The Spaceborne Infrared Atmospheric Sounder for Geosynchronous Earth Orbit (SIRAS-G) – Pathfinder IR Imaging Spectrometer for Space Missions

Thomas U. Kampe, Holden Chase, Vincent Kotsubo, Paul Hendershott, Gary Mills, John Wassmer

Ball Aerospace & Technologies Corp.
Civil Space Earth Science Advanced Programs
MS RA-4, 1600 Commerce Street
Boulder, CO 80301

Abstract*: The Spaceborne Infrared Sounder for Geosynchronous Earth Orbit (SIRAS-G) was developed by Ball Aerospace & Technologies Corp (BATC) under NASA's 2002 Instrument Incubator Program (IIP-4). SIRAS-G provides a compact, low mass solution for IR sounders exhibiting low spectral smile and keystone distortion suitable for future Earth science needs. The SIRAS-G technology is ideally suited for measuring atmospheric temperature, water vapor, trace gases and dust aerosol from satellite, providing high spectral resolution over a broad IR spectral range and extended field of view. The SIRAS-G dispersive spectrometer module is readily adaptable for missions in LEO, GEO or MEO orbits and can be optimized for spectral resolution over subsets of the total spectral range. A LEO version of SIRAS-G has the potential to provide high spatial resolution, improving on current generation sounders, comparable to that of MODIS. This instrument would provide a significant improvement in the yield of cloud-free pixels. We have completed the 3-year SIRAS-G IIP development effort, including the successful testing of the demonstration instrument at cryogenic temperatures. The performance of the demo instrument has been quantified including measurement of keystone distortion, spectral smile, MTF, and the spectral response function (SRF) to high accuracy using a novel proprietary test methodology developed at BATC. We present the results of the laboratory instrument development including results of our characterization of the demonstration instrument. We discuss instrument concepts utilizing SIRAS-G technology for potential future missions including an anticipated airborne flight demonstration.

I. INTRODUCTION

The Spaceborne Infrared Atmospheric Sounder for Geosynchronous Earth Orbit (SIRAS-G) is being developed under the NASA Instrument Incubator Program (IIP) by Ball Aerospace & Technologies Corp. (BATC) to provide accurate atmospheric temperature and water vapor profile measurements from geosynchronous orbit (GEO) at high spatial resolution. These measurements are critical for weather forecasting, severe storm tracking, and scientific research. A secondary objective is to provide measurements of trace gases, particularly carbon dioxide (CO_2), carbon monoxide (CO), ozone O_3) and methane (CH_4), and mineral dust. In addition, with an optimized band set, the instrument can provide a range of land surface measurements.

As part of the IIP effort, a laboratory instrument was developed which has served to demonstrate the feasibility of the SIRAS-G imaging spectrometer architecture. The SIRAS-G laboratory demonstration instrument operates from 3.34 to 4.8µm with a nominal spectral resolution of 1.4cm^{-1}. SIRAS-G utilizes a wide field-of-view (WFOV) infrared optical system in conjunction with large area IR focal plane technology to provide simultaneous high spatial and spectral resolution over a large field of view. Beamsplitters in collimated space following the shared entrance slit serve to split scene radiation into up to four separate grating spectrometer channels. This architecture provides broad spectral coverage, and each channel can be tuned to match the spectral resolution required. The SIRAS-G architecture allows for slow scanning of the scene (whiskbroom configuration) or pushbroom scanning. While both the Fourier Transform Spectrometer (FTS) and the dispersive spectrometer architectures are suitable for the GEO sounding application [1, 2], the benefits of the dispersive SIRAS-G instrument are that it offers high radiometric accuracy, requires no moving parts except for a scan mirror lending itself to high system reliability over extended mission lifetimes, wide field-of-view imaging, and low distortion.

SIRAS-G builds on the success of the Atmospheric Infrared Sounder (AIRS) [3] which is currently providing an unprecedented set of high-spectral resolution data for weather prediction and climate research. AIRS is providing measurements of tropospheric atmospheric temperature profiles to an accuracy of 1K over 1-km thick layers and moisture profiles of accuracy comparable to radiosonde measurements. The 1999 NASA-sponsored SIRAS (Spaceborne Infrared Atmospheric Sounder) Instrument Incubator Program [4] which was lead by NASA JPL and executed by BATC resulted in the development of a 12µm to 15.4µm spectrometer module as a potential follow-on instrument to AIRS. SIRAS-G builds on the success of this program and further extends the technology to a true IR imaging spectrometer suitable for future Earth science applications such as an advanced GOES sounder and the Atmospheric Infrared Environmental Sensor (ARIES) [5].

