SIRAS-G, the Spaceborne Infrared Atmospheric Sounder for Geosynchronous Earth Orbit

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Abstract*: The Spaceborne Infrared Sounder for Geosynchronous Earth Orbit (SIRAS-G) is enabling technology for future spaceborne IR sounders. The instrument is being developed by Ball Aerospace & Technologies Corp (BATC). SIRAS-G was selected for development under NASA's 2002 Instrument Incubator Program (IIP-4) and provides an approach for compact, low mass IR sounders when compared to contemporary instruments. The SIRAS-G technology is ideally suited for measuring atmospheric temperature, water vapor, and research products such as trace gases and mineral dust from satellite. The SIRAS-G technology offers significant benefits for future Earth and planetary science missions, providing high-spectral resolution in conjunction with high spatial resolution along with broad spectral coverage and extended field of view. Improved spatial resolution, comparable to that of MODIS, has the potential for improving the yield of cloud-free pixels, improved tracking of trace gas transport, and is suitable for assimilation into next-generation chemical transport and climate models. The SIRAS-G dispersive spectrometer module is readily adaptable for missions in LEO, GEO and MEO orbits and can be optimized for spectral resolution over subsets of the total spectral range. We are now in the third and final year of this three-year program and preparing for cryogenic testing of the SIRAS-G laboratory demonstration instrument. Primary measurement parameters include keystone distortion, spectral smile, MTF, and the spectral response function (SRF) to high accuracy using a proprietary test methodology developed at BATC. We discuss instrument concepts utilizing SIRAS-G technology developed for potential future missions.

I. INTRODUCTION

The Spaceborne Infrared Atmospheric Sounder for Geosynchronous Earth Orbit (SIRAS-G) is being developed with the goal of providing 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, carbon monoxide, ozone and methane. In addition, with an optimized band set, the instrument can provide a range of land surface measurements.

SIRAS-G demonstrates the use of a wide field-of-view (WFOV) infrared optical system in conjunction with large area IR focal plane assembly (FPA) technology 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 required spectral resolution required. The WFOV and large area FPAs allow for slow scanning of the scene (whiskbroom configuration) or pushbroom scanning and improved radiometric sensitivity. Unlike the Fourier Transform Spectrometer, the dispersive SIRAS-G instrument requires no moving parts except for a scan mirror, leading to improved system reliability over extended mission lifetimes.

SIRAS-G builds on the success of the Atmospheric Infrared Sounder (AIRS) [1] which is currently providing an unprecedented set of high-spectral resolution data. The 1999 NASA-sponsored SIRAS (Spaceborne Infrared Atmospheric Sounder) Instrument Incubator Program [2] which was lead by NASA JPL and executed by BATC resulted in the development of a 12 to 15.4 μm spectrometer module for a potential follow-on instrument to AIRS. SIRAS-G builds on the success of this program and further extends the technology to a true imaging spectrometer suitable for future Earth science applications such as the GOES Hyperspectral Instrument Suite (HES) [3] and the Atmospheric Infrared Environmental Sensor (ARIES) [4].

A. NASA Instrument Incubator Program

SIRAS-G was one of nine proposals selected in IIP-4 (2002), but the only industry-led proposal selected. 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. On SIRAS-G, we are well along in demonstrating the feasibility of this IR hyperspectral technology in-line with the goals of IIP.

B. SIRAS-G Overview

Ball Aerospace & Technologies Corp. (BATC) is responsible for executing the SIRAS-G program. Our focus is on advancing the SIRAS-G instrument concept for future earth science missions. A major aspect of this effort is the development of a laboratory demonstration instrument which will serve to advance the technology readiness of the technology. While the SIRAS-G demonstration instrument is primarily intended for laboratory demonstration, our intent is to build an instrument with sufficient robustness to be easily upgradeable to airborne flight and be representative of what could be expected for space flight. In addition, we have undertaken a series of mission architecture studies to demonstrate the applicability of SIRAS-G to critical 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 in the architecture development for the ARIES instrument being proposed by NASA JPL in the NASA Decadal Survey [5]. The improved spatial resolution 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, with AIRS in low Earth orbit (LEO), it is estimated that only 4.5% of fields observed over oceans exhibited less than 0.6% cloud contamination [6]. This is largely attributable to the relatively large footprint of AIRS (13.5-km). SIRAS-G, on the other hand, is designed for a 4-km footprint from GEO. SIRAS-L (for LEO) more directly comparable to AIRS has been conceived with a 0.5-km ground footprint. We would expect significant improvement in the percentage of cloud-free scenes from these instruments.

