MightySat II.1 hyperspectral imager: summary of on-orbit performance

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ABSTRACT

The primary payload on a small-satellite, the Air Force Research Laboratory's MightySat II.1, is a spatially modulated Fourier Transform Hyperspectral Imager (FTHSI) designed for terrain classification. The heart of this instrument is a solid block Sagnac interferometer with 85cm^{-1} spectral resolution over the 475nm to 1050nm wavelength range and 30m spatial resolution. Coupled with this hyperspectral imager is a Quad-C40 card, used for on-orbit processing. The satellite was launched on 19 July 2000 into a 575km, 97.8 degree inclination, sun-synchronous orbit. The hyperspectral imager collected its first data set on 1 August 2000. To the best of our knowledge, the MightySat II.1 sensor is the first true hyperspectral earth-viewing imager to be successfully operated in space. The paper will describe the satellite and instrument, pre-launch calibration results, on-orbit performance, and the calibration process used to characterize the sensor. We will also present data on the projected lifetime of the sensor along with samples of the types of data being collected.

1. BACKGROUND: WHY HYPERSPECTRAL IN SPACE

Imagery from space has been limited to black and white high resolution and multispectral imagery. Black and white imagery cannot differentiate between types of vegetation or road materials. Multispectral imagery can differentiate these objects, but at a limited number of bands. To enhance the multispectral capability additional spectral bands need to be imaged. Hyperspectral imagery expands the number of spectral bands that are collected.

Previously, hyperspectral imagers have been mounted in light aircraft. These imagers are limited by flying conditions and airspace boundaries (i.e. national borders and restricted flight areas). When the imager is space-based, however, the airspace

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14. ABSTRACT
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boundary issues are eliminated. Space-based imagers can be affected by earth weather conditions and the satellite's orbit, however, these effects can be minimized with knowledge of the orbit and weather reports.

The benefits of spaceborne hyperspectral imagery are numerous. The creation of spectral signature libraries can provide a wealth of more specific global terrain data for agriculture, meteorology, rain forest management, geology, and urban population studies. Seasonal weather conditions, biomass and insect infestation, mineral data, housing density, as well as object recognition are useful to both the military and civilian scientific communities.

2. MIGHTYSAT II.1: BIG BANG, SMALL BUCKS

The MightySat mission is to provide a tailorable, affordable method to rapidly demonstrate the Air Force Research Lab's high payoff, enabling space technologies.[1] The total cost of the MightySat II.1 satellite program was $38 million. The Fourier Transform Hyperspectral Imager construction, testing, and integration accounts for $6 million of the total cost. The adaptability of the satellite is seen in the amount and variety of experiments. Ten experiments are on board MightySat II.1, consisting of Experimental Bus Components and Stand-Alone Experiments. There are five Experimental Bus Components from solar array structures to the transponder. All of these components were unproven hardware. Two of the five Stand-Alone Experiments are used in the collection of the hyperspectral image. The Fourier Transform Hyperspectral Imager (FTHSI) is the primary payload, and the Quad-C40 (QC40) is utilized for on-board processing.

MightySat II.1 bus was designed by Spectrum Astro Incorporated to be universal and adaptable to fit various payloads. The 266-pound satellite was launched at 2:09 PM MDT on 19 July 2000 from Vandenberg AFB, California.[2] The launch vehicle was the Minotaur 2, the DoD-developed Orbital/Suborbital Program's second launch vehicle. MightySat II.1 was inserted into a sun-synchronous orbit at 575km and 97.8 degree inclination.

3. PAYLOAD DESIGN

Two components form the FTHSI payload. The hyperspectral instrument (HSI) is the imager, and the hyperspectral instrument interface card (HII) allows the user to control the amount and parameters of the data collected. More discussion of the HSI and HII card will follow in later sections. In addition to the payload, FTHSI uses two other Versa Module Europa (VME) boards to complete the electrical system of the instrument: the solid-state memory card and the processor board.

Spectrum Astro, Inc built the solid-state memory (SSM) card. The SSM contains 256 MB of RAM dedicated to FTHSI for data storage.[1] Data is written to the SSM and read out using normal VME protocols. This storage area is used for raw FTHSI data. The SSM was expected to lose 4 MB of memory per month due to the space environment. To date there is no evidence that any memory has been irreversibly corrupted.

The processor board is the QC40 and is composed of four TMS320C40 DSP chips.[1] The QC40 was originally designed as an experiment to demonstrate the operation of the radiation hardened C40 chips and "smart-sensor" capabilities. The board is configured as a two-slot, two board package and utilizes four tantalum shielded C40 processors.[1] The first board contains the C40 and associated memory, while the second card is the auxiliary interface card (QIB). The QIB allows camera imagery to be routed directly from the camera to the processors. Each tile of the focal plane is hard wired to one processor, there are four tiles and four processors. FTHSI planned to use the QC40 to do post-collection image processing and some real-time imagery collection and processing.

4. IMAGER CHARACTERISTICS

FTHSI is a spatially modulated Fourier transform based instrument that encodes wavelength through an interferometer. The sensor is operated in a pushbroom mode, which provides individual 1D frames consisting of 1 by 1024 spatial element strips. When transformed these frames are collated into a contiguous swath with spatial dimensions up to n lines by 1024 samples. Once reassembled the pushbroom image consisting of x and y dimensions (comprising the spatial image) also possesses a third dimension, z, that contains the spectral data information; approximately 142 discrete spectral bands from 475 nm to 1050 nm.

The interferograms are produced by a monolithic Sagnac interferometer.[3,4] The scene is observed through a set of foreoptics that images the scene onto a field stop. The one-dimensional image is then passed through the interferometer where the rays are split, slightly sheared, and recombined to create an interference pattern in one dimension. From the interferometer, a Fourier lens collimates the light and a cylindrical lens images the energy onto the detector, preserving the one by n spatial dimension and the interference pattern. A cut-off filter and CCD sensitivity prevent interference from wavelengths outside of the spectral range of interest.[3]

The purpose of the hyperspectral instrument is to demonstrate the utility of a Fourier transform imaging spectrometer operating in a space environment. The design was optimized for measuring vegetation in the visible to near infrared (600 to 900 nm) for terrain categorization purposes. Table 1 shows the design and actual payload characteristics.