A. NASA Instrument Incubator Program

SIRAS-G was one of nine projects selected for IIP-4 in 2002, but the only industry-led project. IIP was established as a mechanism for developing innovative technology suitable for future space-borne earth science programs and as a means to demonstrate and assess the performance of these instrument concepts in ground, airborne and engineering model demonstrations. The goals set forth for an IIP program are to (1) develop and demonstrate mission development in less than thirty-six months; (2) develop the technology such that it is suitable for integration in an operational space instrument within eighteen months following the 3-year IIP development; (3) the instrument concepts developed under IIP must reduce instrument and measurement concept risk to allow the concept to be competitive in an NASA Earth-Sun System Announcement of Opportunity; and (4) the concepts shall enable new science and/or reduce instrument cost, size, mass and resource use. With SIRAS-G, we have successfully demonstrated the operability of the demonstration spectrometer in the laboratory and aim toward converting the instrument into a suborbital instrument suitable for supporting science measurements, with an eventual goal of flying this instrument architecture on a satellite mission.

B. SIRAS-G Overview

The SIRAS-G program has been successfully completed. A major aspect of the SIRAS-G IIP was the development of a laboratory instrument built to demonstrate the feasibility of the instrument architecture and to advance its technology readiness. The SIRAS-G laboratory demonstration instrument is shown in **Fig. 1** as it was being integrated into the BATC IR test facility. While this instrument was primarily intended for laboratory demonstration, we developed the instrument with sufficient robustness such that it would be upgradeable to a suborbital instrument. As such, the demonstration instrument was developed as a complete

Fig.1. SIRAS-G laboratory demonstration instrument being integrated into the Universal Hyperspectral Test Bed (UHTB), a dedicated facility developed at BATC for characterizing and validating the performance of hyperspectral instruments.

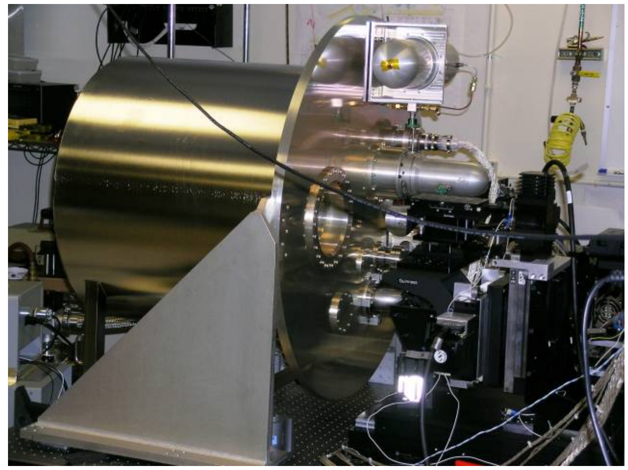

Fig. 2. The SIRAS-G laboratory instrument under test. The primary interface plate is visible in this view. This plate served as the primary interface for all electrical and thermal connections to the instrument. The SB235 Cryocooler condenser and displacer are visible in this view. The cryocooler maintained the spectrometer optical bench and FPA at their respective operational temperatures during test. The entrance window for optical stimuli is also visible.

system representative of a flight instrument; incorporating not only the spectrometer but also the focal plane in a flight-heritage package, flight-like FPA cables, and it was actively cooled using a Ball SB235 Stirling Cycle cooler (see **Fig. 2**). The instrument performance was characterized at cryogenic temperatures.

An additional focus of the SIRAS-G program was mission architecture studies to demonstrate the applicability of SIRAS-G to future earth remote sensing needs and identify suitable architectures for specific mission goals. A major benefit offered by SIRAS-G is the improved spatial resolution that can be obtained simultaneously with the required high spectral resolution. This capability is a major feature that been taken advantage of in the architecture development for the ARIES instrument being developed by NASA JPL. The ARIES instrument combines features of two highly successful earth observing instruments, MODIS [6] and AIRS. AIRS accurate spectral radiances have produced a positive forecast impact when assimilated into the NOAA/NESDIS operational forecast system, while its water vapor profiles, temperature, and trace gas products have proved useful for climate studies. MODIS high spatial resolution and its high radiometric sensitivity have proved extremely useful for studies of surface temperature, clouds, and atmospheric water vapor. AIRS and MODIS cover approximately the same spectral regions in the infrared (i.e. 3.7 to 15.4µm for AIRS, and 3.7-14.4µm for MODIS). AIRS spectral resolution ($\lambda/\Delta\lambda$) is approximately 1200, with a 13.5 km footprint, while the MODIS spectral resolution in the infrared is approximately 100, with a 1km footprint. Scientists are beginning to see the value on using both instruments together to understand the spatial, spectral and radiometric variability in the scene and for cross-calibration. It is the goal to use ARIES to continue this capability into the future. SIRAS-G is the ideal instrument architecture for this mission.

