Mineral and Gas Identification Using a High-Performance Thermal Infrared Imaging Spectrometer

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***Abstract*—A novel multi-channel, thermal-band airborne imager to address HyspIRI-type measurement applications such as rock and soil identification, and volcano characterization and monitoring, is currently in the final year of development. The high-performance instrument, MAGI (Mineral And Gas Identifier), will use 32 bands covering the 7 to 12.7 micron region to both exceed the capabilities of existing thermal IR imagers and to enable additional missions, such as detection of gases from natural and anthropogenic sources. The higher spectral resolution, compared to existing thermal-infrared sensors, will improve discrimination of rock types, greatly expand the gas-detection capability, and result in more accurate land-surface temperature retrieval (important in evapotranspiration and drought studies). Data from The Aerospace Corporation's SEBASS sensor have been used to examine the trade-offs between spectral resolution, spectral range, area-coverage rate and instrument sensitivity. To maximize swath width, MAGI will use a whiskbroom scanner. The optical design for MAGI will incorporate a novel compact Dyson spectrometer mated to a high-frame-rate 2-D HgCdTe focal plane array. The Dyson spectrometer can operate at low f-numbers while still maintaining very small optical distortions. The optics and detector will be cooled by separate Stirling cryocoolers. Assembly and lab testing of the MAGI sensor will occur in the early summer timeframe with flight testing on a Twin Otter platform scheduled for August 2011. Comparison of data from these flights with data from ASTER and The Aerospace Corporation's Mako sensor will demonstrate the utility of this moderate spectral resolution sensor. Our program objectives include formulation of a concept for a space-based version of MAGI that would have a smaller pixel size and smaller NEDT than current sensors, thereby enabling smaller thermal changes to be tracked and more compact gas-emission sources to be monitored. It would include a field-splitting mirror and two-module design, thereby doubling the along-track field-of-view, and hence swath width, while halving the sensor revisit time.**

I. Introduction

A new thermal-infrared (TIR) imaging spectrometer MAGI ("Mineral and Gas Identifier") is in its final construction and test phases. MAGI is an airborne sensor that will demonstrate key technologies for a proposed satellite sensor MAGI-L (MAGI in Low Earth Orbit), that will in turn address space-based Earth observing needs specified in the National Research Council's Decadal Survey [1]. MAGI-L is a TIR sensor that is specifically targeted as an option for a potential HyspIRI follow-on mission, in the mold of the ASTER sensor (small pixel size) [2]. MAGI-L will have a 60-meter ground sampling distance (GSD), a 120-km swath width and a 0.1°C Noise Equivalent Delta Temperature (NEDT). In contrast, the ASTER TIR sensor has a 90-meter GSD, a 60-km swath width, and a 0.2°C NEDT. The MAGI-L sensor will expand the current ASTER thermal-infrared legacy in important ways, and have particular impact in the following six areas: volcano monitoring, natural resources mapping, surface-temperature determination, drought monitoring, air pollution studies, and acute pollution-event monitoring.

For volcano monitoring, MAGI-L's smaller GSD and increased temperature sensitivity will allow smaller thermal anomalies to be tracked, and smaller gaseous venting episodes to be detected. In addition, its larger swath width will enable shorter revisit times. The ability to determine surface composition will be greatly improved by the additional spectral channels of MAGI-L over ASTER. The new channels will also enable in-scene atmospheric compensation, leading to greater accuracy in surface temperature estimation, which is important for studies of heat flux for evapotranspiration, urban heat island monitoring, and for mapping regions affected by drought. MAGI-L will also enable detection of point sources of gases important in pollution studies (e.g., ammonia, SO_2), ozone depletion (e.g., methyl chloride), and climate change (e.g., CO_2, SF_6).

II. Trade Studies

We used data from our SEBASS sensor [3] to conduct trade studies for various sensor parameters: number of spectral bands, wavelength cut-offs, and sensitivity. The trade studies were conducted for mineral mapping applications, gas detection, atmospheric compensation effectiveness and cirrus cloud detection. Details of these studies can be found in [4].