Table 1: FTHSI design and actual on-orbit characteristics.

Payload Characteristics	Design	Actual
Spectral Range	500-1050 nm	475-1050 nm
Spectral Resolution/Accuracy	97 cm^{-1}/0.5 cm^{-1}	84.4 cm^{-1}/0.1 cm^{-1}
Number of Useful Bands	146	146
Field of View (FOV)	3 degrees	3 degrees
IFOV	0.0058 degrees or 0.0029 degrees	0.0058 degrees or 0.0029 degrees
Swath Width at 500 km Altitude	6.5 km to 26 km	7.5 km to 30 km
Swath Length	10 km to 20.25 km (nominal)	10 km to 15.3 km (nominal)
GSD	30 m	30 m
Pointing (Control/Knowledge)	0.15 degrees/ 0.15 degrees	0.15 degrees/ 0.15 degrees
Spatial Coverage Technique	Pushbroom	Pushbroom
Payload Weight	33 kg	20.45 kg
Power Requirement (Peak/Steady)	66 watts/ 60 watts	55 watts/ 47 watts
Payload Volume	17,045 cubic cm	17,043 cubic cm
RMS Radiometric Calibration Accuracy	20%	10-15%
Life Span	90 days	>2 years

5. IMAGER DESIGN

The optical system is composed of a telescope and a re-imaging system[4] (Figure 1). The telescope is a 165mm clear aperture Ritchey-Cretien design.[3] The system has an F/# of 3.4 in the spatial dimension and an F/# of 5.3 in the spectral dimension.[2] Alignment of the lenses and interferometer in the system is maintained by using a solid-block interferometer. This design uses no moving parts and helps to avoid alignment shifts during launch. The interferometer is composed of two glass elements that are both one half of the beamsplitter and mirror. These glass pieces are bonded together and then mounted into an aluminum housing. The pieces and housing are bolted together and then bolted to an aluminum base, resulting in the ability to hold very tight tolerances.

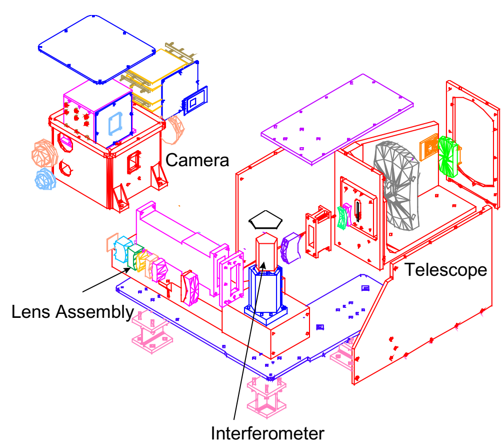

Figure 1: Exploded view of the Fourier Transform Hyperspectral Instrument on-board MightySat II.1.

In order to avoid vacuum qualifying the camera, the camera is housed inside of a sealed compartment and the optical system is vented locally to vacuum conditions. The final lens in the system seals the camera compartment. A commercial Silicon Mountain Design (Kodak) 1M60-20 camera based on a 1024 x 1024 frame-transfer detector built by Thomson (7887A) was modified by Kestrel for this application.[3] The imager is composed of four tiles (A to D) each with 256 x 1024 pixels. Each tile has its own amplifier and RS422 digital output driver, but share clock drivers and power supply electronics and was not hardened for space applications. Using this configuration, the data stream is a 48-bit word at 10 or 20 MHz depending on the binning mode. Data rates from 7.5 frames per second to 110 frames per second, various binning combinations, camera gains, 8 or 12 bit depths, and tile combinations can be used depending on the imaging requirements. This allows for the spectral and spatial resolution and camera performance to be varied electronically. To protect the camera from radiation effects in space, the housing walls were made 0.95 cm thick.[3]

6. LIFETIME STATISTICS

The optical system was designed to meet the system requirements in Table 1, in thermal conditions of –20 to +20 degrees C, with the temperature band being determined by changes in the index of refraction of the various refractive materials.[5] This temperature range is maintained through a cold biased design that uses thermal isolation, blankets, and heaters. Thermal vacuum testing and on-orbit results have verified the ability to maintain the temperature range. Figure 2 shows the value of three FTHSI temperature sensors during the collects since launch.

