Infrared Technology & Applications XXIII *SPIE Vol. 3061, April 1997; Orlando, FL*

Thermal Infrared Imaging Spectrometer (TIRIS) Status Report

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ABSTRACT

The TIRIS is a pushbroom long wave infrared imaging spectrometer designed to operate in the 7.5-14.0 µm spectral region from an airborne platform, using uncooled optics. The focal plane array is a 64x20 extrinsic Si:As detector operating at 10K, providing 64 spectral bands with 0.1 µm spectral resolution, and 20 spatial pixels with 3.6 milliradians spatial resolution. A custom linear variable filter mounted over the focal plane acts to suppress near field radiation from the uncooled external optics. This dual-use sensor is developed to demonstrate the detection of plumes of toxic gases and pollutants in a downlooking mode.

Keywords: Imaging Spectrometer, Hyperspectral, Thermal IR, Linear Variable Filter, Uncooled Optics, Plume Tracking, Chemical Detection, TIRIS.

1. INTRODUCTION

The TIRIS[1], Fig. 1, is a long wavelength infrared (LWIR, 7.5 to 14.0 µm) imaging spectrometer designed to demonstrate operations using uncooled optics for dual use applications that include the detection of airborne toxic gases and pollutants, and target detection.[2-5] The concept of using uncooled optics represents an important advancement in design of long wave-length infrared (LWIR) spectral imaging systems that results in much smaller systems. The sensor uses a 64x20 focal plane array (FPA), and operates in a pushbroom mode, to generate image cubes with 20 pixels in the cross-track direction and 64 spectral bands. The spatial resolution of the system is about 3.6 milliradians while the spectral resolution is about 0.1 µm.

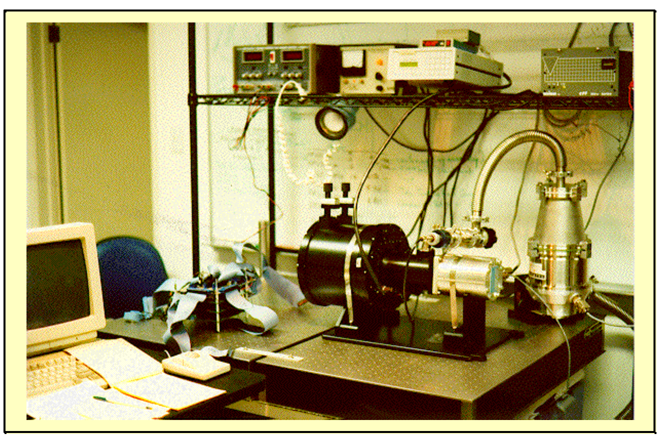

Figure 1. TIRIS-II laboratory calibration and characterization test setup.

Since the spectral signature of most organic compounds encompasses a wide range in the infrared (IR), an extrinsic silicon FPA was selected to allow operations across the entire LWIR atmospheric window. Alternative matrix arrays such as HgCdTe do not provide coverage over the entire range up to 14 µm. The downside of extrinsic silicon FPAs is that they are very expensive and they operate at 10K. The 10K operations introduces operational logistics problem: liquid helium is not readily

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available at all field locations from where the sensor may operate, and the use of a mechanical closed cycle cryocooler increases to overall sensor size, weight and power consumption. Since the TIRIS is expected to operate from sites where Lhe may not be readily available, the mechanical cryo-cooling approach was selected.

One unique aspect of the TIRIS design approach is the use of a linearly variable filter (LVF),[6] also known as a wedge filter, to suppress near field radiation and permit operations with uncooled optics. Although LVFs are used[7] in the visible, near infra-red (VNIR) and in midwave IR (MWIR), to the best of our knowledge TIRIS is the first system to adapt the LVF for the LWIR. A significant effort was invested on developing the understanding and the technology associated with building an LVF based LWIR spectrometer. This includes the manufacturing of the LVF and integrating it with the FPA. Since Si:As FPAs are not commonly used in commercial applications, the FPA drive and readout electronics were also designed from the ground up.