Table 1 summarizes the results of these studies, which specify that the sensor should have 28 bands covering the wavelength region 7.0 to 12.0 microns. Fig. 1 shows how the MAGI-L wavelengths compare to those of sensors already in orbit or planned. For the airborne MAGI sensor, we maintain the spectral sampling bandwidth of MAGI-L while increasing the long wavelength cut-off to 12.7 microns, resulting in 32 spectral channels.

III. INSTRUMENT DESIGN

The key components of the MAGI-L sensor are: a compact grating-based spectrometer built according to a modified Dyson prescription; a high frame rate focal plane array (FPA); a field-splitting mirror assembly to double the swath width; and Stirling cryocoolers to cool the FPA and spectrometer optics. MAGI will not use a field-splitting mirror.

System considerations, in particular the desire to maximize the number of cross-track pixels, favor HgCdTe for the MAGI detector. We have chosen a Rockwell 128x128 HgCdTe array with 40μm square pixels that has deep wells (10 Me$^-$), high quantum efficiency (>80%), and very high readout rate (up to 15 kHz). The ideal detector would have up to 512 pixels in the spatial direction, to maximize spatial coverage, and fewer in the spectral direction. In the current array, eight output taps deliver the necessary 32 contiguous spectral elements. Because under-performing pixels are a known issue with HgCdTe arrays, flexibility to select the best-performing 32-row contiguous sector of the array at the time of assembly is a significant benefit. For MAGI-L, the 40-μm pixel size combines with the 60-m GSD and 710-km nadir range to set the system effective focal length at 473mm. An aperture of 240 mm (similar to ASTER TIR instrument) collects adequate signal, while fixing the final focal ratio at f/2.

Fig. 2 shows a schematic for a generic thermal infrared sensor that we have refined in the course of building five aircraft instruments since SEBASS. The section cooled to cryogenic temperatures comprises imaging optics, slit, dispersive spectrometer, and focal plane array. A blocking filter and real cold stop near the cryostat window facilitate thermal management and control out-of-field background radiance. The cryogenic section can be operated independently for laboratory check-out, and is common to both MAGI and MAGI-L. An afocal external telescope reduces the IFOV of the cryogenic optics and also relays the cold pupil to a real, accessible location to minimize the size of the pointing mirror and black body calibrators. The afocal interface between the external telescope and the cryogenic optics reduces the sensitivity of the system to axial (defocus) and lateral misalignment across the warm/cold interface.

TABLE I. RESULTS OF TRADE STUDIES

Study	Short λ Cut-off	Long λ Cut-off	Bandwidth (μm)	NEDT (°C)
Gas Detection	7.2	12.0[a]	0.19	0.1
Mineral Detection	7.8	12.0[a]	0.19	–
Atmos. Comp.	7.5	12.0[a]	0.25	–
Cirrus Detection	7.0	–	–	–
Summary	**7.0**	**12.0**	**0.19**	**0.1**

a Minimize detector noise; maximize operability

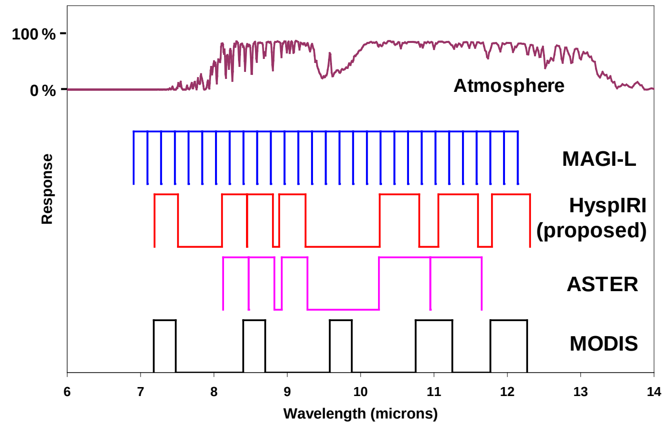

Figure 1. Comparison of MAGI-L spectral channels with those of other satellite sensors (on-orbit and proposed), and the transmission of the atmosphere. MAGI will add four additional channels on the long wavelength end.

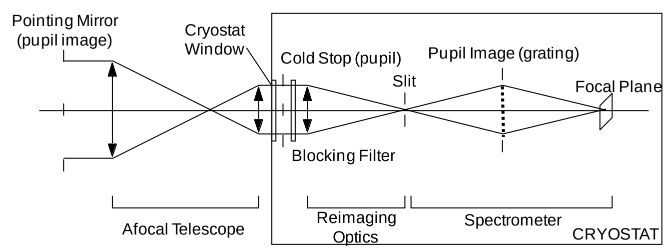

Figure 2. Generic thermal infrared sensor schematic. The cryostat optics are common to both airborne and spaceborne instruments.