The improved spatial resolution afforded by SIRAS-G should allow more opportunities for cloud clear observations, which is of particular importance in the absence of simultaneous microwave measurements. This is a crucial factor in improving the yield of retrieved cloud-free scenes that can be assimilated into Numerical Weather Prediction (NWP) models. As an example, for the AIRS, it is estimated that only 4.5% of fields observed over oceans exhibited less than 0.6% cloud contamination [7]. This is largely attributable to the relatively large footprint of AIRS (13.5-km). SIRAS-G is being designed with a 4-km footprint from GEO. SIRAS-L (for LEO) is more directly comparable to AIRS is designed with a 0.5-km ground footprint.

C. *Science Measurement Requirements*

SIRAS-G addresses several high priority research areas identified in proposals to the National Research Council's Decadal Survey. High spectral and spatial resolution makes it broadly applicable to a wide range of future missions. We focused on several potential future missions during the SIRAS-G study:

AIRS Follow-On: An instrument concept was developed to continue the AIRS mission. Requirements generated for the AIRS follow-on instrument are shown in Table 1. This instrument concept would utilize 4 spectrometer legs to cover the full 3.3 µm to 15.4µm spectral region.

Table 1
Preliminary Spectral Channel Set for AIRS Follow-On Instrument and Science Measurement Objectives

Parameter	Spectral Range (cm^{-1})	Min. res (cm^{-1})	Goal res (cm^{-1})	Notes
Temp profiles	650 - 768 2228 - 2255 2380 - 2410	0.5 2.0 2.0	0.5	Higher spectral resolution improves Temp sounding throughout range
H_2O profiles	1370-1610	2.0	0.5	Weaker water lines near 2600 cm^{-1} used AIRS
O_3 Column	1001-1069	0.5	TBD	Very high resolution necessary for profile info.
Surface Temp	750-1200	~1.0	0.5	Several channels: 750-1235 cm^{-1} and >2400 cm^{-1}
Dust properties	750-1200	~1.0	0.5	Higher resolution improves Upper Trop/Lower Stratosphere retrievals
Cloud properties	750-1200	~1.0	0.5	3 channels: 8,10,12 µm

Tropospheric Atmospheric Chemistry Mission: Key measurement objectives for a Tropospheric Chemistry Mission include observations of ozone, aerosols, and atmospheric trace gases such as CO, CH_4 and NO_x. The combination of SIRAS-G sounder and a multi-channel high-resolution spectrometer such as IMOFPS [8] could provide these measurements in a compact, solid-state instrument suite. IMOFPS consists of three co-boresighted correlation spectrometers for measuring vertical profiles of CO and column amounts of CO_2 and CH_4. This instrument concept has been developed under BATC IR&D funding. The addition of a fourth spectrometer channel for measuring NO_x is easily accommodated and would provide a tracer of motion and cloud detection. A three-channel version of SIRAS-G, one channel extending from 12.3µm to 15µm, the second centered at the 9.6µm ozone band, and the third in the MWIR could provide measurements of atmospheric temperature, water vapor and ozone column.

All instruments in this suite have no moving parts, except for a scene-selecting scan mirror. For in-flight calibration, the scan mirror would be used to periodically view on-board blackbody calibration sources and cold space.

ARIES: SIRAS-G technology is ideally suited to the ARIES mission concept and in fact has been identified as an enabling technology in the proposal to the Earth Science Decadal Survey. ARIES will provide spectral coverage from 3.6µm to 15.4µm, with spectral resolving power ($\lambda/\Delta\lambda$) ranging from 1200 to 1500. The measurement objectives for ARIES include temperature and water vapor sounding, surface temperature and emissivity, cloud opacity and distribution, retrieval of minor gases and mineral dust, and the measurement of total ozone. A primary feature of ARIES is the high spatial resolution (2 km) desired and this can be obtained with the SIRAS-G technology.

