SIRAS-G, the Spaceborne Infrared Atmospheric Sounder for Geosynchronous Earth Orbit – A Pathfinder for IR Imaging Spectroscopy from Space

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Abstract. **The Spaceborne Infrared Sounder for Geosynchronous Earth Orbit (SIRAS-G) is an infrared spectrometer being developed at Ball Aerospace & Technologies under IIP that offers significant benefits for future Earth and planetary science missions. SIRAS-G, selected for development under NASA's 2002 Instrument Incubator Program (IIP-4), is an instrument concept of lower mass and power than contemporary instruments offering enhanced capabilities for atmospheric temperature, water vapor, and trace gas column measurements. We are now in the second year of this three-year program. SIRAS-G utilizes grating spectrometers coupled with refractive IR cameras to provide high spectral and spatial resolution. The SIRAS-G concept is adaptable to airborne, low-Earth orbit and geosynchronous deployment. We present the status of the laboratory instrument development and discuss instrument concepts for potential future missions. For SIRAS-G, we are building a laboratory demonstration instrument all major subsystems. We present status on planned and on-going development activities, including the fabrication and testing of the reflective triplet objective, the aft-optics and FPA for the demonstration instrument.**

I. INTRODUCTION

The Spaceborne Infrared Atmospheric Sounder for Geosynchronous Earth Orbit (SIRAS-G) has been developed with an emphasis on providing highly accurate atmospheric temperature and water vapor profile measurements from geosynchronous orbit (GEO). These measurements would facilitate weather forecasting, severe storm tracking, and scientific research. In addition, with increased spectral coverage and spectral resolution, the instrument architecture can also support trace gas, aerosol, and land surface measurements.

SIRAS-G employs a wide field-of-view hyperspectral infrared optical system that splits the incoming radiation into up to four separate grating spectrometer channels. This allows for slow scanning of the scene, increased dwell time, and improved radiometric sensitivity. Unlike competing technologies, such as Fourier Transform Spectrometers (FTS), SIRAS-G employs no moving parts or metrology lasers except for a scan mirror, leading to improved system reliability over the mission lifetime.

SIRAS-G build on the successful completion of the 1999 NASA-sponsored SIRAS (Spaceborne Infrared Atmospheric Sounder) Instrument Incubator Program [1], where the 12-15.4μm spectrometer module was developed and demonstrated. SIRAS-1999 focused on developing spectrometers as potential follow-on to the Atmospheric Infrared Sounder (AIRS) [2].

A. NASA Instrument Incubator Program

Ball Aerospace & Technologies Corp. (BATC) is responsible for executing the SIRAS-G program. SIRAS-G was one of nine proposals selected in the third IIP in 2002, but was uniquely 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

We are focused on advancing the SIRAS-G instrument concept for insertion into future earth science missions. While the SIRAS-G demonstration instrument is primarily intended as a laboratory demonstration, it our intent to build an instrument with sufficient robustness to be easily upgradeable to airborne flight and representative of what could be expected for space flight. We are also undertaking a series of mission architecture studies to evaluate the applicability of SIRAS-G to critical earth remote sensing needs and identify suitable architectures for specific mission goals.

One of the key benefits offered by SIRAS-G is the improved spatial resolution it offers for future sounders over the state-of-the-art instruments of today (i.e., AIRS, CrIS).

This is achieved while simultaneously providing the necessary high spectral resolution needed for accurate temperature and water vapor sounding. The improved spatial resolution should allow more opportunities cloud clear observations, which is of particular importance in the absence of simultaneous microwave measurements; 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, on the current Low Earth Orbit (LEO) AIRS instrument, it is estimated that only 4.5% of fields observed over oceans exhibited less than 0.6% cloud contamination [3]. This is largely attributable to the relatively large footprint of AIRS (13.5-km). SIRAS-G is being designed for a 4-km footprint from GEO. SIRAS-L (for LEO) has a 0.5-km footprint. Therefore, we would expect a significant improvement in the percentage of cloud-free scenes from these instruments.