The heart of the MAGI-L instrument is a Dyson spectrometer designed to meet the instrument requirements. The Dyson design permits a compact spectrometer with low distortion (<4% of the pixel pitch) and excellent image quality, even at low f-number. We modified the original Dyson concept by adding a patented aspherical "corrector" lens. This modification results in a more practical design as it allows the object and image planes to be moved away from the surface of the ZnSe Dyson lens. Optically faster designs translate into smaller spectrometers, alleviating optical bench cooling power requirements, and shorter pixel integration times, permitting larger areal scan coverage using a whiskbroom scanner. The grating is machined onto a spherical concave surface. The spectrometer requires a relatively coarse ruling for this grating, ~3 grooves/mm, rendering it suitable for manufacture by diamond-turning. The predicted peak grating efficiency is 97% at 9 microns, falling to a minimum of 72% at both the 7-micron and 12.7-micron extrema. The complete spectrometer system, excluding focal plane array, was built by Corning Specialty Materials to our design specifications and is shown in Fig. 3. The whole assembly weighs 0.45 kg. Reference [5] describes

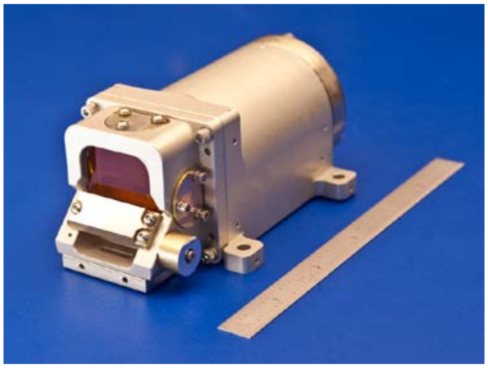

Figure 3. MAGI/MAGI-L Dyson spectrometer.

our Dyson design in more detail.

The Dyson spectrometer modules are compact, and two can readily be accommodated in the MAGI-L design to double spatial coverage (and provide redundancy). Fig. 4 shows how offset and staggered modules follow field splitting mirrors. Note that the individual fields need to be separated perpendicular to the slits to permit field splitting without vignetting.

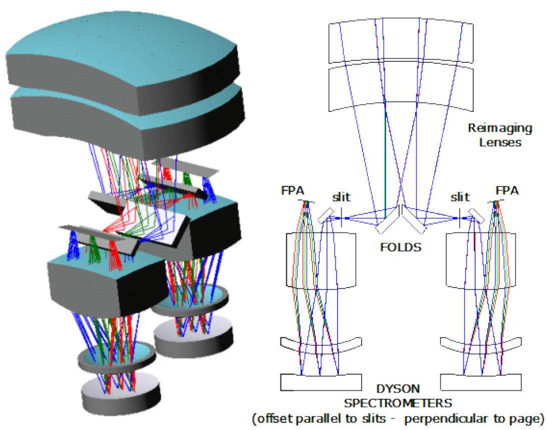

Figure 4. Dual spectrometer concept using field-splitting mirrors.

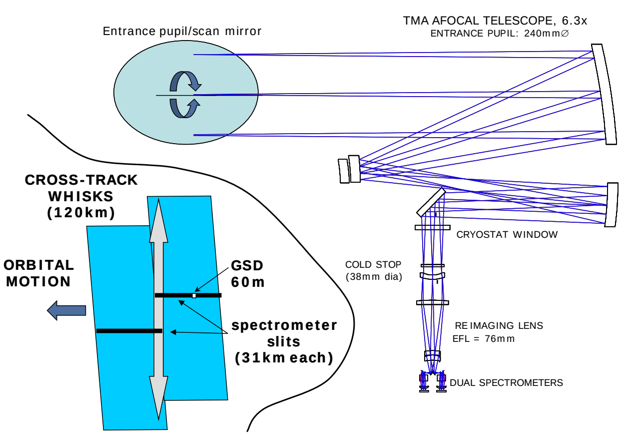

Figure 5. End-to-end optical model of MAGI-L. The components downstream of the cryostat window are common to both MAGI and MAGI-L. The inset shows the resulting footprint on the ground.