2. SYSTEM DESIGN

The TIRIS consists of a vacuum enclosure containing the cooled FPA, an optical train, control and readout electronics, a cryocooling system, and diagnostics. Table 1 summarizes key specifications of the TIRIS-I system. The required operational temperature of 10K for the FPA is achieved using a Gifford-McMahon closed cycle helium refrigerator that consists of a compressor and a two stage expander, an 80K and a 10K stage (cold finger). The two stages are rated to handle heat loads of 10W (at 80K) and 1W (at 10K) respectively. The cold finger on which the FPA is mounted is enclosed in a 80K radiation shield. The vacuum enclosure uses a ZnS viewing window. Five temperature measuring sensors (Si diodes) are mounted at various locations inside the dewar to monitor the 10K and 80K stages, the inside surface of the 80K shield directly facing the FPA, and the FPA itself (a diode was epoxied in the chip cavity on the LCC and its leads wire-bonded to extra available pads). The FPA is placed in an 84 pin plastic socket and clamped to the cold finger using an Indium foil in between the ceramic carrier and the cold finger to improve heat transfer. All internal wiring use manganin leads to reduce parasitic heat load; in addition the wires are heat sunk to the cold stage. Hermetic electrical feedthrough connectors provide ample connections for all the control, signal, and diagnostics leads. Fig. 2 shows the overall layout of the TIRIS system.

TIRIS Design Parameters

• SENSOR DESIGN PARAMETERS:

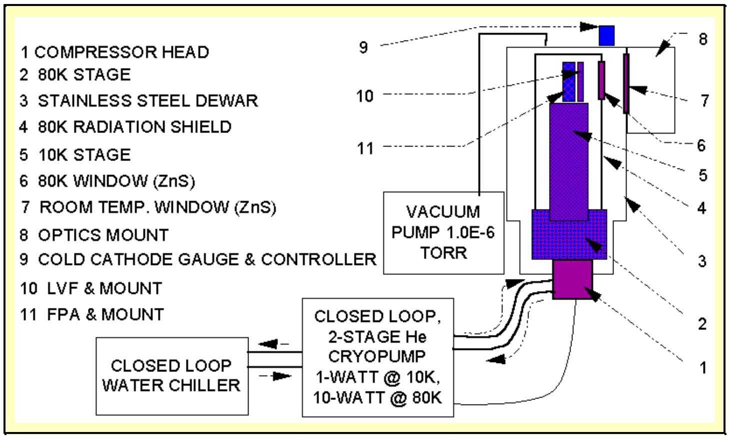
– SPECTRAL RANGE:	7.5 - 14.0 µm
– BANDPASS:	~100 nm
– FPA:	AEROJET-BUILT, 64X20 Si:As OPERATING @ 10K
– FPA SETTING:	64 SPECTRAL BANDS, 20 SPATIAL
– OPTICS:	ROOM TEMP., 3 SCHWARZCHILD TELESCOPES
– DISPERSION:	29.6471 g/mm GRATING
– LVF:	CUSTOM TAPERED INTERFERENCE FILTER 7.5-14 µm
– COOLING:	CLOSED LOOP He REFRIGERATOR, WATER CHILLED
– SPATIAL RESOLUTION:	~3.6 mrad
– ADC RESOLUTION:	12 BITS
– FRAME RATE:	~1,000 FPS

Table 1**.** Summary of TIRIS-I, a laboratory prototype, design parameters.

The sensor operates at a nominal frame rate of 1,000 fps, although the pixel rate is twice as high to allow for correlated double sampling or subtractive double sampling (CDS/SDS) operations. Data are digitized to 12-bit and passed on to the computer as 2 byte words. The data rate under these conditions is (1,000x2 frames/sec) x (64x20 pixels/frame) x (2 bytes/pixel) = 5.12 Mbytes/sec.