C. Science Measurement Requirements

SIRAS-G is being developed to address several high priority research areas identified in NASA's ESE Research Strategy for 2000-2010. 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:

AIRS Follow-On: The first potential future application we are considering is a follow-on instrument for the AIRS instrument that is currently flying on NASA's Aqua satellite. AIRS provides global measurements of water vapor and temperature from LEO at high resolution and accuracy. SIRAS was originally designed to meet all the requirements of AIRS but in a significantly smaller system.

Table 1.0: Preliminary Spectral Channel Set for AIRS Follow-On Instrument

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 about 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.

Originally, we envisioned this system would be used in a "pushbroom" scan mode. However, a recently developed "whiskbroom" architecture provides both the desired high spatial resolution and near-daily global coverage. The proposed instrument architecture is optimized to provide the primary AIRS science data products; atmospheric temperature profiles, water vapor profiles, and ozone column. The preliminary channel selection for this instrument concept is presented in Table 1.0.

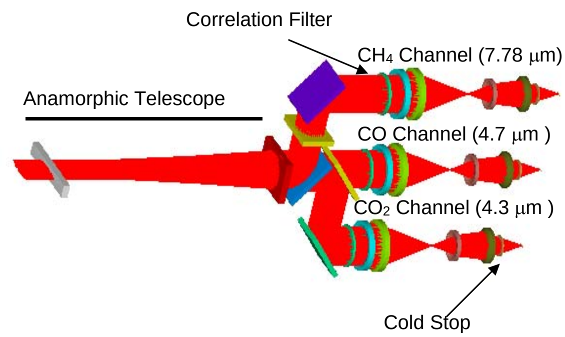

Fig. 1. The Imaging Multi-Order Fabry-Perot Spectrometer (IMOFPS) provides enhanced high-resolution spectroscopy well suited for trace gas measurement. A combined SIRAS-G/IMOFPS instrument suite could provide targeted measurements of key trace gases and atmospheric parameters in a compact package.

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 the IMOFPS [4] shown in Figure 1 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.

ASTER Follow-on: A third future application that could benefit from SIRAS technology is for land thermal imaging. Follow-on missions to the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) mission will require improved atmospheric correction that can be achieved with an optimized version of one of the four SIRAS-G spectrometers. Currently an enhanced spatial resolution instrument concept to perform ASTER type observations has being has been developed. This instrument concept carries a single SIRAS spectrometer to accompany a larger high-resolution multi-spectral thermal imager. The SIRAS atmospheric correction system has similar spatial resolution to the LEO sounder of approximately 0.6 km.

II. SIRAS-G TECHNOLOGY DEVELOPMENT

A. *Results from SIRAS-1999*

The NASA JPL-lead SIRAS team [1] developed an advanced instrument concept as a possible future replacement for AIRS. This instrument concept is referred to as SIRAS-L (for SIRAS-Low Earth Orbit). 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. However, 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 showed that key performance requirements could be achieved. Spectrometer-level testing was performed in a thermal vacuum chamber at cryogenic temperatures. Thermal sources were viewed included a collimator and source assembly for spatial performance tests, and a blackbody for radiometric performance testing. Spectral measurements were made by adjusting the air path length between the test thermal-vacuum chamber and the blackbody and measuring the CO_2 absorption features.

Fig. 2 shows the results of the 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. The results show that the SIRAS-1999 spectral resolution is 1200 ± 300. The entry point for SIRAS-1999 IIP was TRL-3. On completion, the spectrometer was at TRL-5.