Fig. 5 shows an end-to-end optical model of a MAGI-L sensor concept including dual spectrometer modules and a 6.3x afocal external telescope. The end-to-end imaging performance is excellent, with geometric images remaining small compared to the pixel and diffraction point spread function at all fields and wavelengths. Fig. 6 shows a model of the internal components of the cryostat, and Fig. 7 shows how the final MAGI sensor will look.

IV. CURRENT STATUS

This project will culminate in a set of airborne flights to demonstrate the new sensor's capabilities and will leverage techniques and technologies demonstrated during the successful completion of The Aerospace Corporation's Mako TIR sensor [6]. The two instruments share a number of ancillary hardware and software system elements (e.g., stabilization mount, gimbal electronics, inertial navigation sensors, and calibration sources). The Mako sensor concluded a successful inaugural flight series in September 2010, paving the way for this year's MAGI aircraft integration. Mako is currently being provided with an improved pre-amplifier that is designed to be compatible with both MAGI and Mako sensors. This new configuration will be tested on the Mako sensor in July before its implementation on MAGI.

Unlike the Mako sensor, MAGI uses mechanical cryocoolers for its cooling needs. Analysis of the thermal loads suggested the need for two separate cryocoolers, one to cool the detector to its nominal 50K operating temperature, and the other to cool the spectrometer optics to around 100K. The computed heat lift requirement for the detector cooling was the most stressing, for which a Sunpower model GT Stirling cooler will be used. Also of concern was the cooldown rate of the focal plane array. In order to control this rate to minimize thermal stress we have added heaters slightly upstream of the

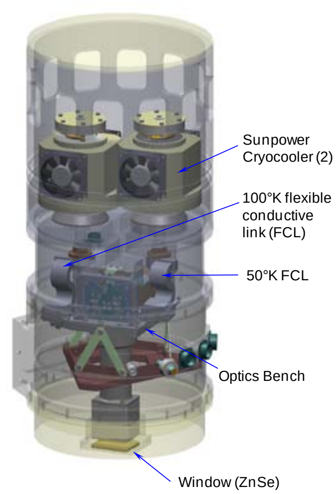

Figure 6. Model of the MAGI cryostat and two cryocoolers. This assembly will be mounted to a commercial 3-axis-stabilized platform.

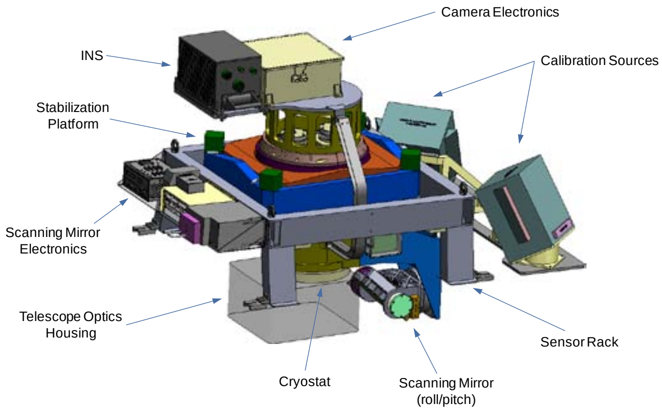

Figure 7. Model of the MAGI airborne sensor showing the major components. The Dyson spectrometer is inside the cryostat.

focal plane array. These may also provide a superior method for fine control of the FPA temperature during sensor operation. Flexible conductive links manufactured by the Space Dynamics Laboratory will provide the requisite thermal conductance between the cryocoolers and spectrometer while minimizing transmission of cryocooler vibrations.

The sensor is due to be assembled and lab tested during the months of June and July, 2011. Testing will include a measurement of the sensor NEDT, and assessment of its smile and keystone distortion as a function of field angle. It is currently scheduled to be flown in a Twin Otter aircraft in August 2011. Besides engineering flights to test out the system and measure parameters such as NEDT and spatial resolution, the flights will include acquisition of science targets that have already been flown by our Mako sensor and by ASTER so that the impact of spectral resolution can be assessed.

ACKNOWLEDGMENT

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