II. SIRAS-G TECHNOLOGY DEVELOPMENT

A. *Results from SIRAS-1999*

The NASA JPL-lead SIRAS team [4] developed an advanced instrument concept as a potential follow-on for AIRS. This effort was funded under the first IIP (IIP-1999). The original SIRAS-1999 instrument concept was designed to meet the requirements of AIRS, but in a smaller package and with improved spatial resolution (0.5-km vs. AIRS 13.5km). As part of this effort, a high-resolution infrared imaging spectrometer operating from 12µm to 15.4µm was designed, built and tested at cryogenic temperatures in a laboratory environment. A detailed study of the size, mass, and power of a SIRAS-L (LEO) instrument configuration was performed. In addition, it was demonstrated that the same spectrometer could meet the requirements of a GEO sounder. However, unlike the more recently developed SIRAS-G technology, the SIRAS-1999 spectrometer viewed only a single IFOV, which was then dispersed over a linear detector array. An AIRS detector array was used for this instrument demonstration.

Successful demonstration of the SIRAS-1999 demo spectrometer demonstrated that the key sounding performance requirements could be achieved with the SIRAS dispersive spectrometer architecture. Spectrometer-level testing was performed in thermal vacuum at cryogenic temperatures. Spectral measurements were made by adjusting the air path length between the thermal-vacuum chamber and the source blackbody and determining how well CO_2 and water vapor absorption features were resolved.

Fig. 3 shows the results of an air path test. The data were analyzed for spectral resolution by comparing them to theoretical atmospheric transmission spectra for a 3-meter path length with varying spectral response widths. The response widths were varied until the resulting convolved modeled spectra matched the measured spectra. We were able to demonstrate a resolving power ($\lambda/\Delta\lambda$) of 1200 ± 300 for the SIRAS-1999 spectrometer. The entry point for SIRAS-1999 IIP was TRL-3. On completion, the spectrometer was TRL-5.

B. *SIRAS-G Laboratory Demonstration Instrument*

The SIRAS-G spectrometer assembly was developed at BATC in Boulder, Colorado. Major subsystems of this instrument have been integrated and the instrument testing in the thermal vacuum chamber (**Fig. 2**) completed. The demonstration spectrometer consists of one complete spectrometer channel including the Reflective Triplet Objective (RTO) (see **Fig. 4 and 5**), the spectrometer subassembly mounted in the optical bench, a Teledyne Hawaii 1-RG 5µm-cutoff FPA, FPA electronics, and the SB235 cryocooler. The demo instrument operates over the 3.3 to 4.8 µm spectral range with a nominal spectral resolution of 1.4 cm^{-1}. Testing to-date has been to the spectrometer level, without the RTO integrated.

As stated earlier, the objective of IIP is to retire the risk of key technologies needed for next-generation earth science missions. The goal is to save flight program costs and schedule delays by developing technologies to their flight configuration well in advance of program needs. The SIRAS-G technology demonstration is aimed at specifically mitigating these concerns.

A major consideration for a cryogenic instrument employing refractive optics is designing the lens mount to avoid introducing stresses into the lens elements at operational temperatures, or worse yet, causing mechanical failure in the lens due to excessive stresses resulting from different coefficients of thermal expansions of the optical materials and the lens mounts. The elastrometric mounts employed on SIRAS-G are based on extensive heritage on BATC programs and have been designed specifically to avoid these issues while providing a rigid lens mount suitable for flight environments [9].

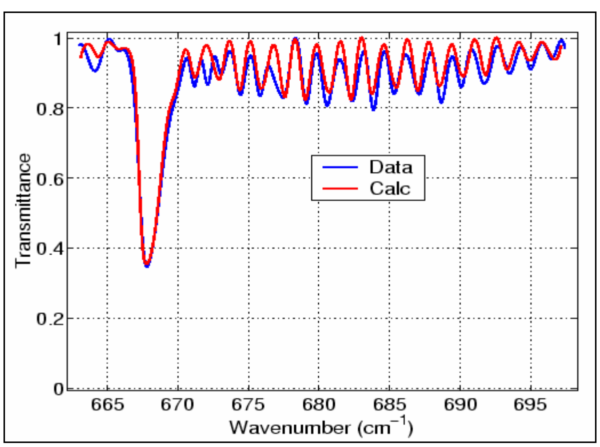

Fig. 3. SIRAS measurements of laboratory air confirmed that desired spectral resolving power ($\lambda/\Delta\lambda$) between 900 and 1400 was achieved.

