SIRAS-G, The Spaceborne Infrared Atmospheric Sounder: The Potential for High-Resolution IR Imaging Spectrometry From Geosynchronous Orbit

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Abstract

The Spaceborne Atmospheric Infrared Sounder for Geosynchronous Earth Orbit (SIRAS-G) represents a new approach to infrared atmospheric sounding of the Earth from geosynchronous orbit. SIRAS-G, one of nine proposals selected for development under NASA's 2002 Instrument Incubator Program, is an instrument development effort for an instrument of less mass and power than heritage sounding instruments that offers enhanced capabilities for the measurement of atmospheric temperature, water vapor profiles, and trace gas column abundances. The SIRAS-G flight instrument concept is designed to measure infrared radiation in 2048 spectral channels with a nominal spectral resolution ($\Delta\lambda/\lambda$) of 1100. Combined with large area 2-D focal planes, this system simultaneously provides both high-resolution spectral and spatial imaging. In 1999, the SIRAS team built and tested the LWIR (12.0 – 15.4μm) SIRAS spectrometer under NASA's Instrument Incubator Program (IIP-1999). SIRAS-G builds on this experience with a goal of producing and demonstrating a laboratory prototype instrument. In this paper, we describe planned development activities and potential future scientific instrument applications for this instrument concept.

Introduction

The Spaceborne Infrared Atmospheric Sounder for Geosynchronous Earth Orbit (SIRAS-G) is an instrument concept designed to provide highly accurate atmospheric temperature and water vapor profile measurements from geosynchronous orbit (GEO) to facilitate weather forecasting, severe storm tracking, and scientific research. The flight instrument concept measures infrared radiation in 2048 channels extending from 3.7μm to 14.8μm with a spectral resolution ($\lambda/\Delta\lambda$) of 700 to 1100. As currently envisioned, large format 512 x 512 (spatial by spectral), focal plane arrays (FPAs) will provide the maximum information collection given the current state of technology. SIRAS-G employs a wide field-of-view (WFOV) hyperspectral infrared optical system that splits the incoming radiation into four separate grating spectrometer channels. This allows for slow scanning of the scene, increasing dwell time, and improved radiometric sensitivity. Unlike competing technologies, such as Fourier Transform Spectrometers (FTS), the SIRAS-G grating spectrometers employ no moving parts or metrology lasers, leading to improved reliability over mission lifetime. SIRAS-G follows the successful completion of the 1999 NASA-sponsored SIRAS (Spaceborne Infrared Atmospheric Sounder) Instrument Incubator Program (Kampe and Pagano, 2002) which focused on the development of a compact LWIR spectrometer module as a potential follow-on to the Atmospheric Infrared Sounder (AIRS) instrument (Aumann et al., 2001).

NASA Instrument Incubator Program

SIRAS-G, one of nine, but the only industry-led proposal, selected for the third IIP solicitation in 2002 and is being managed by Ball Aerospace & Technologies Corp. (Ball). The NASA Instrument Incubator Program was established as a mechanism for the development of innovative technology concepts suitable for future space-borne Earth Science Enterprise (ESE) programs and as a means to demonstrate and assess the performance of these instrument concepts in ground, airborne, and engineering model demonstrations. IIP is funded through NASA's Office of Earth Sciences Technology Office (ESTO). 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 Earth Science Enterprise Announcement of Opportunity; and finally, (4) the concepts shall enable new science and/or reduce instrument cost, size, mass and resource use. More information on the Instrument Incubator Program can be found at *http://esto.gsfc.nasa.gov/programs/iip/*.

SIRAS-G Overview

The SIRAS-G IIP effort will focus on advancing the SIRAS instrument concept for insertion into future Earth Science missions and on developing an engineering demonstration instrument. While the SIRAS-G hardware demonstration instrument is primarily intended as a laboratory demonstration, it will be built sufficiently robust to be upgradeable to an airborne instrument. As part of this program, a series of engineering studies will be conducted to demonstrate the applicability of SIRAS-G to a variety of critical earth remote sensing needs.