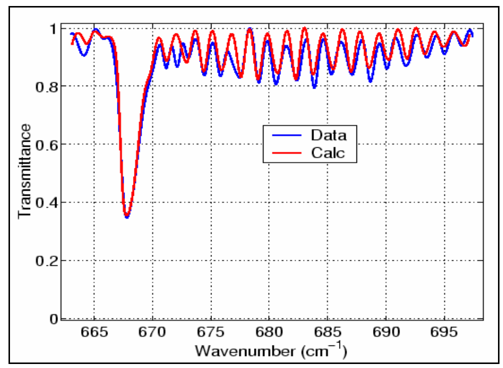

Fig. 2. SIRAS measurements of laboratory air confirmed that desired spectral resolving power (λ/Δλ) between 900 and 1400 was achieved.

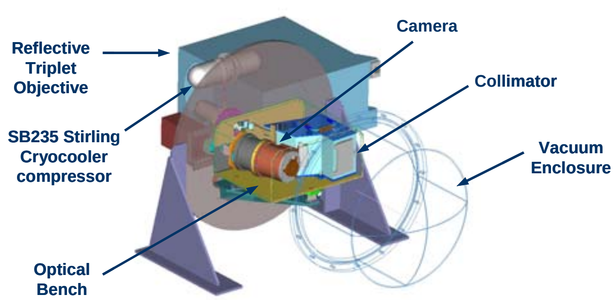

Figure 3. Solid model representation of the SIRAS-G Laboratory Demonstration Instrument showing major subsystems.

B. *SIRAS-G Laboratory Demonstration Instrument*

A major focus of the SIRAS-G program is on the development of the technology demonstration instrument. A solid model representation of this instrument is shown in Fig. 3. 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.

Fig. 3 shows the SIRAS-G demonstration instrument architecture and major subsystems. Our strategy has been to develop one complete channel of the instrument including the Reflective Triplet Objective (RTO), spectrometer subassembly, FPA, yielding digital data delivered from the FPA electronics. We have elected to build the demonstration instrument to operate in the 3.3 to 4.8µm spectral range with a nominal spectral resolution of 1.4 cm^{-1}.

What had previously been referred to as the Optically-Enhanced Cryogenic Dewar [1], but is now more accurately called the multi-stage warmshield assembly, will also be demonstrated as part of this system. The optical components making up this subsystem are machined directly into the lens cells.

The SIRAS-G spectrometer assembly is being developed at BATC in Boulder, Colorado. Rockwell Scientific Corporation (RSC) in Camarillo, California is providing the FPA, clock, bias and A/D conversion electronics under subcontract. The FPA and electronics will be integrated with the spectrometer at BATC. Active cooling of the aft optics to 140K and the FPA to 40K will be demonstrated as well. A two-stage BATC Model-232 Sterling Cycle cooler has been made available for this demonstration. The BS-235 cooler is optimal for SIRAS-G FPA and optics cooling, being mass and power efficient, and exhibiting high cooling capacity. The BS-235 cooler mass is 10.5 kg, comparing favorably to the 37 kg AIRS cooler.

While the design form of the SIRAS-G spectrometer is largely based on the SIRAS-1999 spectrometer, an important difference is that it is a true imaging spectrometer with an appreciable spatial FOV. Primary emphasis has been placed on minimizing key image defects, particularly spectral smile and keystone distortion, while maintaining excellent imaging performance. For this system, which employs true Nyquist sampling, these image defects are limited to less than 20% of a spectral/spatial resolution element over the entire FPA.

A design meeting these stringent performance requirements is a necessary condition but not sufficient. One must also be able demonstrate performance through test. As such, test methods are currently being developed at BATC to provide these measurements. Keystone distortion, spectral smile, MTF and spectral response function (SRF) will be measured on the SIRAS-G demonstration instrument. The spectrometer assembly will then be integrated with the RTO and the entire system tested for radiometric response in the laboratory. Finally, an atmospheric measurement will be made by viewing the sky via relay mirrors to the outside.

C. Current Hardware Status

As shown in Figure 3, 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 development is on track and hardware is due mid-summer, 2005. All single processing and control software and hardware will be delivered along with the actual 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 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 Figure 54.

