of the camera for two different types of mirror coating (aluminum or silver with a MgF_2 protective layer). Dependence of throughput on wavelength and polarization plane orientation was considered.

As an indication of the maximum possible magnitude of polarization-related errors, the difference of throughput for vertical and horizontal polarization (at the center of the field of view) was calculated for two types of coating, and for the MISR-2 IIP layout with and without a beamsplitter in the optical path. Figure 3 shows that the silver coating produces much lower polarization-related errors up to a wavelength of 1.2 μm (and comparable errors within 1.2 to 1.6 μm).

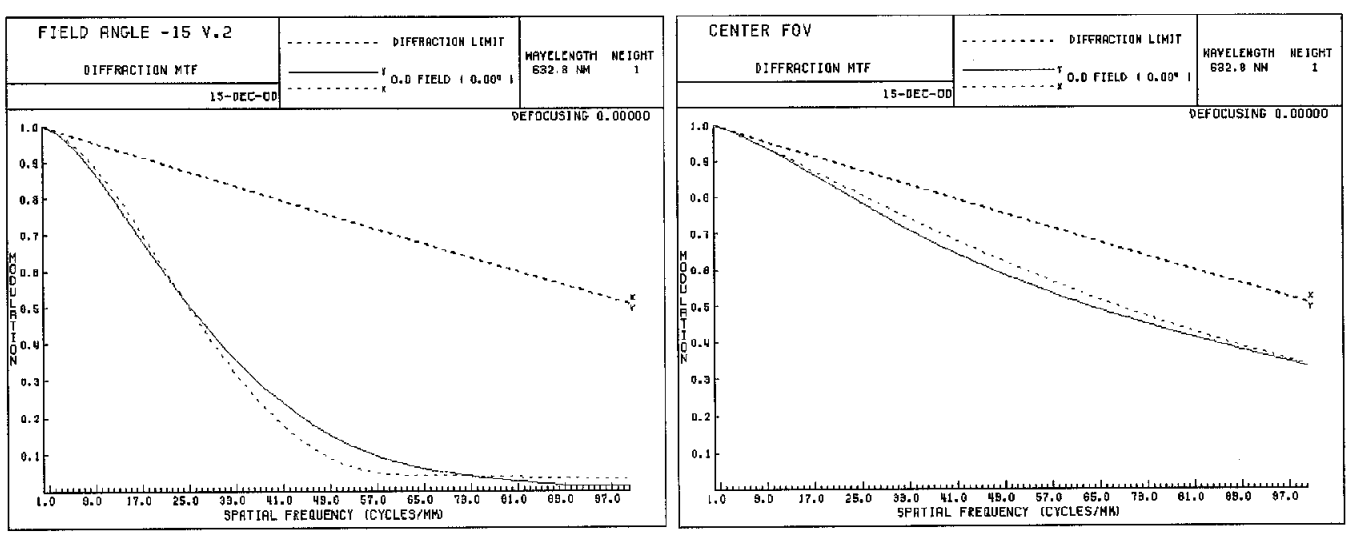

Fig. 2. Modulation transfer function for the end and center field of view. We see good performance for most of the field of view except near the ends. This is expected for the quality of fabrication used in the IIP.

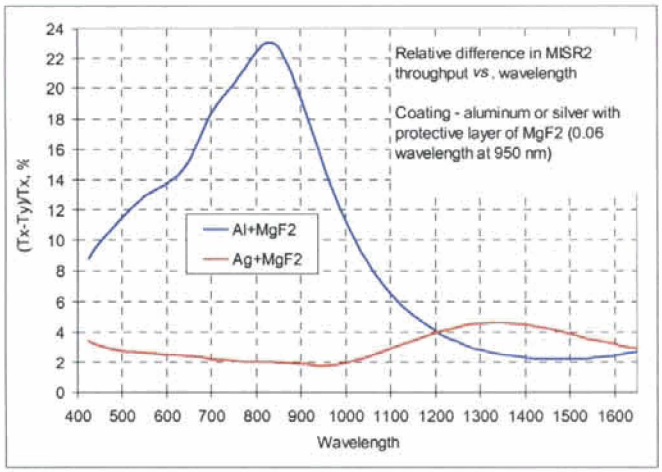

Fig. 3. Relative throughput errors caused by polarization in the MISR-2 layout with beamsplitter.