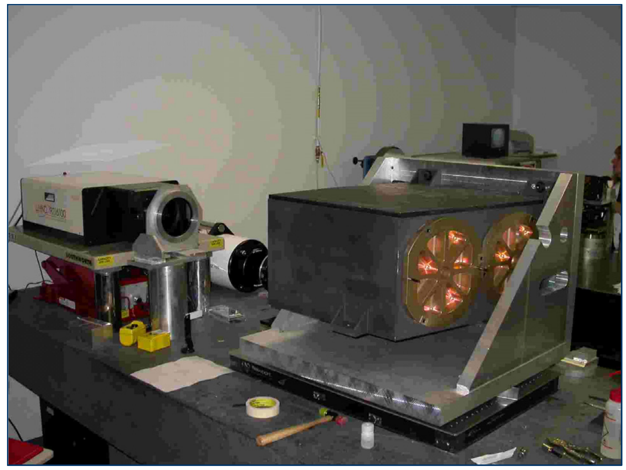

Fig. 4. The RTO undergoing final double-pass interferometric performance test. Testing was conducted at a wavelength of 632.8nm.

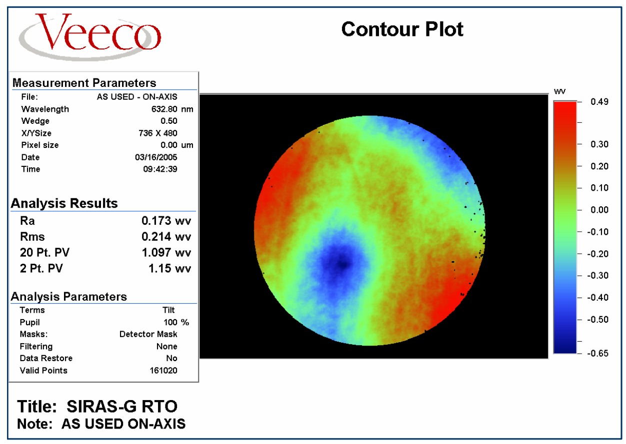

Fig. 5. Measured WFE (632.8nm) measures 0.20 to 0.30 waves RMS. This corresponds to 0.03 to 0.047 waves RMS at central operational wavelength of 4.0 µm.

Imaging spectrometer performance is largely dependent on minimizing key image defects, particularly spectral smile and keystone distortion, while maintaining excellent imaging performance [10, 11]. For the SIRAS-G demo instrument we employed 2x oversampling to provide Nyquist sample in the spectral domain. Smile and keystone distortion are limited to less than 20% of a spectral/spatial resolution element over the entire FPA.

The Hawaii 1-RG 1024 x 1024 FPA was provided by Teledyne Imaging Systems and meets all performance requirements. All signal processing and control software & hardware has been delivered along with the FPA.

The RTO was designed specifically for the laboratory demonstration instrument and was fabricated by Corning NetOptix. This optical subsystem has been delivered to BATC. This 3-mirror all-reflective objective is of all aluminum construction and utilizes three powered mirrors and one flat, all single-point diamond-turned and gold coated for high transmission in the MWIR. The RTO, shown in **Fig. 4** during qualification testing, provides diffraction-limited performance over the full IR region of interest, as well as telecentric input to the spectrometer. A double-pass interferogram of the system at 632.8 nm is shown in **Fig. 5**.

The optical components, including the camera refractive elements, one of which is shown in its lens mounts in **Fig. 6**, the grating (**Fig. 7**) and FPA window/spectral filter were also provided by subcontractors. All of these components met their performance requirements and have being integrated into the instrument. The excellent performance of the SIRAS-G spectral filter is shown in **Fig 8**. A thorough transmission analysis and allocation of transmission/reflection requirements across elements of the system ensured good in-band transmission and efficient rejection of out-of-band radiation. The estimated system transmission, based on component measurements is shown in **Fig. 9**.

C. SIRAS-G Demonstration Instrument – Test Results

A dedicated test facility, the Universal Hyperspectral Test Bed (UHTB) has been developed at BATC for characterizing and validating the performance of imaging spectrometers. This facility provides the capability to rapidly measure all the major performance parameters associated with imaging spectrometer performance, including keystone distortion, spectral smile, modulation transfer function (MTF), dispersion, and spectral response function (SRF). These capabilities are based on proprietary methodologies and apparatus developed on BATC internal research and development funds. The capabilities of the UHTB were used to characterize and optimize the performance of the SIRAS-G laboratory MWIR instrument. As an example, we show in