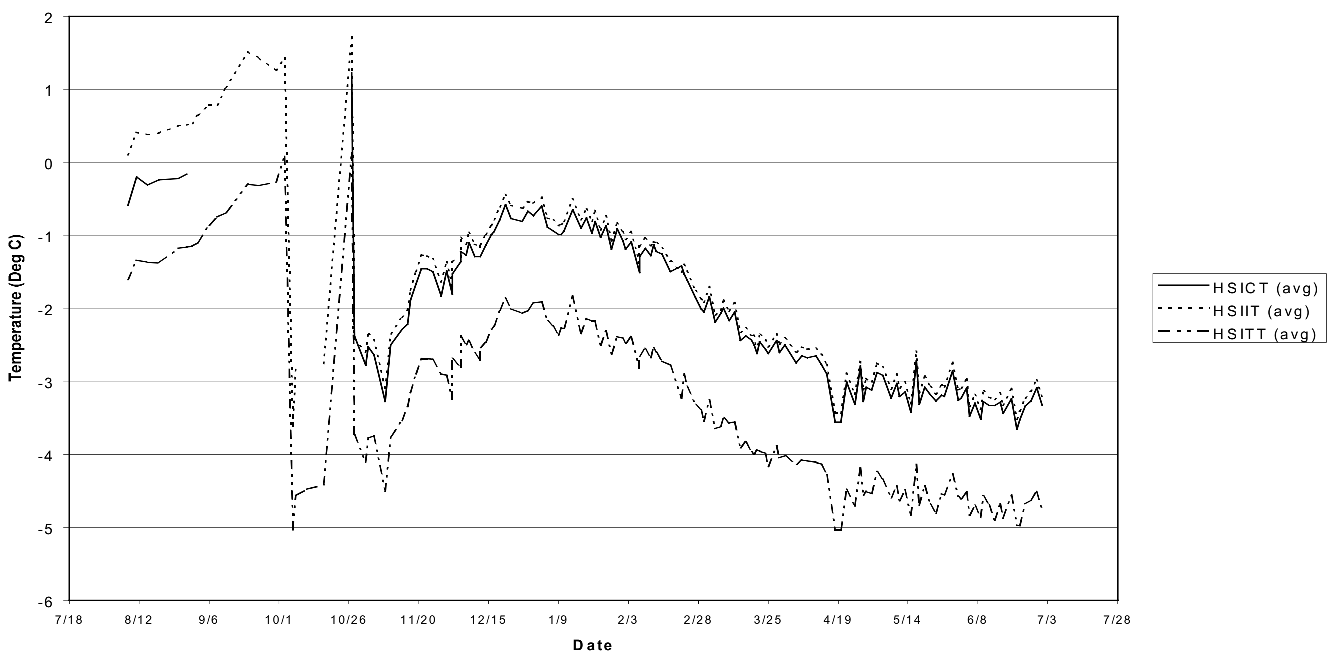

Figure 2: FTHSI imaging temperatures since launch (as of 2 July 2001).

The temperature sensors are located on or near the telescope (HSITT), interferometer (HSIIT), and the camera (HSICT). All images have been taken within -5^{o} and 2^{o}C, which is well within the nominal operating range. The gradual decrease in temperature continues at this slow rate until the heaters are triggered. Heater vents are programmed to open when the temperatures reach approximately -5^{o}C.

The large temperature variations that occur in the beginning of the mission are due to attitude changes of the satellite during a spacecraft anomaly. The central processing unit (CPU) experienced a gradual increase in the time it took to finish tasks during the beginning of the mission. The cause of the anomaly was found in a small section of code and has been fixed on board the satellite. Before the anomaly was fixed, a VME reset of the satellite was required to eliminate any tasks that were not responding. When executing a VME reset the satellite was oriented so the solar arrays would point at the sun (Sun Point Mode), and power to the payloads was turned off. In this configuration the temperature of FTHSI decreased until the payload power was turned on and the low temperatures activated the HSI heaters. The heaters increased the FTHSI temperatures to above zero and then deactivated.

Since the camera is not qualified for vacuum conditions, the pressure in the compartment must be monitored. The compartment was filled with dry nitrogen gas to approximately 110kPa prior to launch. The digital pressure sensor has range of 0 to 103kPa. Figure 3 details the high and low-pressure readings at the time of each collect. Once the pressure falls below 690kPa, capacitors in the optical system should fail. Prior to launch, it was expected that the pressure would be approaching zero within 12 months after launch. From the trends in the camera pressure data, the critical pressure will not be reached for another 12 years. Therefore, the satellite will re-enter the atmosphere before the critical pressure is reached.

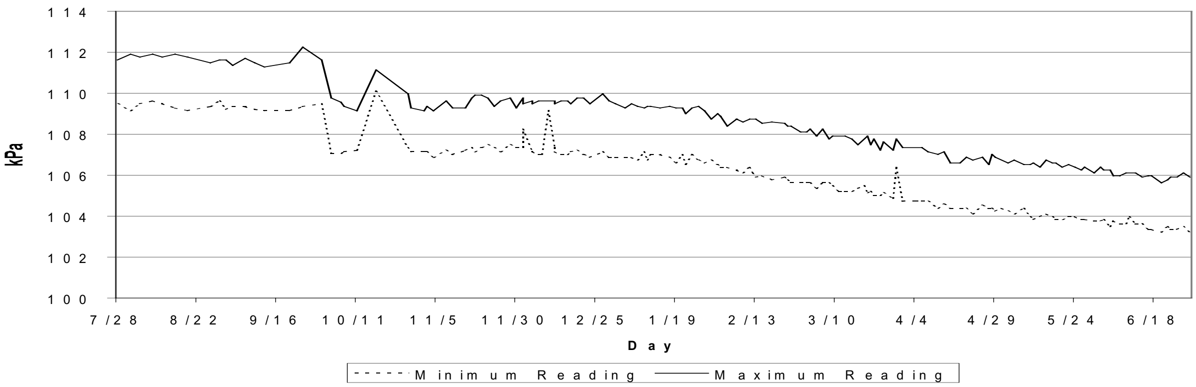

Figure 3: FTHSI camera pressure since launch (as of 2 July 2001).

7. SENSOR CALIBRATION

Calibration of the FTHSI was originally going to be accomplished using two techniques. The first used a pair of fiber optic feeds that direct sunlight onto the edges of the detector at the time of each collect. At the outside edges of tiles A and D, ten pixels are dedicated to calibration. The tile D edge fiber feed contains an Erbium dope with known spectral absorption values. This strip would then be compared with the tile A edge, which is exposed to sunlight, to see if the absorption value has shifted. This method of calibration could not be used due to insufficient signal. The second calibration technique applies a vicarious calibration that depends on knowing the reflectance and radiance of a target at the time of the collect. Since the beginning of 2001, we have successfully collected the same ground area with the satellite, AVIRIS, and ground truth teams over a number of sites. In addition, co-collects with NASA's Hyperion imager have been performed.