VI. Electroincs

A. Electronics Requirements

The MISR-2 IIP electronics development was intended to answer several basic questions regarding the feasibility of significantly reducing the size of a follow-on MISR-like instrument. The Camera Support Electronics (CSE) was chosen for implementation in the IIP because it is replicated nine times in the current MISR instrument; reducing the CSE's size and mass would facilitate a much smaller instrument. The following requirement goals were used in this phase of the IIP development:

a) Reduce the volume and mass of the CSE by 75%
b) Reduce the mass and complexity of the cabling by 75%
c) Increase the number of signal chains from 4 to 6
d) Reduce the power required by the CSE
e) Operate an off-the-shelf CCD and SWIR detector with little modification to the MISR electronics

B. Design and Fabrication

Using existing MISR electronics designs and newer, smaller surface-mount packages, new multi-layer printed circuit boards (PCBs) were developed that yielded a MISR-2 CSE chassis having a 75% reduction in volume and a corresponding reduction in mass compared to the MISR CSE electronics. One of the system tradeoffs was to remove the CSE internal power supply and replace it with a system CSE supply that would feed all nine cameras. A common supply will also reduce mass at some reduction in redundancy. This supply was not developed at this time and was simulated by lab power supplies.

In the original MISR design, there are 36 wires in the cable for the CSE. The MISR-2 design has 10. This is a 72% reduction in cabling volume. This reduction was accomplished by going to single-ended drivers and an improved command and data transfer scheme. The single-ended drivers were made possible by the reduced cable lengths of the smaller instrument.

The MISR design has a four-channel hybrid signal chain. Consultations with the hybrid manufacturer made it clear that a six-channel hybrid in one package was impractical. The solution was to modify the existing hybrids to a two-channel configuration and package three of these hybrids for a total of six channels. The three hybrid chips can be seen in Figure 4. This hybrid was designed, fabricated, and tested, and meets or exceeds all MISR-2 requirements.

C. Electrical Ground Support Equipment (EGSE)

The MISR-2 IIP electrical ground support equipment (EGSE) has a custom interface box. This box simulates the system electronics that a complete instrument would provide. In place of an instrument power supply there are 120V AC linear power supplies that provide +5 Volts, + and – 12 volts, and + 30 volts to the camera. In the place of an instrument data system, an Actel A1240 FPGA was implemented; this FPGA interlaces between the National Instruments 16-bit parallel interface and the 4 Mb/s serial interface of the MISR-2 IIP camera and allows the camera data to be placed upon a PC computer. This computer also controls and operates a rotary stage that rotates the camera so that a pushbroom image can be collected. Additional manual micrometer stages are available to position the detector at the best focus of the camera. These stages are shown in Figure 5, which also shows a stereo lithographic model of the camera. The detector and electronics are mounted on standoffs to allow for clearances.

D. As-Built Performance

The electronics have been fabricated and tested, and function as a six-channel MISR CSE meeting almost all the MISR-2 requirements. All functions available in the current MISR instrument are demonstrated. The two-channel hybrid was designed, fabricated, and tested and meets or exceeds almost all MISR-2 requirements.

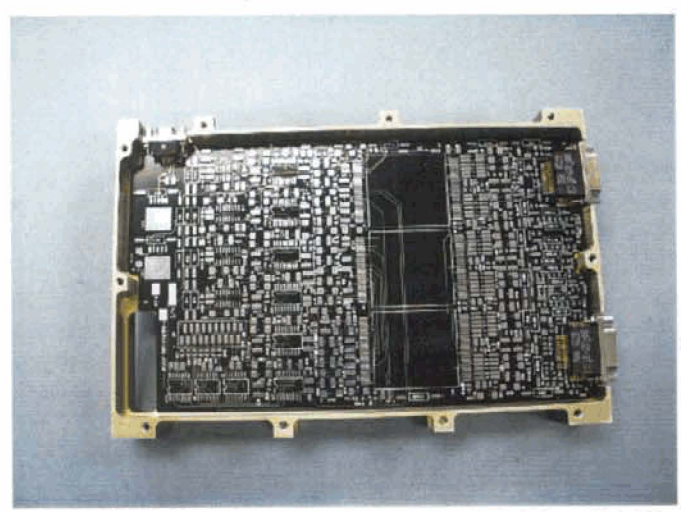

Fig. 4. MISR-2 camera support electronics showing three 2-channel hybrids using surface mount fabrication techniques.