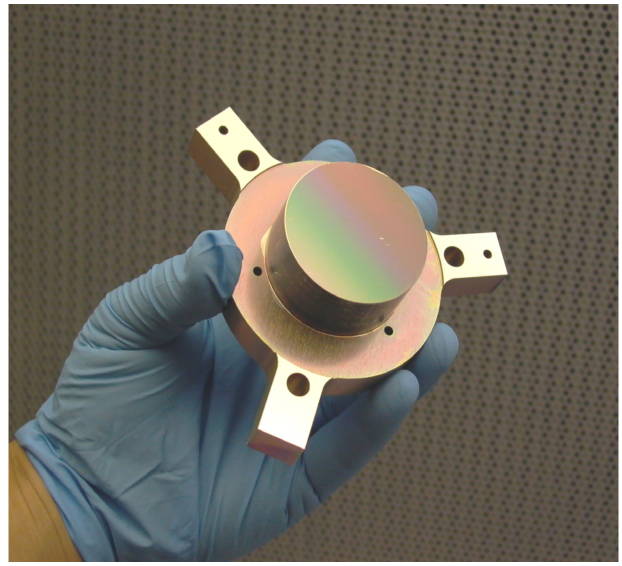

Fig. 7. The SIRAS-G Demonstration Instrument Grating

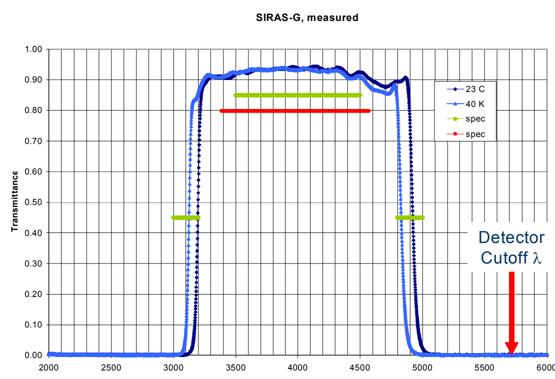

Fig. 8. Measured performance of the SIRAS-G demonstration instrument FPA window/spectral filter

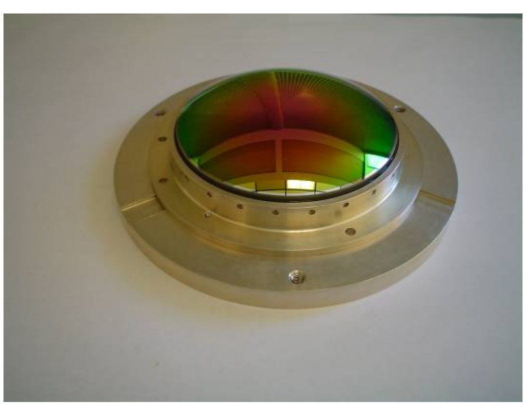

Fig. 6. One of the SIRAS-G refractive camera elements, shown bonded into its lens cell. Bondline thickness have been optimized for temperature range.

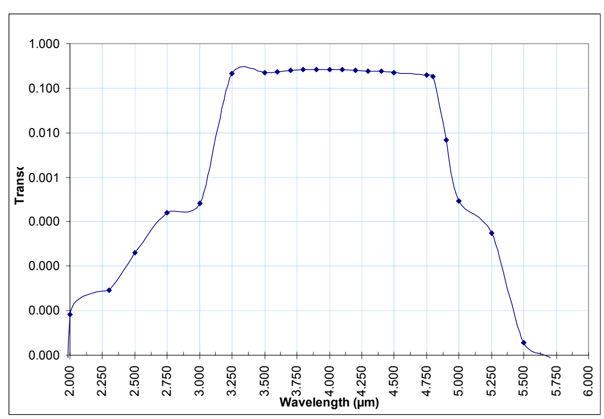

Fig. 9. Transmission estimate for the SIRA-G demonstration instrument based on component measurements

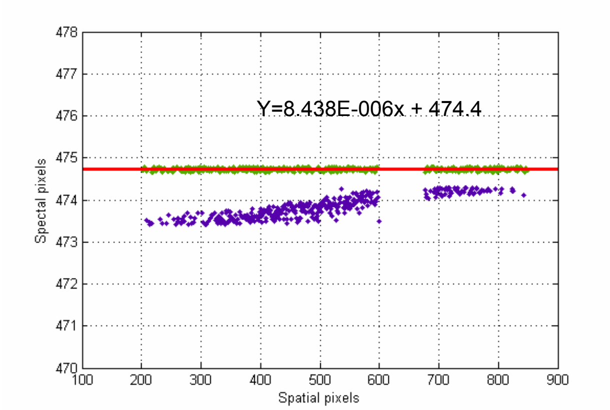

Fig. 10. Measured keystone distortion using image centroids for single dispersed image of point at slit. Improvement resulting from clocking FPA is shown. Residual error is less than 0.1-pixel after clocking of FPA.