SIRAS-G builds on the success of the earlier SIRAS-1999 IIP effort. Here we successfully demonstrated a compact long wavelength infrared (12-15.4μm) grating spectrometer with a spectral resolution ($\lambda/\Delta\lambda$) of 900 to 1200. In SIRAS-G, we will improve on the SIRAS-1999 spectrometer by increasing the spatial FOV to provide true hyperspectral imaging capability. One of the key benefits offered by SIRAS-G is in its ability to improve the spatial resolution of future sounders while simultaneously providing high spectral resolution. This allows more opportunities for clear sky measurements in the absence of a microwave instrument; 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 current state of the art instrument flying, the Atmospheric Infrared Sounder, currently on NASA's Earth Observing System (EOS) Aqua satellite, Goldberg et al. (2003) found that only 4.5% of fields observed over oceans exhibited less than 0.6% cloud contamination. This is largely attributable to the relatively large footprint (13.5-km) of AIRS, which is flying in Low Earth Orbit (LEO). SIRAS-G, on the other-hand, is being designed for a 4-km footprint from GEO, and a LEO version of the same instrument concept would yield a 0.5-km footprint.

SIRAS-1999 Results

In 1999, the NASA JPL-lead SIRAS team undertook the development of an advanced instrument concept as a potential replacement for AIRS. This instrument concept is referred to as SIRAS-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). This effort focused on the development the SIRAS flight instrument concept suitable for LEO and the development of a hardware demonstration of the SIRAS LLWIR (12-15.4 μm) spectrometer (Spectrometer No. 4 in Table 1). A high-resolution infrared imaging spectrometer was 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 also performed. Finally, it was demonstrated that the same spectrometer could meet the requirements of a GEO sounder. A system concept was developed that included scanning, passive and active cooling systems, the infrared spectrometers, fore-optics and the focal plane arrays offering a system of comparable performance, yet with considerable size, mass, and power savings. Reductions in subsystem complexity through modular design, the use of standard format FPAs and low-order gratings results in significant cost reductions when compared to AIRS.

The flight instrument concept developed in SIRAS-1999 has four spectrometer modules that cover the 3.4 to 15.4 µm spectral region with the spectral bands broken out as shown in Table 1. A barrel scan mirror provides the ground coverage, and an all-reflective fore optic serves to focus the scene energy onto the slit. Scene energy was then split into four separate spectrometer modules via beamsplitters. The requirement for low background required that the spectrometer modules be cryogenically cooled to 140 K, and the focal planes to 60 K. Active cooling of the detectors was proposed for the flight instrument configuration using a split-Stirling pulse-tube cooler.

Table 1. Preliminary Design Parameters for SIRAS

Parameter		Spectrometer Number			
		1	2	3	4
λ_{min}	(µm)	3.7	6.2	8.8	12
λ_{max}	(µm)	4.61	8.22	12	15.4
$\lambda/\Delta\lambda$ Avg. Sampling		2200	2200	2200	2200
$\lambda/\Delta\lambda$ Avg. Resolution		1100	1100	1100	1100
Ruling	(µm)	8	14	10	13
Order	(-)	2	2	1	1
λ_{blaze}	(µm)	8.31	14.42	10.40	13.70
Incidence Angle	(deg)	45	45	45	45
Avg. Disp	(rad/µm)	0.2677	0.1534	0.1082	0.0832
Field of View	(deg)	13.957	17.752	19.844	16.201
Detector IFOV	(mr)	0.500	0.500	0.500	0.500
Slit IFOV	(mr)	1.000	1.000	1.000	1.000
EFL	(cm)	5.00	5.00	5.00	5.00
F-Number	(-)	1.70	1.70	1.70	1.70
Aperture Size	(cm)	2.94	2.94	2.94	2.94
Resolution	(mr)	0.1723	0.2991	0.4314	0.5683
Detector Size	(µm)	25	25	25	25
No. Channels	(-)	487	620	693	566
Transmission	(-)	0.5	0.5	0.5	0.5
FPA-Length	(cm)	1.22	1.55	1.73	1.41