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. Our current focus is on several potential future mission scenarios:

ARIES Follow-On: The first potential future application we are considering is a follow-on instrument for AIRS, currently flying on NASA's Aqua satellite. A list of candidate requirements for the AIRS follow-on instrument is shown in Table 1.

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 mm

As we learn more from AIRS and assimilation of data by the weather forecasting community, it has become clear that clouds significantly degrade the number of clear sky retrievals that can be obtained. We project that future sounding systems will require significantly improved spatial resolution. We now have designs for SIRAS that offer spatial footprints of less than 0.6 km (as compared to the AIRS 13.5 km footprint) without sacrificing SNR.

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 [7] 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 12.3-µm to 15-µm and a second centered at the 9.6-µm 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 periodically view on-board blackbody calibration sources and cold space.

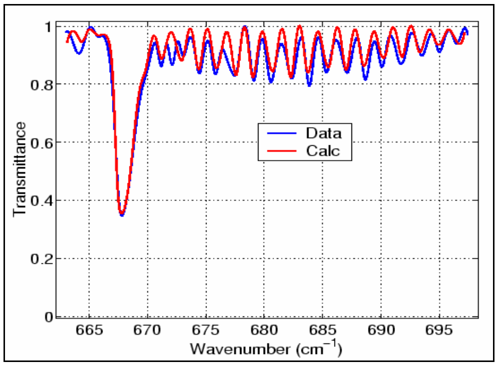

Fig. 1. SIRAS measurements of laboratory air confirmed that desired spectral resolving power (λ/Δλ) between 900 and 1400 was achieved.

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. ARIES is proposed to provide spectral coverage from 3.6 to 15.4 µm, with spectral resolution (λ/Δλ) 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 [2] developed an advanced instrument concept as a potential follow-on for the 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 13.5-km). As part of this effort, a high-resolution infrared imaging spectrometer operating in the 12 to 15.4µm spectral region 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 (Low Earth Orbit) instrument configuration was performed. In addition, it was demonstrated that the same spectrometer could meet the requirements of a GEO sounder. Unlike the current SIRAS-G technology, SIRAS-1999 viewed only a single IFOV, which was then dispersed over a linear detector array.

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.

Figure 1 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 resolution 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 is being developed at BATC in Boulder, Colorado. A major focus of the SIRAS-G program is on the development of the technology demonstration instrument. Major subsystems of this instrument are currently being assembled and our goal is to integrate the demo instrument into the thermal vacuum chamber in August 2006 to begin systems-level testing. A solid model representation of the demo instrument is shown in Fig. 2. This figure shows the SIRAS-G demonstration instrument architecture and major subsystems. We are building one complete spectrometer channel of the instrument including the Reflective Triplet Objective (RTO), spectrometer subassembly, FPA, and FPA electronics. The demo instrument operates over the 3.3 to 4.8 µm spectral range with a nominal spectral resolution of 1.4 cm^{-1}.

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.

What had previously been referred to as the Optically-Enhanced Cryogenic Dewar [2] is now more accurately called the multi-stage warmshield assembly. This technology will also be demonstrated as part of the demo instrument. The optical components making up this subsystem are single-point diamond-turned components that mount onto the lens cells. A major consideration for a cryogenic instrument employing refractive optics is designing the lens mount to avoid introducing stresses into the lens elements at

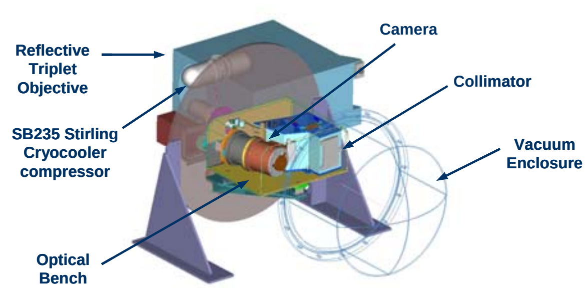

Fig. 2. Solid model representation of the SIRAS-G Laboratory Demonstration Instrument showing major subsystems.

operational temperatures, or worse yet, causing mechanical failure in the lens due to excessive stresses due to the differential 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.