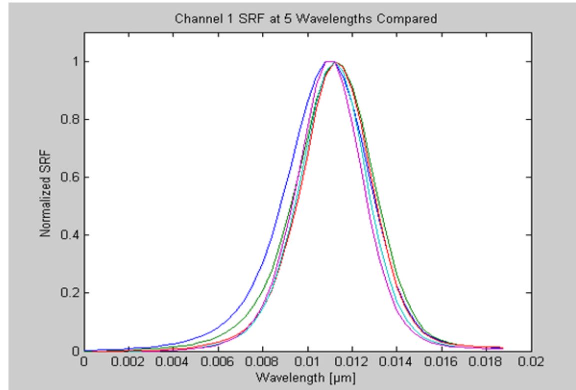

Fig. 11. Spectral response function (SRF) measurements Measured SRF for 5 wavelengths at a single slit location for demonstration LWIR spectrometer. The average FWHM for this instrument was 3.8nm.

Fig. 10 the measurement of keystone distortion (at a single slit position) and the improvement gained after clocking and adjusting the position of the FPA for best focus. As seen from the figure, we were able to reduce misregistration of the dispersed spectra to less than 0.2-pixel after these adjustments. **Fig. 11** shows measurements of SRF at several wavelengths at a single slit position obtained simultaneously for a complementary LWIR imaging spectrometer, also developed at BATC.

D. Warmshield Development

IR optical systems are often designed for 100% cold stop efficiency. This is when the cold stop is matched to the exit pupil to reduce parasitic radiation or unwanted vignetting over the field of view. However, in an optical system such as an imaging spectrometer where the pupil is not at the cold stop, 100% cold stop efficiency cannot be met when a simple camera is used. An additional optical relay in the camera would be required to reimage the pupil onto the cold stop. To avoid the additional throughput losses and alignment complexity that would be required, we have taken an alternative approach to this problem and use a series of reflective warm shields to reduce the thermal background that is "seen" by detectors. When the cold stop is not matched to the exit pupil, a detector element will be able to see warm structure outside of the solid angle of the scene. By placing reflective surfaces of appropriate shape (the warm shields) between optical elements it is possible to redirect rays from the detectors such that they are imaged onto cold surfaces at or near the FPA. Multiple warm shield elements may be required to capture the full solid angle viewed by detectors, as is the case for imaging spectrometers of the SIRAS-G design. This is illustrated in **Fig. 12**. The design of these reflective surfaces must be done carefully to avoid directly reimaging onto the FPA surface and avoid producing spurious ghost images. While warm shields can not provide 100% cold stop efficiency due to (albeit small) absorption in the reflective coatings and the inability to capture all rays that come from the cavity to the detector, they can reduce the total thermal background at the FPA significantly as has been demonstrated at BATC. **Fig. 13** shows the reduction in thermal background observed in the LWIR spectrometer with warm shields installed compared with warm shields removed. The improvement in performance is quite evident. Incorporating warm shields in the system design allows one to increase the optical bench temperature without significantly impacting the thermal background, providing a lever for the system designer to trade optical bench temperature and power for cooling while still providing the required system SNR. Although multi-stage reflective warm shields have been suggested in the past [10], this is, to the best of our knowledge, the first application of this technology to an imaging spectrometer. The functionality of these components in a functional cryogenic imaging spectrometer has been demonstrated.

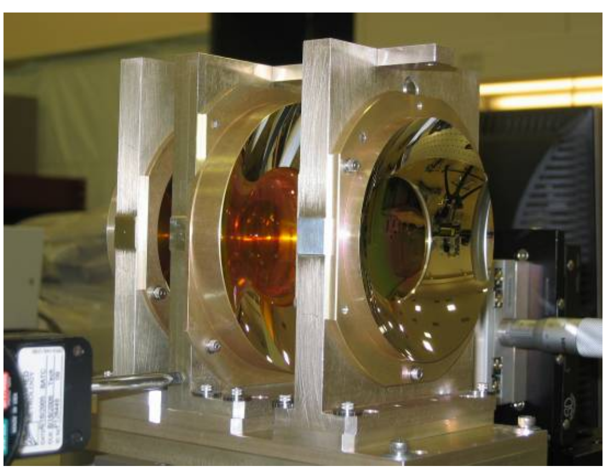

Fig. 12. Warm shield elements shown installed on camera assembly of the complimentary LWIR imaging spectrometer.