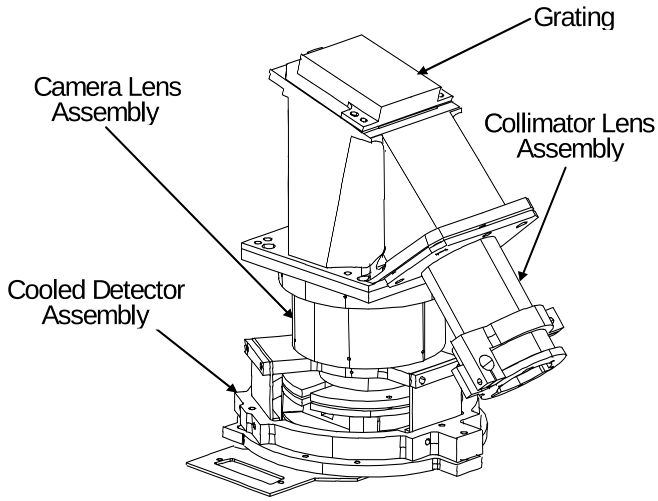
The laboratory spectrometer developed on this program is shown in Figure 1. The spectrometer measures 10 x 10 x 14 cm and weighs only 2.03 kg. For the purposes of laboratory measurements, a PV HgCdTe multiplexed detector array was provided on loan from the AIRS program. All hardware development and testing was performed at BALL. The most challenging optical system was the camera. This fast (F/1.7) optical system required near diffraction-limited performance over a wide field-of-view.

Key results from the SIRAS-1999 program included demonstration of the performance of the SIRAS spectrometer concept, including:

1. Demonstrated optical quality and spectral resolution consistent with the required resolving power ($\lambda/\Delta\lambda$) between 900 and 1400.
2. Demonstrated that the optical transfer function (spatial performance) required to perform as an accurate radiometer in the presence of high scene contrast (referred to as the Cij requirement on AIRS) was achieved.
3. Demonstrated that the high optical throughput required meeting the NEdT requirement could be achieved.
4. Demonstrated a spectrometer system of significantly reduced size, weight, and volume but of comparable performance to that of AIRS.

The entry point for SIRAS-1999 IIP was TRL 3. The TRL level of the SIRAS-1999 spectrometer on completion was 5.

Spectrometer-level testing was performed in a thermal vacuum chamber operating at cryogenic temperatures. Thermal sources were viewed through a zinc selenide window and included a collimator and source assembly for spatial performance tests, and a blackbody for radiometric performance testing. Spectral measurements



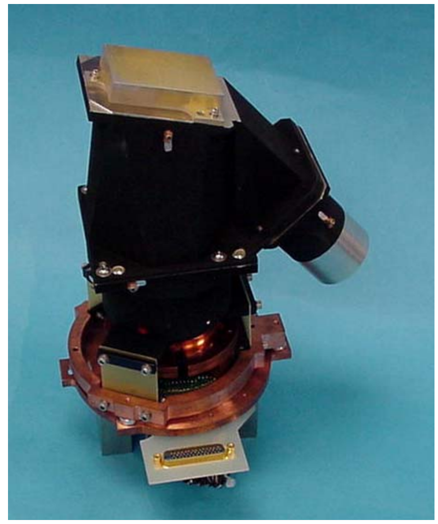


Figure 1. SIRAS-1999 IIP spectrometer design (left) and as-built configuration (right).

were made by adjusting the air path length between the test thermal/vacuum chamber and the blackbody, and then measuring the CO_2 absorption features.

Figure 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.

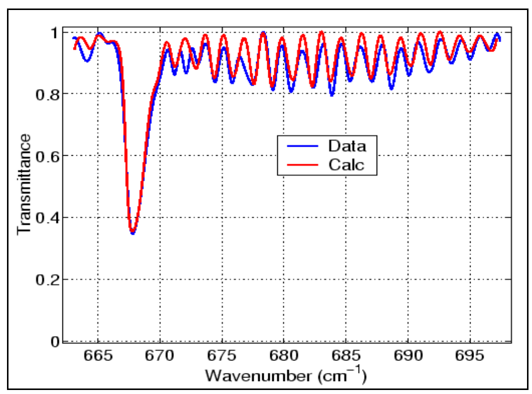


Figure 2. SIRAS-1999 measurements of laboratory air confirmed that spectral resolution was achieved.

SIRAS-G IIP Program Objectives

The SIRAS-G spaceborne instrument is being developed to address several high priority research topics identified in NASA's ESE Research Strategy for 2000-2010. The high spectral resolution and compact size of SIRAS-G make it broadly applicable to a wide range of future missions. Key ESE research topics that SIRAS-G is targeted toward include:

How are global precipitation, evaporation, and the cycling of water changing?