Fig. 5. A MISR-2 camera model is mounted in the center of a computer controlled rotary stage (red disk). A set of manual micrometer positioners (left) is used to position the detectors and associated electronics at the best focus of the camera.

The MISR CSE requires 6 watts; it was hoped that this power could be reduced in the MISR-2 flight-instrument implementation. Testing indicates that the current MISR-2 design will consume approximately 8 watts. Initial estimates assumed that power reductions in the drivers would reduce some of the overall power; however, in further testing it became apparent that the signal chains dominate the power requirements. The addition of two more signal chains comes with a commensurate increase in power.

Funding did not allow the development of custom detectors for the MISR-2 IIP. An off-the-shelf commercial CDD and a commercial InGaAs IR detector were procured in the hopes of simulating the sampling and pixel size of a MISR-2 focal plane. The CCD was made to work, and image data was acquired by the EGSE. Figure 6 is one of the images of an optical test pattern. The CCD is oriented up-down and was scanned sideways. An apparent MTF problem (blurring in the image) that appears to be related to the CCD itself was not resolved due to lack of time. Likewise, the IR detector proved to be very difficult to integrate and operation was de-scoped due to schedule and funding constraints.

VII. Filters

A. Filter Requirements

The optical-performance requirements of the MISR filters have not changed in the IIP camera system design. However, given the reductions in camera size and detector pixel pitch, the filters are required to shrink from 160-μm spectral band line spacing to 80-μm spectral band line spacing. The following are the requirement/goals used in our IIP effort.

a) The spectral band line space will be 80 μm
b) The filters will be bonded directly to the detector
c) A polarizing filter array shall be developed

Barr Associates, Inc. provided linear array filters for the MISR instrument with 160 μm line spacing. The MISR-1 filters were constructed through microfabrication of all oxide ion aided deposition coatings. The filters had aperture defiling masks both above and below the filter coatings to reduce scattered light and optical crosstalk between bands. JPL installed the filters into the focal planes with a 40-μm air space between the filter and the CCD.

Based on previous work with Barr Associates on the MISR instrument, a study contract with them was initiated to develop the techniques for producing the narrow filter spectral band spacing needed for MISR-2. Additionally, the contract asked Barr to investigate polarizer materials that could be used to develop a set of polarizing MISR-2 filters.

B. Demonstrations

A simplified filter design has been developed that eliminates the need for a second set of aperture masks on the bottom surface of the filters by use of an opaque epoxy in the vertical bond lines between bands, which will eliminate optical crosstalk between the bands. Barr Associates also developed a revised assembly procedure that decreases the fabrication tolerances by a factor of two. Barr produced a set of five filter mockups, which demonstrated ability to meet the tighter fabrication requirements. The combination of these two factors results in a reduction of the achievable line spacing from 160-μm to 100-μm. Figure 7 shows one of the demonstration filter mockups.

Corning Polarcor has been identified as a polarizing material that could be used to produce polarizing filter arrays for wavelengths between 600 nm and 1600 nm. The material is durable enough to survive its fabrication into a 100-μm array and has excellent optical performance with contrast ratios in excess of 10,000:1.