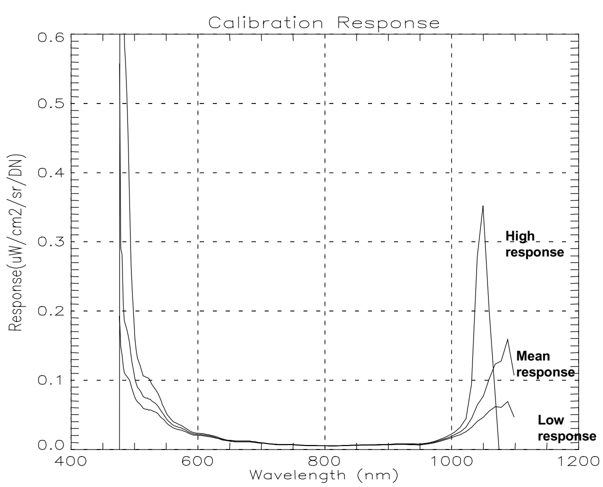

Figure 4: Calibration response graph with standard radiance using data from 5 January 2001.

A sample of the type of calibration being applied is shown in Figure 4. These were the first successful radiometric vicarious calibrations obtained in early January 2001. The data shows well collapsed calibration curves over the designed optimal operating band of the sensor (550 nm to 900 nm). The variations at the long and shorter extremes are related to the decreased quantum efficiency of the silicon detector at these extremes.

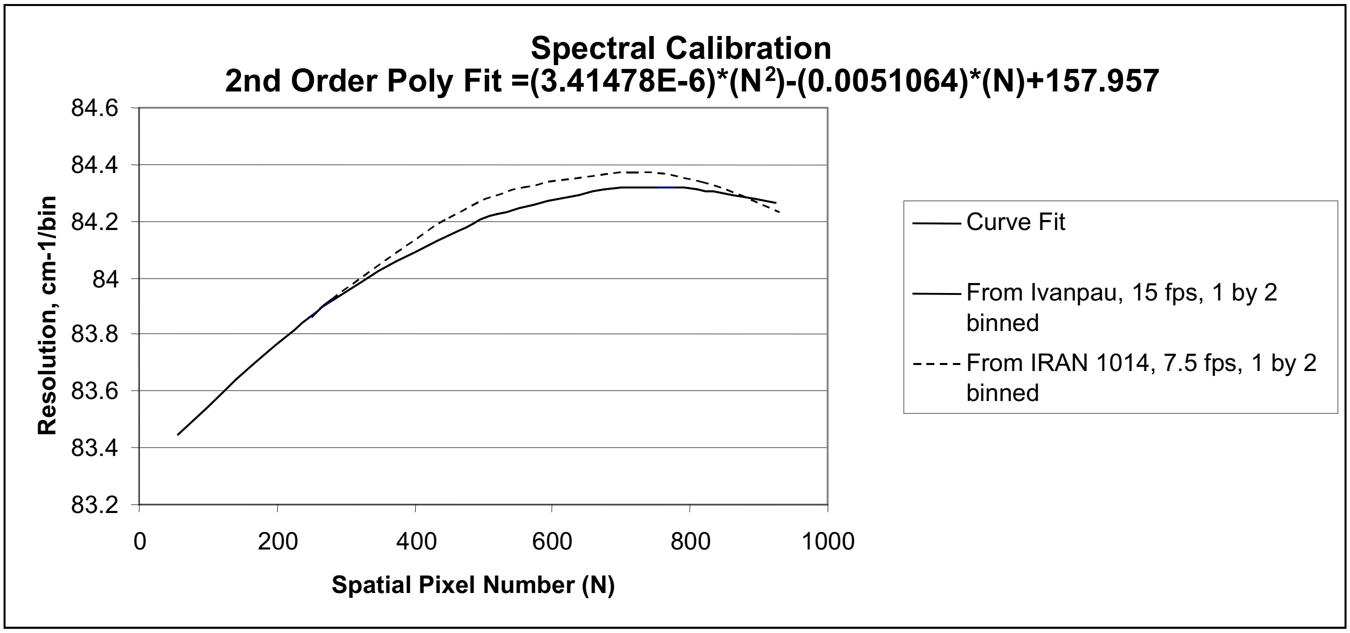

Figure 5: Calibration curve for the FTHSI sensor based on 16 December 2000 data.