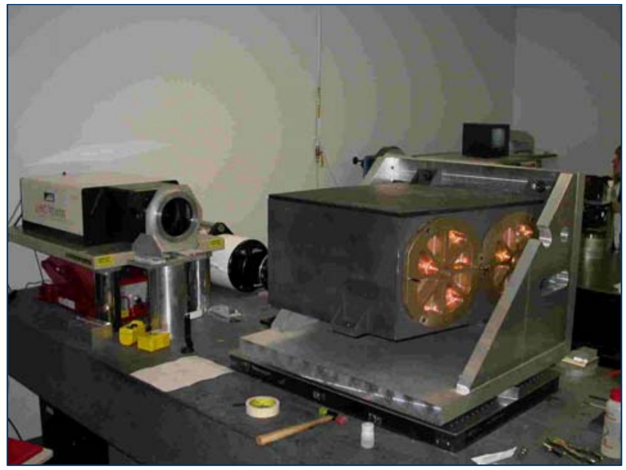

Fig. 4. The RTO undergoing final double-pass interferometric performance test. Testing was conducted at a wavelength of 632.8nm.

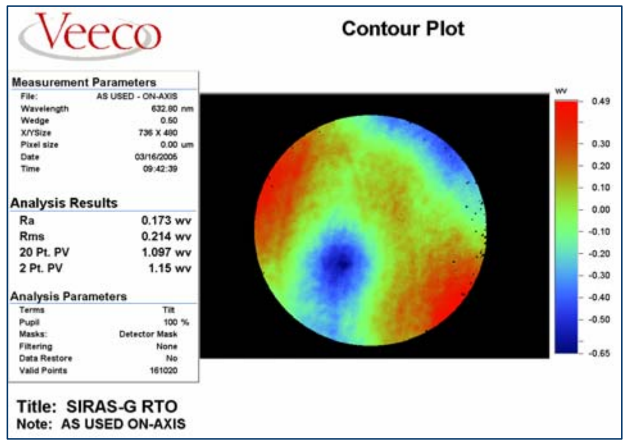

Fig. 5. Measured WFE (632.8nm) measures 0.20 to 0.30 waves RMS. This corresponds to 0.03 to 0.047 waves RMS at central operational wavelength of 4.0μm

D. Warmshield Development

With 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. Here, we have elected to take an alternative approach to this problem utilizing 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 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. Our goal is to demonstrate this system and validate it for application to a broad range of future applications.

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 spectroscopic instruments such as NAST-I or with spaceborne instruments such as AIRS. As such, we will strive to design and assemble the SIRAS-G instrument demo in a manner suitable for 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.

A. Pathway to Space

Technologies being developed 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 climate and weather forecasting. 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. The AIRS instrument has already demonstrated the feasibility of grating-based imaging dispersive spectrometers for atmospheric sounding, although being a pupil-imaging system [5]; it has somewhat different characteristics. Our goal is to provide an instrument of lower mass, volume, and ultimately, lower cost, with enhanced capabilities including improved spatial resolution and greater flexibility afforded by modular spectrometer assemblies that will find utilization in future earth remote sensing missions.

V. SUMMARY

NASA'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 represented by SIRAS-G and developed under IIP will provide shorter mission development cycle time and reduced overall cost, and ultimately, to more frequent science missions at lower overall cost. We feel that SIRAS-G exemplifies this goal, and represents an important advance in high-resolution IR atmospheric sounding much needed for earth observation. The SIRAS-G grating architecture is well suited to a wide variety of high priority missions, both from GEO and LEO, and potentially even from MEO. The further realization that the combination of SIRAS-G with other innovative instrument concepts such as IMOFPS offers paths to smaller, more capable instruments for future NASA Earth-Sun System and NOAA missions, needs to be appreciated as well. IIP provides 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 we are rapidly approaching.

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