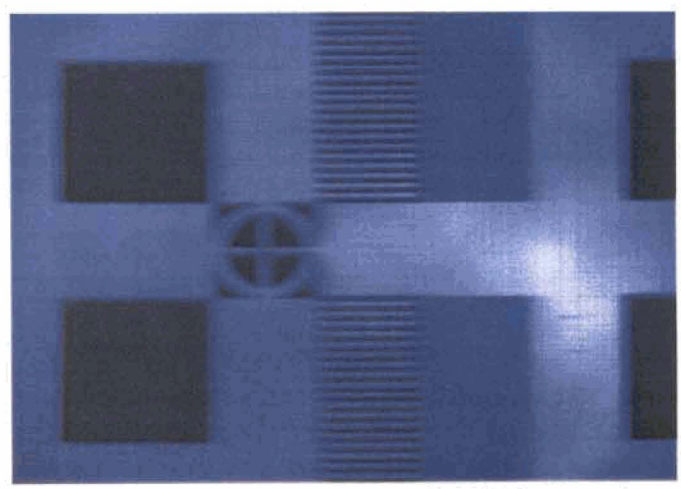

Fig. 6. Image taken of optical test target with MISR-2 camera and commercial CCD

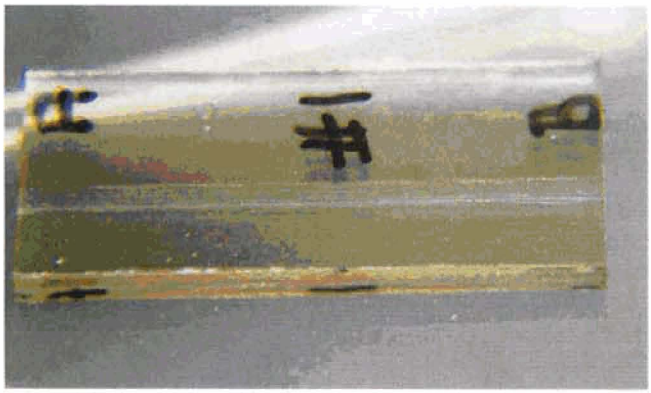

Fig. 7. 100-mm spectral band spacing demonstration filter mockup.

Because of resource limitations, the task of developing a technique for bonding the filters to the CCD was not completed. The task utilizes the same highly sophisticated and unique high-precision, microscope-based positioning system that was used to assemble the MISR focal planes. The failure to complete this task will require an up-front development effort in the flight phase of this project.

VIII. MISR-2 Instrument Configuration

The purpose of the MISR-2 IIP is to demonstrate critical technologies to support enhanced measurement capability and reduced mission-resource requirements for future MISR missions. The MISR-2 flight instrument design offers new scientific measurement capability (as discussed above) while preserving the EOS Terra MISR measurement set. This is to be achieved in a significantly reduced size and mass compared to the MISR instrument to facilitate implementation into smaller spacecraft on future missions. These primary objectives are achieved in the MISR-2 instrument concept as follows:

Instrument Objective	How Achieved
• 3x Mass Reduction	• Lighter Camera and Electronics
• 6x Volume Reduction	• Smaller Camera and Electronics
• 2 Additional SWIR Bands	• InGaAs Uncooled IR Detectors at 1.37 μm and 1.60 μm
• Polarization Sensing Capability	• Miniature on-FPA Polarizer Filters
• Non-Obtrusive Calibration	• Gimbaled Cal Camera (10th Camera)

Figure 8 shows the existing MISR instrument side by side with a conceptual MISR-2. Design studies performed in this IIP have indicated that it is possible to meet the above design goals in a MISR-2 instrument.

IX. Summary and Conclusions

The MISR-2 Instrument Incubator Program has successfully designed and developed a miniature optical system and electronic signal-processing chain that results in a projected 6× reduction in instrument volume and a 3× reduction in instrument mass from the prior MISR instrument. Additionally, the system is capable of imaging two additional SWIR bands and polarization sensing. The end-to-end system was tested, and it demonstrated the performance expected for this class of experiment. The reduction in size and mass achieved in this IIP opens up opportunities for new multi-angle measurements while allowing easier accommodation on the smaller spacecraft expected for future NASA Earth Science missions.

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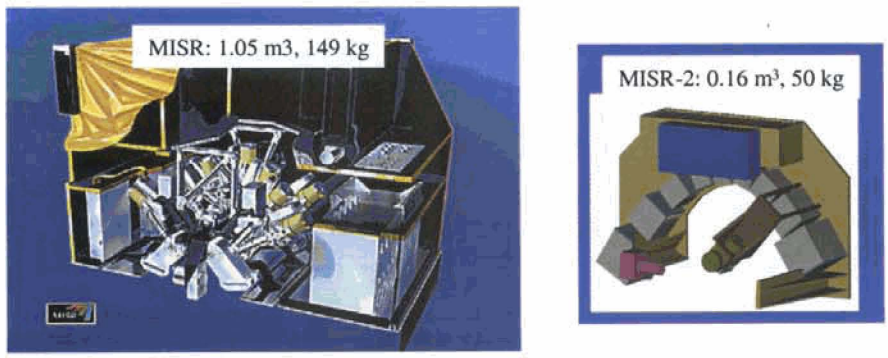

Fig. 8: MISR instrument (left) compared with MISR-2 concept (right)