Rockwell Scientific Corporation (RSC) in Camarillo, California has provided the FPA, clock, bias and A/D conversion electronics under subcontract. The FPA will be packaged at BATC and the FPA package and electronics are being integrated with the spectrometer at BATC. Active cooling of the aft optics to 140K and the FPA to 40K will be demonstrated with the two-stage BATC Model-232 Sterling Cycle cooler. The BS-235 cooler is optimal for SIRAS-G FPA and optics cooling, being mass and power efficient, and exhibiting high cooling capacity.

Imaging spectrometer performance is largely dependent on minimizing key image defects, particularly spectral smile and keystone distortion, while maintaining excellent imaging performance [8, 9]. For the SIRAS-G demo instrument we employ true Nyquist sampling and limit these image defects to less than 20% of a spectral/spatial resolution element over the entire FPA. Performance to this level will be demonstrated through spectrometer-level test. Keystone distortion, spectral smile, MTF and spectral response function (SRF) will be measured on the SIRAS-G demonstration instrument. Test methods developed on BATC internal research and development funds have the demonstrated capability to provide these measurements to the required levels of accuracy.

C. Current Hardware Status

As shown in Figure 2, the SIRAS-G laboratory demonstration instrument is composed of several major hardware elements. While the majority of these have been designed by the SIRAS-G team at BATC, several are being provided by subcontractors. The HAWAII 1-RG FPA has been delivered by RSC 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 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. The RTO, shown in Figure 3 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 Figure 4.

Major optical components, including the camera elements, the grating (Figure 5) and FPA window/spectral filter have been delivered by subcontractors. All of these

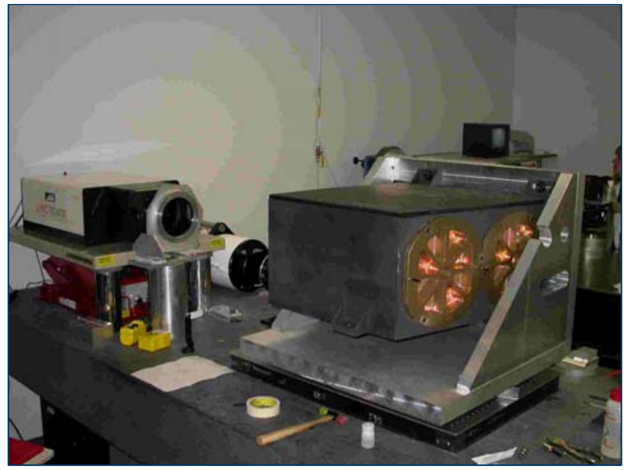

Fig. 3. The RTO undergoing final double-pass interferometric performance test. Testing was conducted at a wavelength of 632.8nm.

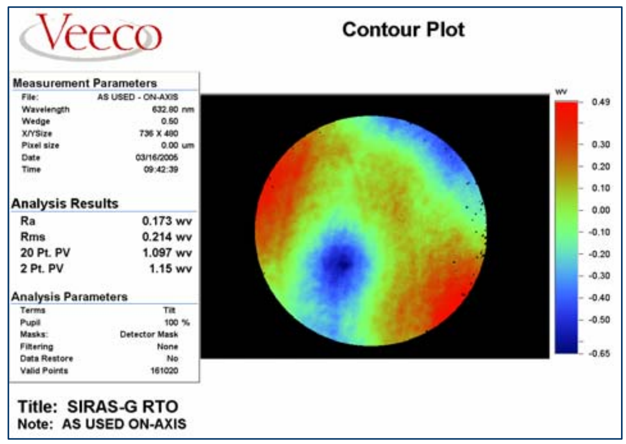

Fig. 4. Measured WFE (632.8nm) measures 0.20 to 0.30 waves RMS. This corresponds to 0.03 to 0.047 waves RMS at central operational wavelength of 4.0 µm.

components have met performance requirements and are currently being integrated into the instrument. The excellent performance of the SIRAS-G spectral filter is shown in Figure 6.