SIRAS-G will make measurements similar to those currently being made by AIRS but from GEO. It will provide measurements of atmospheric temperature and water vapor, cloud properties, and land and ocean skin temperatures, with the accuracy and spectral resolution required for numerical weather prediction models. The goal is for SIRAS-G to provide significantly more rapid revisit time (6 minutes regional) and higher spatial resolution (4-km compared to 13.5-km for AIRS). These are well suited to addressing weather forcing factors on shorter time scales. Without synergistic microwave instruments, SIRAS-G will require ancillary data from the National Center for Environmental Prediction (NCEP), the European Center for Medium Range Weather Prediction (ECMWF) or other surface analysis data to retrieve cloud properties. Such retrieval methods have been developed by the AIRS Science Team as contingency algorithms to be used in case of ASMU failure. SIRAS-G offers a pathway to providing a continuous long-term data set complementary to that currently being provided by AIRS.

What are the effects of regional pollution on the global atmosphere, and the effects of global chemical and climate changes on regional air quality?

The ability of SIRAS-G to provide simultaneous observations of the Earth's atmospheric temperature, ocean surface temperature, and land surface temperature, as well as humidity, clouds, and the distribution of atmospheric trace gases enables SIRAS-G to provide a single data set that can be used to understand the horizontal and temporal changes in column abundances of important minor atmospheric gases such as CO_2, CO, CH_4, and N_2O. This capability is potentially greatly enhanced by combining SIRAS-G with a high spectral resolution (0.05 – 0.1 cm^{-1}) instrument such as the Imaging Multi-Order Fabry-Perot Spectrometer (IMOFPS) described in Johnson, et al (2003).

What are the consequences of climate and sea level changes and increased human activities on coastal regions?

SIRAS-G provides high spectral resolution in the atmospheric window regions in the infrared, and will be able to observe the surface temperature in these regions with minimum atmospheric absorption. This can prove to be particularly useful in coastal regions where higher atmospheric water vapor amounts may be present. With the higher spatial resolution offered by SIRAS-G, there is a higher probability of finding cloud-free regions near the coastline than with larger footprints instruments such as AIRS or the NPOESS Cross-track Infrared Sounder (CrIS).

The flight system requirements established for SIRAS-G at the proposal stage were largely based on the requirements outlined for the NOAA GOES Hyperspectral Environmental Sounder (HES) at the time of the IIP proposal submission. These requirements have evolved over time and, in fact, are now compatible with grating spectrometer instrument architecture. The systems studies that are a part of the SIRAS-G effort will continue to explore the feasibility of SIRAS-G for technology insertion into the HES program. In addition, we continue to explore other mission opportunities for which the SIRAS-G technology is suitable.

Technology Demonstration Objectives

SIRAS-G will increase the capability of the SIRAS hardware to accommodate a wide field of view (WFOV) and demonstrate the high level of performance required in a system configuration. This will be achieved by building a demonstration instrument consisting of a WFOV reflective collimator, a spectral separation subassembly, and a single grating spectrometer module. The complete SIRAS-G demonstration instrument will also incorporate an active cooler, a 256 x 256 element FPA, a low heat-load dewar, and electronics. A non-flight, laboratory grade telescope of the proper aperture and F/# will be mated to the Spectrometer Assembly for system level performance measurements including a measurement of the night sky. An unobscured reflective telescope is our baseline for the flight instrument configuration, but due to cost considerations, an obscured on-axis Ritchey-Chretrien telescope will be used for the technology demonstration instrument. We aim to build and test a nearly complete SIRAS-G instrument, including as least one spectrometer channel, moving the Technical Readiness Level (TRL) of SIRAS-G to TRL-5 or 6.