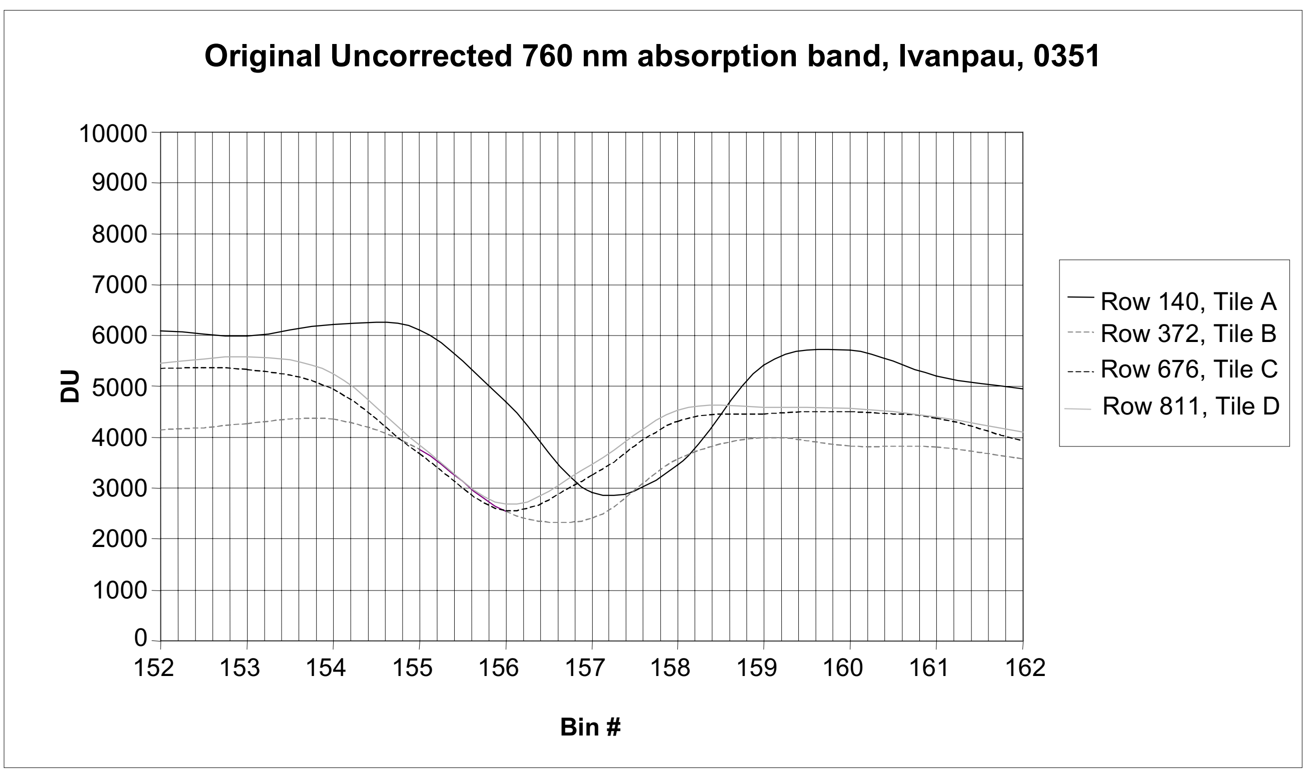

Figure 6: Spectral shift in the 16 December 2000 collect.

The spectral calibration curve, Figure 5, shows how the spectral resolution of the sensor changes over the focal plane. The source of this 0.05% variation in the spectral resolution is an 8-micron shift in the offset in the Sagnac interferometer over its 10 cm length. Uncorrected, the spectral variation produces a spectral shift in the data (Figure 6). Figure 6 details the shift of the O_2 absorption band at different locations on the focal plane. This difference can be adjusted by applying the calibration noted in Figure 5.

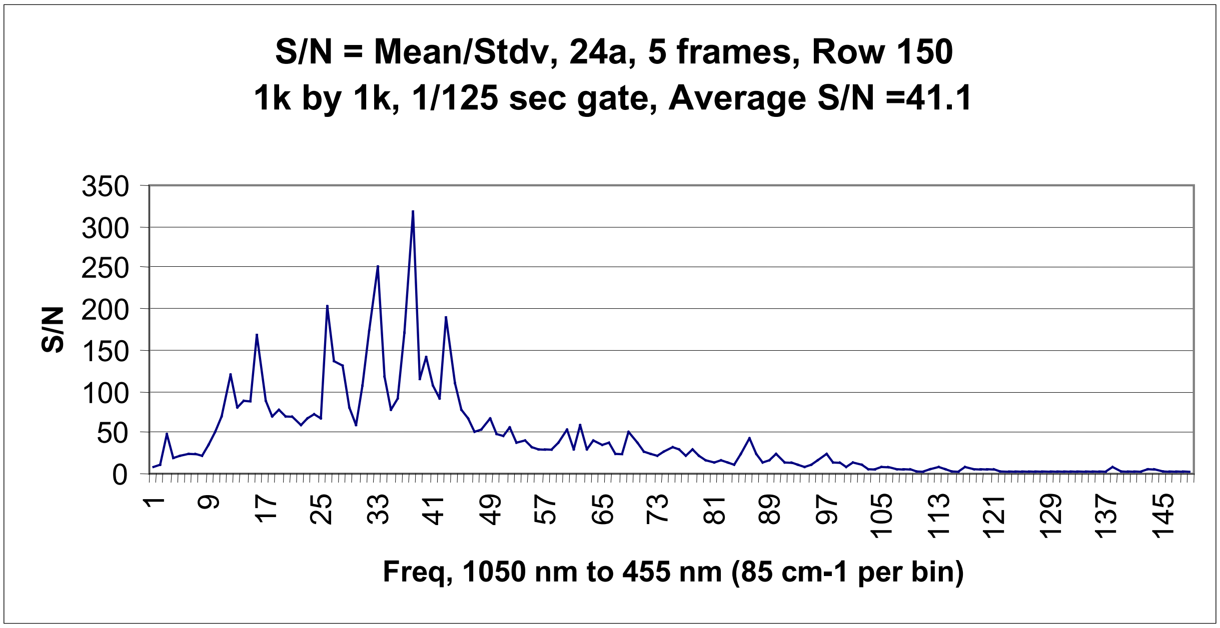

Figure 7: Prelaunch signal to noise ratio (SNR) of the sensor.

Signal to noise data was taken using Labsphere as an extended uniform source prior to launch (Figure 7). This data is for 1/124th second gating and 1 x 1 binned parameters. To convert this to the more normal operating mode of 15 frames per second (fps) with 1 x 2 binning, the SNR values should be multiplied by 14. This gives an average signal to noise ratio of 575. Best optical performance is obtained with a slower frame rate. However, this slower frame rate requires satellite roll back rate to increase, which decreases the time before the effects of the earth's rotation are noticeable, even with a two-axis maneuver. A compromise of 15 fps is now used for most observations.

8. SENSOR STATUS

The sensor is surviving well in space. Dark current collects are used to determine bad pixels on the focal plane. On every nominal collect, three dark current frames are taken looking into deep space. In addition, about once a month a larger dark current collect is taken over an ocean at night. Dark current collects will show "hot" pixels on the focal plane. To find "cold" pixels, an image of a bright scene is taken. Most recently, ice fields in Canada have been imaged to find any cold pixels. These collects allow the changes in the bad pixel map to be tracked, and images to be corrected for bad pixels during processing. Over the course of the mission, the focal plane has shown only a very slow increase in the number of pixels with non-standard response (Figure 8). The cold pixel comparison, Figure 8, details how few additional cold pixels can be seen on the focal plane. Compensation for cold or hot pixels is easily accomplished, using the raw data, by taking advantage of how a Fourier transform sensor multiplexes the spectral data over the entire interference pattern and interferogram symmetry. We are able to compensate for bad pixel effects, even when they appear as a cluster.