2.1. FPA Sensor

The TIRIS-I system is based on an Aerojet PATHS 64x20 hybrid consisting of an extrinsic Si:As detector with a 100 µm unit cell size, indium bumped to a Si multiplexer readout integrated circuit (ROIC). The mux consists of two staggered 64x10 p-channel MOSFETS arrays and a 6 bit gray code CMOS decoder. Each switching array is configured in 10 parallel columns which multiplex 64 source follower buffered pixel elements per line. A unit cell diagram of the multiplexer is shown in Fig.3. The FPA is sensitive to radiation in the range 6-24 μm.[8]



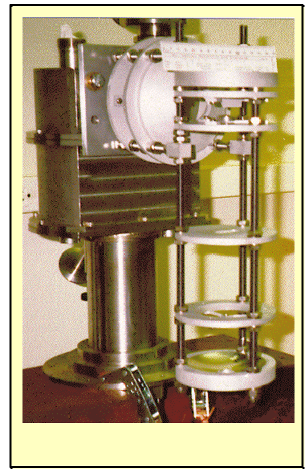
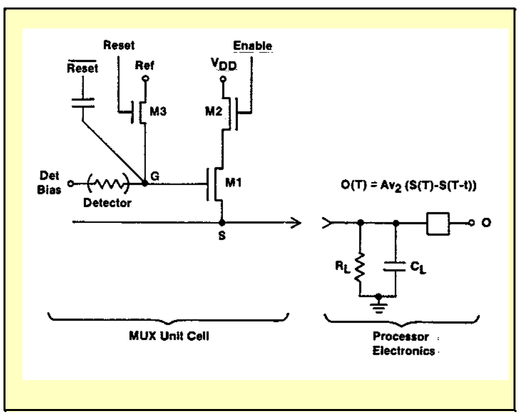


Figure 2. Overall layout of TIRIS-I (left), sensor assembly (right).



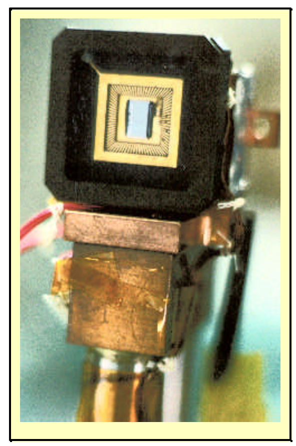


Figure 3. Unit cell diagram of FPA's multiplex readout IC. The detector is a 64x20 Si:As device operating at 10K.

Figure 4. The Aerojet PATHS FPA in TIRIS-I mounted on top of the on 10K stage

2.2. Optics and Radiometry

The TIRIS can function in two different pushbroom modes. First, as a slitless wedge spectrometer, and second as a dispersive spectrometer. In the former, the spectral separation is obtained solely by means of the LVF that is placed over the imaging array. In this mode, full 2-D images are grabbed in each frame. In these images, however, each cross-track strip of scene is imaged in a different "color" or spectral band. As the sensor moves forward, each strip of scene is reimaged in consecutive spectral bands ("colors"). Eventually, a full image cube is constructed. In this configuration, the foreoptics is simply a reflective telescope of any design (e.g., Cassagrain).

In the dispersive mode, the foreoptics is based on 3 all reflective Schwarzchild telescopes (fig. 5). Schwarzchild telescopes are selected because they use spherical elements, are easy to fabricate and hence relatively inexpensive. They do however introduce spherical aberrations which are absent in aspherical systems.[9,10] Moreover, because of the very fast optics (~f/1), inherent to this design, focal plane curvature is present. However, for the very small FPA, the imaging quality based on simulation studies (on ZEMAX) seem satisfactory.

The first two telescopes in Fig. 5 gather and collimate radiation from the scene. These two back-to-back telescopes also focus the radiation to the entrance slit (and spatial filter) that is located at the focal plane of each. The collimated radiation is then incident on the grating which disperses it. The dispersed radiation is finally collected by a third telescope that brings it to focus on the focal plane.