There are several challenges that will be addressed on SIRAS-G before implementation of a flight system. These include the following:

- **Spatial & Spectral Errors in Spectral Response Function (SRF):** In an imaging spectrometer such as SIRAS-G, the slit is dispersed and imaged onto an area array of detectors. This is shown conceptually in Figure 3. The introduction of distortion (keystone and smile) and variation in point-spread function (PSF) width by the optical system can cause different spectral response profiles to be obtained at each pixel. This must be controlled by constraining the allowable distortion and balancing the requirements on image

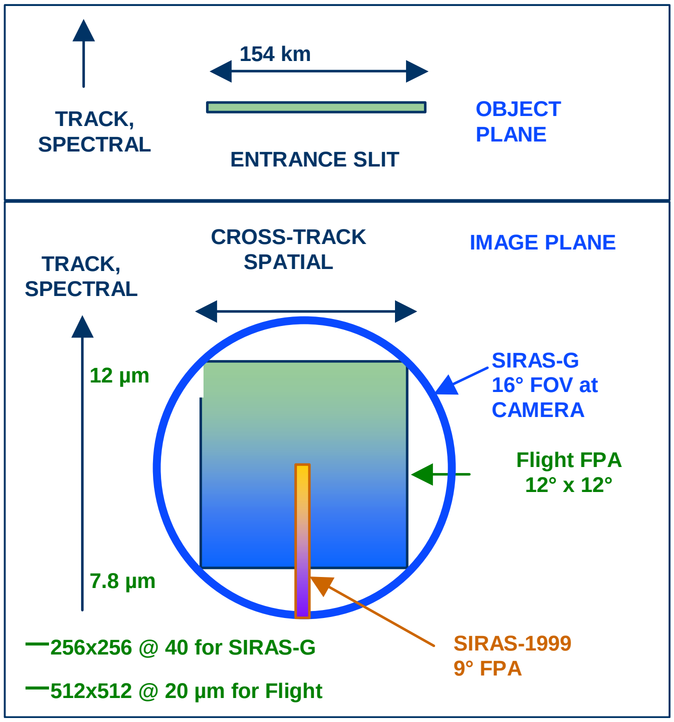


Figure 3. SIRAS-G, unlike SIRAS-1999, provides imaging over an appreciable cross-track FOV

quality, spatial and spectral distortion (Mouroulis et al. 2000). Similar control must be maintained during integration to ensure that the "as-built" instrument achieves the predicted level of performance.

- **Dewar Thermal Loads**: The increased number of cold shields (due to the use of 4 dewars and FPAs) increases parasitic cryocooler heat loads. Mitigation includes a full thermo-optical study of the loads at the dewars and the development of the dewar module for SIRAS-G. The tested and characterized dewar subsystem will be integrated into the SIRAS-G hardware demonstration instrument and tested.
- **Background thermal noise suppression**: The reduction of background flux at the detectors is key for a high performance IR system. Rigorous radiometric modeling is employed in the design process with careful attention to reducing background photon flux and controlling in-field stray light (Kampe and Waluschka 1994).
- **Co-registration of 4 Spectrometers**: Four physically separate spectrometer modules complicate the co-registration amongst channels. This concern is mitigated by using a common entrance slit and collimator and by employing temporal phase delay as done on the Moderate Resolution Imaging Spectroradiometer (Barnes et al. 1998) to allow on-orbit adjustment of residual alignment errors in the aft optics.

SIRAS-G Hardware Demonstration

A Major aspect of the SIRAS-G IIP effort will be the design, fabrication and testing of a hardware demonstration instrument. The key components of the SIRAS-G hardware demonstrator include the optical assembly (full aperture telescope, WFOV reflective collimator, spectral separation subassembly, and a single WFOV grating spectrometer module), the scan mirror assembly, an active cooler, an IR FPA, a low heat-load dewar, and associated electronics. The optical design, tolerancing and analysis for this system will be undertaken at Ball, as will all mechanical, cryogenic, focal plane and electronics engineering. .

A two-stage Ball Model BS-232 Sterling Cycle cooler, the specifications for which are listed in Figure 4, will be used on this program. A 256x256 format engineering-grade FPA with 40 µm pixel pitch will be utilized for the laboratory demonstrator. The selected device provides sufficient well depth and readout rate to support the SIRAS-G instrument requirements. A set of electronics will be supplied which provide all necessary clocks, biases and signals necessary for the operation of the FPA. The electronics will provide analog to digital conversion (14bit) for each output channel of the FPA. The electronics are programmable from a host computer. It is anticipated that a custom format FPA will be required to provide the ideal spectral sampling in the flight implementation.