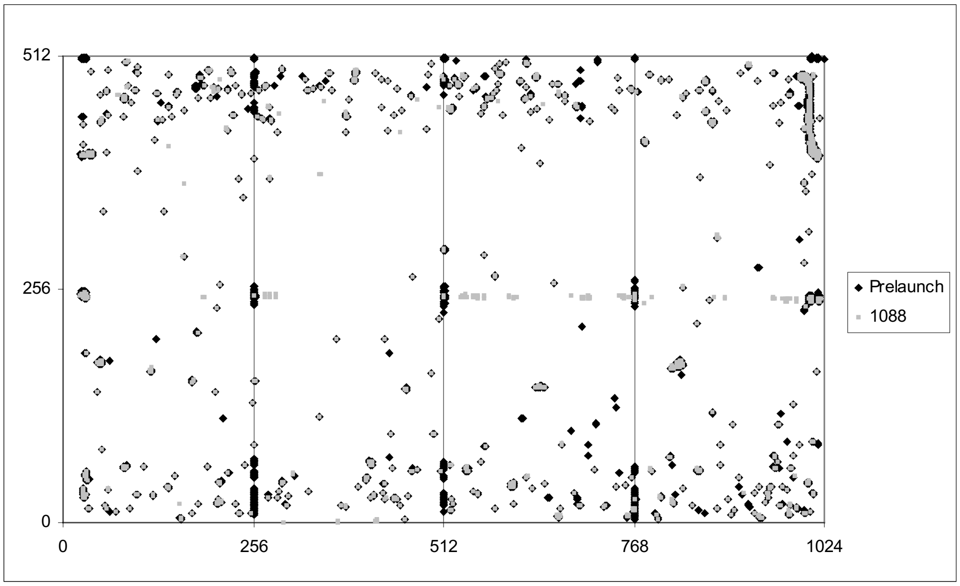

Figure 8: Comparison of focal plane cold pixels from prelaunch to 29 March 2001.

Throughout the mission a ghost image in the data has been noticed. Originally, this was not recognized due to the along track spatial resolution being up to twice the designed values and the use of the two center tiles which exhibit less ghosting. As the mission progressed the along track resolution decreased to 30 m and images started to include tile D, making the ghosting more prevalent. The ghosting of the image is least noticeable on tile A where there is from zero to 3 pixel image difference and gradually becomes more noticeable until tile D where there is a 12 pixel shift (Figure 9). The exact cause of the ghosting is still being investigated although it appears to be related to the lack of an AR coated cover over the detector. While the use of a cover is nominally used in a silicon charge-coupled device (CCD) device, it was removed due to concerns on the vacuum compatibility of the banding agent and concern over mechanical survivability. Through ground processing we have been able to apply a linear version of a maximum expected value algorithm to the data that should remove most of the ghost. More work to refine the algorithm is being completed at Kestrel Corporation.

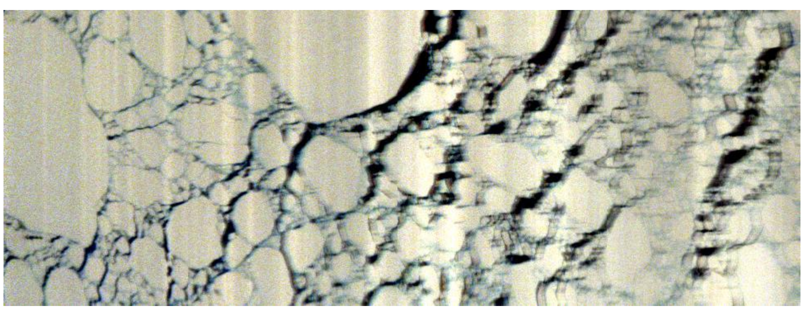

Figure 9: Image of ice flows in the Bering Strait detailing ghosting.

9. ON-BOARD PROCESSING

FTHSI uses the QC40 processor to run a variety of processing options. The most successful of the options is the Cyclical Redundancy Check (CRC).[1] For every collect, a CRC is performed on the data in the SSM. Then both the CRC and SSM data are downloaded to the ground. Once on ground another CRC is created for the SSM data and then the ground CRC and satellite CRC are compared. This allows for the SSM data to be checked for data errors due to transmission.

The ability to process the data while on-orbit was a goal of the program. Through the utilization of the QC40 processors, the algorithms for processing data on the ground were also put on-board the satellite. The QC40 could be electronically set to process the data using various settings. Algorithms for performing apodization, spectral filtering, and the Fast Fourier

Transform (FFT) are examples of the code that was available for on-board processing. Results of the first attempts to perform on-board processing were not encouraging. All processing was taking longer than expected due the CPU slow down satellite anomaly. In addition the results of the processing were producing unrealistic results.

After ground testing with the engineering model, the causes were found. A misunderstanding of how the data was written in the SSM during a collect resulted in the bits being read into the QC40 backward. This caused the initial problem. It was further found that the spectral filter and magnitude codes were not functioning correctly. The final problem was the conversion from floating point value to integer value. The QC40 EEPROM write pin was disabled prior to launch, so a permanent fix to on-board the satellite processing will not occur. There is a possibility that some of the code could be patched for one processing run, but this chance is unlikely to happen due to time constraints. Ultimately, this means that the raw SSM data must be downloaded and processed on the ground.

The primary objective of the QC40 experiment was to show that the C40 processors could operate in space. Original estimates expected that at least one processor would have been lost by this point in the mission. Currently all four processors are still in nominal working condition. Therefore the QC40 has exceeded its design expectations.