D. Warmshield Development

For an optical system such as an imaging spectrometer that has the pupil at the grating, it is not possible to have an optical system with 100% cold stop efficiency when a simple camera is used. An additional optical relay in the camera would be required to achieve this. To avoid the additional throughput losses and alignment complexity, we have taken an alternative approach to this problem and utilize a series of reflective warm shields to reduce the thermal background "seen" by detectors.

One hundred percent cold stop efficiency in an IR imaging system implies that a detector looking back through the optical system can see only optical surfaces inside the solid angle of the optical system and cold surfaces outside the solid angle of the optical system. One hundred percent cold stop efficiency requires collocating the exit pupil of the

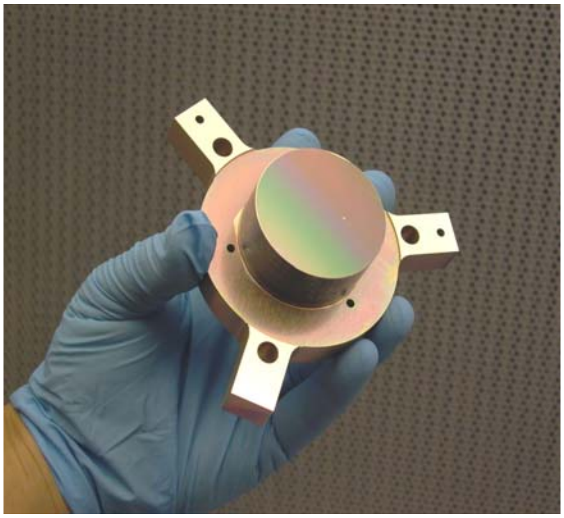

Fig. 5. The SIRAS-G Demonstration Instrument Grating

optical system with the aperture of the cryo-stat, and making the F/# of the cryo-stat the same or slower than the F/# of the optical system.

A warm shield design was developed for SIRAS-G that reduces the thermal background due to the exit pupil not being collocated with the cryo-stat aperture. This is the thermal background due to the detector being able to see outside of the spectrometer camera optics. While warm shields can not provide 100% cold stop efficiency due to (albeit small) absorption in the reflective coatings, they can reduce the total cryo-load by raising the minimum temperature of the surfaces between the cryo-stat and the exit pupil while still providing the required system SNR. Although multi-stage reflective warm shields have been suggested in the past [10], to our knowledge, this is the first application of this technology to an imaging spectrometer. Our goal is to demonstrate the functionality of these components and validate their application to imaging spectrometers.

IV. AIRBORNE DEMONSTRATION

The SIRAS-G instrument demo is intended for laboratory demonstration. However, it is recognized that 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 to develop scientific algorithms based on this instrument architecture and provide the opportunity for cross-validation with other airborne and/or spaceborne sounders such as NAST-I or with spaceborne instruments such as AIRS. 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 SB-325 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. 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.

V. 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 is in 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 will be demonstrated by the end of the summer 2006.

The AIRS instrument has demonstrated the feasibility of dispersive spectrometers for atmospheric sounding, although being a pupil-imaging system [11]; 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.

VI. 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

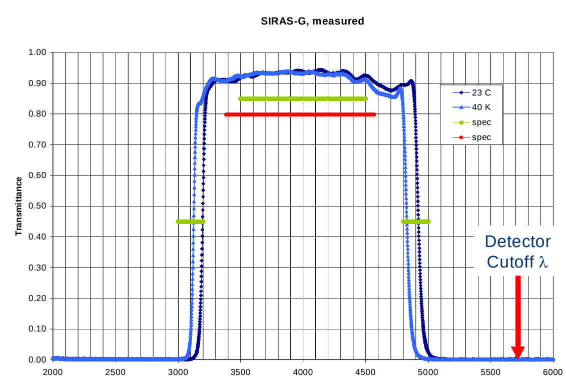

Fig. 6. Measured performance of the SIRAS-G demonstration instrument FPA window/spectral filter

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 is the successful completion and testing of the SIRAS-G demonstration instrument, a goal that we are rapidly approaching.

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