SB235 Cryocooler Parameters

- **3rd Generation Multi-stage 35 K Cooler**
- **Performance: 0.5 W @ 40 K & 3.5 W @ 100 K for 90 W motor**
- **99% reliability at 10 years**
- **10.5 kg mass**
- **Verified non-contacting operation over wide temperature range (-60 to +80 ^{0}C)**
- **Active vibration isolation to below 0.10 N**
- **Fixed-regeneration cold finger capable of withstanding high side loads**
- **Inherently insensitive to 1-g orientation**
- **Proven and verified EM control features**
- **Flight-qualified 2-stage SB235**

Figure 4. Ball Aerospace & Technologies Model SB235 Cryocooler

System Configuration Studies

One of the primary objectives of the IIP is to determine the potential benefits of the technology to future ESE programs. SIRAS-G is widely applicable to a number of Earth Science Enterprise needs. As such, we have identified several key ESTO measurement parameters for which SIRAS-G is well suited. These include:

- Atmospheric temperature and water vapor profiles from GEO
- Total ozone column and precursors, cloud structure and winds, and trace gas sources from GEO
- Sea surface temperature from LEO (in addition to temperature, water vapor profiles, and cloud properties)
- Storm cell properties from an airborne platform (UAV)

In the following paragraphs, we identify several candidate future missions would benefit from the technology developed under this IIP. In many instances, SIRAS is in direct competition with interferometer-based Fourier Transform Spectrometers (FTS). Although FTS instruments exhibit very high spectral resolution over a broad spectral range, they tend to be large expensive instruments with very demanding optomechanical requirements on precision and stability, and the grating technology used by SIRAS offers an approach with potentially greater flexibility, wider field of view and smaller, lower cost sensors.

Hyperspectral Environmental Sounder. The grating technology used on SIRAS-G is well suited to the Hyperspectral Environmental Sounder (HES), the next-generation geosynchronous operational IR atmospheric sounder. With the spectrometer 1-milliradian IFOV for SIRAS-G, we currently estimate a ground footprint of ≤ 5 km would be achieved from GEO with an 8” aperture. Unlike competing technologies, SIRAS grating spectrometers have no moving parts, requires no transforms to obtain spectra, and use proven AIRS data processing algorithms.

AIRS Follow-on (SIRAS-L). Initially, SIRAS was considered as the follow-on for AIRS. The concept developed, shown schematically in Figure 5, offers the high spatial resolution of MODIS and the high spectral resolution of AIRS. SIRAS-L offers a ground footprint of less than 0.6 km (as compared to AIRS at 13.5 km) and is used in “pushbroom” mode to maximize integration time. Further studies will be undertaken in this IIP to explore the utilization of this instrument concept atmospheric sounding from LEO.

Geostationary Atmospheric Chemistry Mission. Key measurement objectives for a GEO Tropospheric Chemistry Mission include observations of ozone, aerosols, and important atmospheric trace gases