10. IMAGING PARAMETERS

Several imaging modes are available using variable camera and imaging parameters and the ability to reorient the satellite. Since the lenses and mirrors cannot move, a data collection requires the satellite to maneuver. In a nominal collect, the satellite first yaws 90 degrees to orient the aperture perpendicular to the satellite velocity vector. Once oriented, the satellite then performs a roll to slow the satellite ground track speed to a speed that sets the desired along track spatial resolution. This allows for contiguous pushbroom swaths to be collected with the space between the strips being less than a centimeter.[6]

The maneuvering commands along with imaging parameters are sent to the satellite 24 to 48 hours prior to the time of the collect. Image parameters allow the user to configure the camera to best suit the type of ground that will be imaged. These parameters are changed electronically in the HII card as a result of the upload. The HII controls the camera and routes the data stream from the HSI into the SSM. The HII is controlled by a single Field Programmable Gate Array (FPGA) responding to commands sent to it from the spacecraft control computer (RAD6000). The commands that that program the HII to select the data to be saved include: desired tiles to collect, line length, lines per frame, bit depth, start of data collect (GMT), and starting and ending memory addresses. Commands that initialize the camera are passed directly between the FPGA and the HSI. Table 2 outlines the possible camera configurations, nominal configuration before launch, and the current nominal configuration.

Table 2: HII card functions and nominal settings.

Function	Selections Available	Prior to Launch Nominal Settings	Current Settings
Camera Frame Rate	7.5, 15, 30, 60, 110 fps	30 fps	15 fps
Camera Gating Time	1/fps, 1/125, 1/250, 1/500, 1/1000 sec	1/fps	1/fps
Camera Binning Mode	1x1, 1x2, 2x1, 2x2	1x2	1x2
Camera Gain	1 or 4	1	1
Data Bit Depth	12 or 8 bit	12 bits	12 bits
Number of Imaging Tiles to Record	1,2,3, or 4	2 (BC)	2 (AB)

11. HYPERSPECTRAL IMAGES FROM SPACE

On 1 August 2000 at 18:47:51 GMT, the first hyperspectral image was taken from a space-based platform and subsequently downloaded. The target was the Denver International Airport (DIA) region in Denver, Colorado. Although the image was taken slightly north of the aim point, several geographical land features allowed the Horse Creek Reservoir, just north of DIA, to be located (Figure 10).

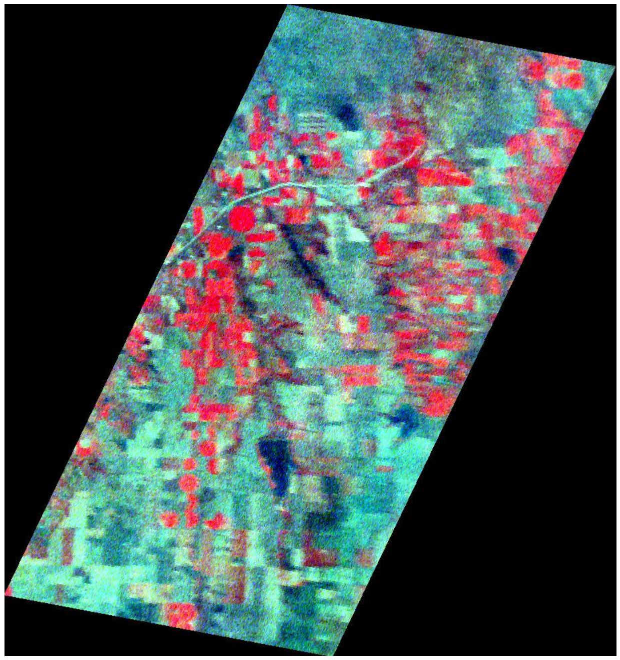

Figure 10: Hyperspectral image of Horse Creek Reservoir, CO taken on 1 August 2000.
Interstate 76 is visible in the upper half of the image.
(No atmospheric correction has been applied.)

Figure 11 and figure 12 are a few of the images that have been taken with FTHSI. The coastal region of Mississippi, Figure 11, shows the healthy vegetation (red) and waterways (blue). Further exploitation of the spectral data will be able to determine the type of vegetation in the region and where large manmade structures are. Figure 12 details the mountains near coastal southern California. The ridgelines and valleys are visible and help to locate areas without many roads.

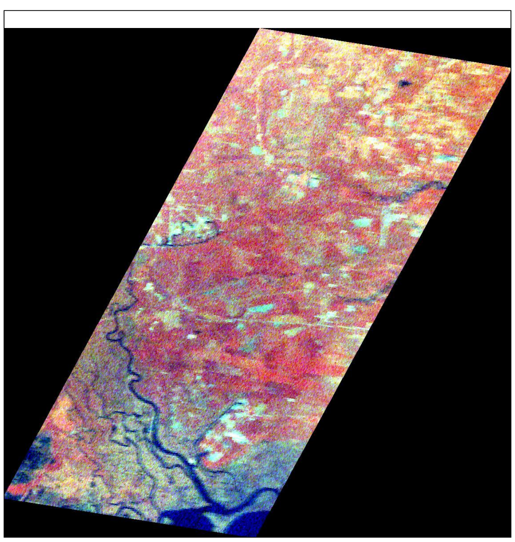

Figure 11: 26 August 2000 image of NASA Stennis, MS highlighting lowland vegetation and waterways. (No atmospheric correction has been applied.)

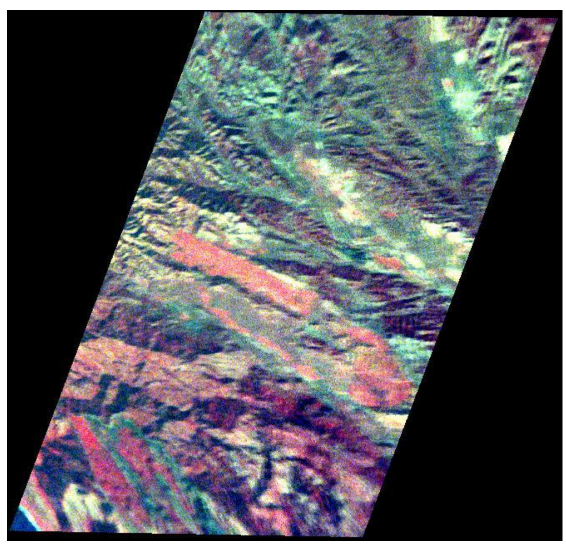

Figure 12: 3 January 2001 image of Fort Hunter Liggett, CA highlighting mountains and valleys. (No atmospheric correction has been applied.)