III. AIRBORNE DEMONSTRATION

The SIRAS-G instrument demo was originally intended for laboratory demonstration. However, it is recognized that

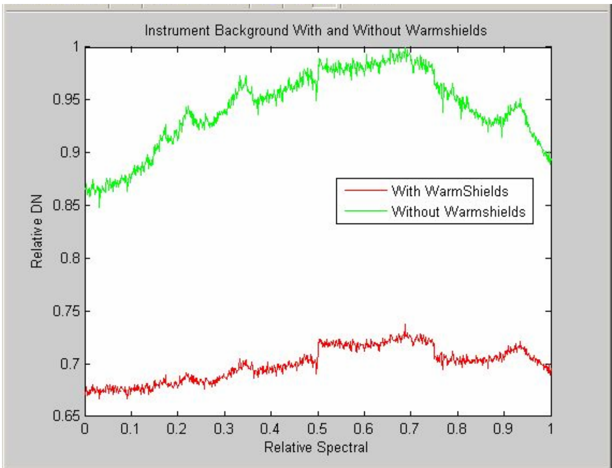

Fig. 13. Reduction in thermal background noise as seen by detectors along on spectral column. These results were obtained by first measuring the background with the warm shields installed at cryogenic operational temperature. The system was brought to ambient, warm shields removed, returned to operational temperature and background remeasured. It can be seen that the thermal background is reduced as well as flattened over the field of view.

airborne flights of SIRAS-G would further demonstrate the suitability of SIRAS-G for actual science measurements. Airborne flights in support of a field campaign would provide the opportunity for scientists to become familiar with the capabilities of the technology and to develop scientific algorithms based on this instrument architecture. This would also provide the opportunity for cross-validation with other airborne instruments such as NAST-I or with spaceborne instruments such as AIRS or CrIS. As such, we have striven to design the SIRAS-G demonstration instrument in a manner suitable for upgrade to airborne operation. For example, since the entire aft-optics bench must be maintained at cryogenic temperatures, we have housed this assembly in a self-contained thermal/vacuum enclosure. The Ball SB325 cryocooler has sufficient capacity to provide all necessary temperature control and refrigeration needed to maintain the aft-optics bench and the FPA at needed operational temperatures; although an option for cooling using liquid nitrogen dewar has also been incorporated. In a similar manner, all components of the SIRAS-G spectrometer subsystem are mounted onto a single instrument palette ensuring that the instrument maintains alignment even when transported. Thus, the SIRAS-G demonstration instrument is largely autonomous and readily adaptable to a variety of potential airborne platforms.

IV. PATHWAY TO SPACE

Technologies developed and being demonstrated on the SIRAS-G IIP have clear pathways to space, being suitable for a number of missions already identified as key in improving our understanding of weather forecasting and climate studies. The principal technical challenge was demonstrating that sufficient control on image degrading errors such spectral smile and keystone distortion can be achieved through appropriate design, fabrication and assembly such that the spectral response functions over the entire FOV are not degraded. This was demonstrated over the deliberately large spatial field of view of the SIRAS-G instrument and for al wavelengths.

The AIRS instrument has demonstrated the feasibility of dispersive spectrometers for atmospheric sounding, although being a pupil-imaging system [13]; it has significantly different characteristics than SIRAS-G. Our goal is to provide an instrument of lower mass, volume, and ultimately, lower cost, with enhanced capabilities that include improved spatial resolution and greater flexibility afforded by the modular spectrometer architecture suitable for future earth remote sensing missions.

V. SUMMARY

NASA ESTO's support of independent technology development for future Earth science needs is a positive step forward offering promising benefits in terms of early identification of appropriate technologies and retiring technical risks. Technologies such as those developed on the SIRAS-G IIP will provide shorter mission development cycle time and reduced overall cost, and ultimately, lead to more frequent science missions at lower overall cost. SIRAS-G exemplifies the benefits of IIP and represents an important advance in high-resolution IR atmospheric sounding for earth observation. The SIRAS-G grating architecture is well suited to a wide variety of high priority missions with the flexibility to support missions in GEO, LEO, and even MEO orbits. The further realization that the combination of SIRAS-G with other innovative instrument concepts such as IMOFPS offer a path to smaller less costly and more capable instruments for future NASA and NOAA missions needs to be appreciated as well. The Instrument Incubator Program has provided the mechanism to move SIRAS-G from concept to hardware demonstration, improving its technology readiness to where it will be ready for insertion into future spaceborne missions. Key to this has been the successful completion of the testing of the SIRAS-G demonstration instrument.

ACKNOWLEDGEMENT

We gratefully acknowledge the support of NASA ESTO, especially the support of our COTR, Janice Buckner. In addition, we wish to acknowledge the contributions from the SIRAS-1999 and SIRAS-G teams. This program is funded by NASA ESTO Contract NAS5-03123.

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