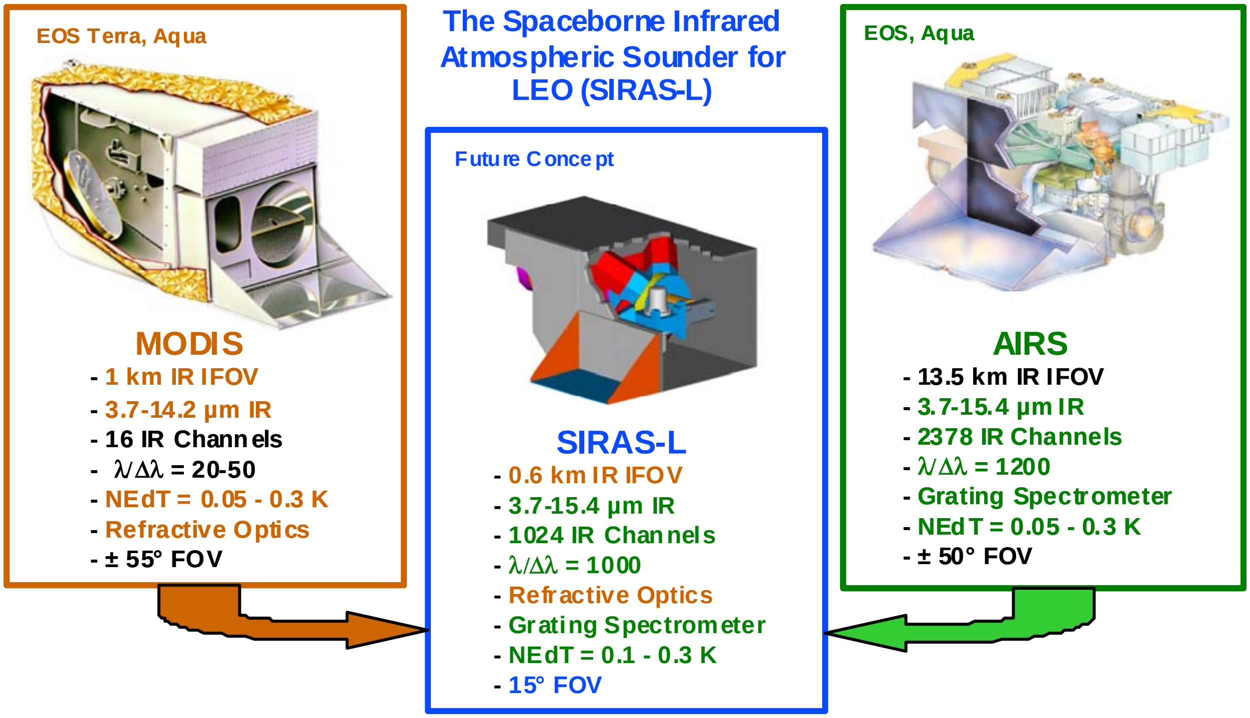


Figure 5. SIRAS-L can also meet the majority of requirements of AIRS and MODIS infrared channels with a significant size, mass and power reduction compared to either instrument

such as CO, CH_4 and NO_x. The combination of a SIRAS-G derivative and a multi-channel high-resolution spectrometer, such as the IMOFPS, can provide these measurements in a compact, solid-state instrument suite. The IMOFPS instrument concept, shown in Figure 6, consists of three co-boresighted correlation spectrometers for measuring vertical profiles of CO and column amounts of CO_2 and CH_4. The addition of a fourth spectrometer channel for measuring NO_x would provide a tracer of motion and cloud detection. A two-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, with spectral resolution "tuned" appropriately in both channels, would provide temperature and water vapor sounding and ozone column.

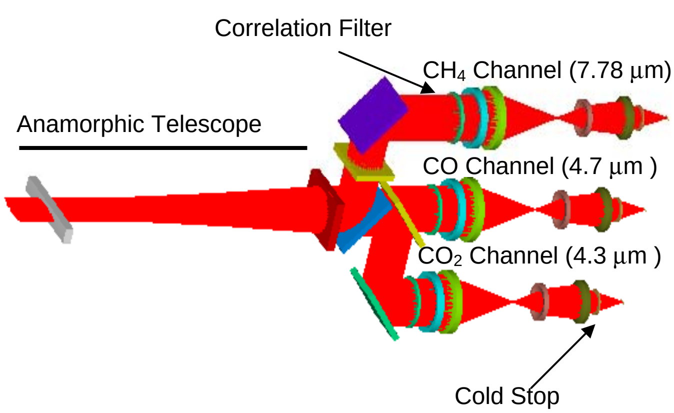


Figure 6. 3-Channel IMOFPS Sensor Concept

Summary And Conclusions

NASA's support of independent technology development for future Earth science needs is a positive step forward. It offers promising benefits in terms of early identification of appropriate technologies and retiring technical risks. This will lead to mission development cycle time from inception to completion and reduce overall cost, and ultimately, lead to more frequent science missions at lower overall cost. SIRAS-G exemplifies this approach and represents an advance in high-resolution IR atmospheric sounding from geosynchronous orbit. The grating instrument architecture on which SIRAS-G is based is well suited to a wide variety of high priority NASA ESE missions, both from GEO and LEO platforms, and is an instrument architecture suitable for next-generation missions aimed at providing continued atmospheric data for long-term climate change research. The combination of SIRAS-G with other innovative instrument concepts such as IMOFPS offers the path to smaller, more capable instruments well suited to future NASA earth science missions. The Instrument Incubator Program, funded out of NASA, 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 hardware demonstration instrument.

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