12. EARTH LIMB COLLECTS

The idea of looking at the earth limb was a research request, but has been useful in several ways. Imaging the earth limb allows us to look at the design of the atmosphere. The first earth limb collect was taken on 29 December 2000 (Figure 13). The image was taken using four tiles, 2x2 binning, and looking east to the horizon at –66.47 degrees off nadir. The satellite was not given a roll back rate, so the along track velocity was 7.5 km/s resulting in large along track pixel sizes. Using these settings two tiles worth of atmosphere were collected and a distinct structure to the atmosphere could be seen through analysis of the spectral data.

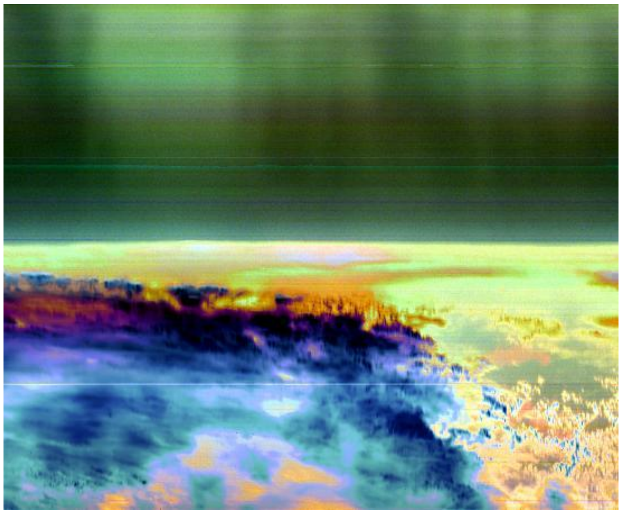

Figure 13: 28 December 2000 Earth Limb Collect.
Taken looking east over the Gulf of Mexico.
(No atmospheric correction has been applied.)

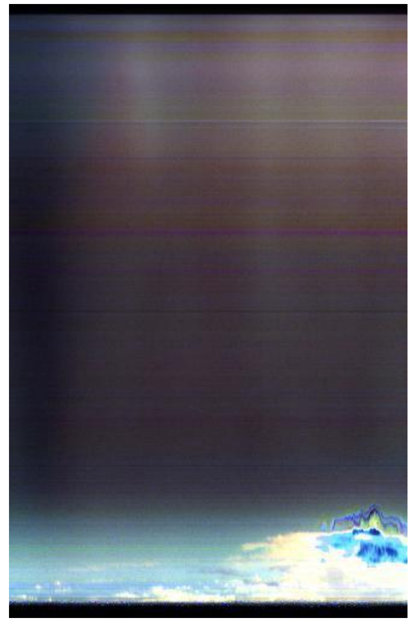

Figure 14: 21 March 2001 Earth Limb Collect.
Taken looking east over the Caribbean Sea.
(No atmospheric correction has been applied.)

After the success of the first earth limb collect it was desired to increase the amount of atmosphere collected. Figure 14 shows the earth limb collect from 21 March 2001. This image captured almost four tiles worth of atmosphere. In order to achieve this off-nadir angle the satellite maneuver commands could no longer be created from the imaging target's latitude and longitude. Instead, the maneuver commands had to be created from angular relations and the required off-nadir angle. At our current elevation, this collect required an off-nadir angle of 68.5 degrees imaging the eastern earth limb.

One of the more significant results of this image was the determination of the instrument offset in the cross-track direction (the pitch axis). Since a particular off-nadir angle is specified for the earth limb collects the difference between collects at the same latitude, one looking east and one west, can determine a misalignment error. When this test was performed it was seen that there was a 0.70 degree cross-track misalignment. The verification of this misalignment improved the cross-track pointing error resulting in better acquisition of the imaging target.

13. IMAGING STATISTICS

The HSI has been active for a total of 4:13:19 hours since launch (as of 2 July 2001). For each nominal image, the camera is turned on twice. First is the image collection, which averages 1:40 minutes. The length of the image is dependent on the time of the collect. Most collections have the data collected for 30-40 seconds. The second time the camera is turned on is to collect 3 frames of dark current data.

One hundred and fifty images have been taken with FTHSI as of 2 July 2001. Of these images, 66 have been able to be geo-referenced and have captured the intended location. 29 images did not collect the intended location, but still contain usable geo-referenced data. Two of the images are still being processed. The rest of the images are research related special collects or are covered in clouds. These collects cannot be geo-referenced. Night and earth limb collects are considered special collects. Night images are used for dark current information.

As of 27 May 2001 we have collected an approximate total of 22160MB worth of data. The total area imaged up to this date is estimated at 27,376 km^2 with nominal ground covering 21,464 km^2. Of the nominal ground area, 19,614 km^2 is unique ground.

14. CONCLUSION: FUTURE OF HYPERSPECTRAL IN SPACE

From the images that have been collected with FTHSI, the benefits of hyperspectral imagery can be seen. With more bands available than multi-spectral imagers, one hyperspectral imager can have an enlarged mission and be more sensitive to spectral variations. All aspects of society can benefit from the hyperspectral imagery. Early drought detection from spectral changes in crops will help farmers. Enhanced land maps with object identification will create more accurate regional vegetation knowledge. Fields of mixed crops will be easily identifiable from their spectral signature. The atmospheric data may eventually show more detailed structure within the atmosphere.

FTHSI on-board MightySat II.1 is nominally funded for one year of operations. Images will be taken util the satellite has to be shut off to keep increasing the hyperspectral library. During this time we are working to image the moon. An image of the moon will assist with calibration since there will be no atmospheric interference. With the data that has been and will be collected we are building a foundation for space based hyperspectral imagery.

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