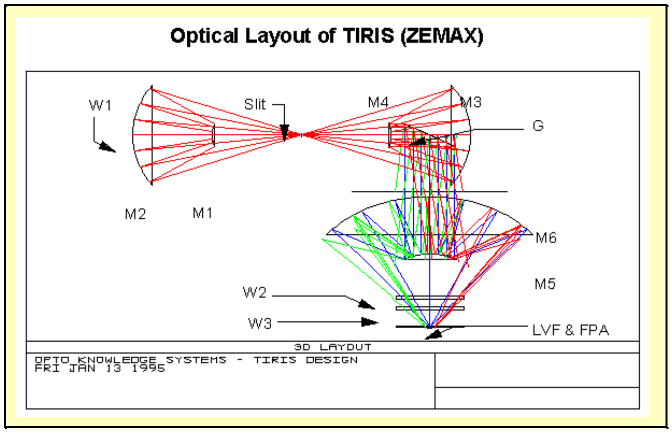


Figure 5. Layout and verification of imaging performance of TIRIS optics. Mirrors (M1, M2) and (M3, M4) are the first and second pairs of Schwarzschild telescopes, that collect and collimate the input beam. G is a grating whose dispersion is matched to the LVF. Mirrors (M5, M6) that form the third Schwarzschild telescope focus the image onto the focal plane. The LVF mounted directly in front of the FPA suppresses all near field thermal emissions from the optical elements.

There are advantages and dis advantages for the two methods of operations. In a dispersive mode of operations the system is much more efficient in terms of utilization of all the photons received from the scene, since the grating is matched with the LVF (see next section), and the LVF suppresses the nearfield radiation from the foreoptics. Photons from nearfield or farfield that are not within the system's field of view (FOV) are also dispersed by the grating, but are effectively blocked by the LVF (as explained in the next section). Optical efficiency is not of a major concem, however, when the system functions under background limited conditions. The photon flux in the LWIR is much higher than that required for the readout data rate of 1,000 fps, in particular since the Si:As FPAs were designed to operate in a low background flux environment (i.e., looking up towards cold space rather than downlooking at the warm earth). In fact, based on radiometric calculations and laboratory calibration, the photon flux has to be attenuated by an IR neutral density filter of about ND-2.

When operating as a slitless wedge spectrometer, minimum radiation is received from the nearfield optics and the suppression issue may be less important. In that case the function of the LVF is to serve as the "color" separation element. The downside of this mode is that in an airborne pushbroom operating mode, the performance of a wedge spectrometer may suffer from difficult-to-control motion of the platform (roll in particular).

2.3. Linear Variable Filter (LVF)

The room temperature foreoptics mounted in front of the dewar may create a condition analogous to placing a light source in the film chamber of a camera. The LVF, Fig. 6, is needed to suppress this bright source. The LVF is a multi-layer narrow band pass interference filter in which the layers of coatings have a wedge shape. The center wavelength of the LVF therefore varies depending on the position in accordance with the coating. The LVF covers the range from 7.5 to 14 µm over a length of 6.4 mm (64 pixels, 0.1 mm each) thus producing a gradient of ~1 µm/mm. It is fabricated on a rectangular Si substrate whose dimensions exactly match that of the focal plane. The operating principal of the LVF is illustrated in Fig. 7a where it's trans-mission is shown as a function of position. Figure 7b shows the LVF mounted about 0.2 mm over the FPA and it is cooled to ~10K.

Fig. 8 shows the LVF suppressing near field radiation from the foreoptics at all wavelengths. This is due to the delta like trans-mission property of the LVF at a particular point, where it allows only a narrow band of wavelengths to pass through and suppresses radiation at all other wavelengths. Since the grating's dispersion is matched to the LVF's spatial transmission characteristics, it couples external radiation very efficiently to the LVF. As a result, background thermal emissions from the optical elements in each of the LVF's transmission windows becomes negligible compared to the signal. We note that the LVF itself starts to transmit radiation above 15 mm but it does not transmit below 7.5 mm. Since the FPA is sensitive up to 24 mm, a ZnS filter is place directly above the LVF to provide total out of band blockage of radiation.

In order to match the grating's dispersion the LVF transmission curve slightly deviates from linear as indicated in Fig. 9. Exact positioning of the LVF relative to the FPA pixels, both in translation and rotation, is therefore critical. No provision is available on TIRIS-I system to micro adjust the LVF position relative to FPA once the dewar is closed. However, the second generation TIRIS-II system has two micrometer adjustments that can be manipulated from outside the dewar, to align the LVF exactly with the focal plane. These micrometers have mechanical feed throughs that extend through the vacuum shroud and radiation sheilds and provide both translational as well as a rotational capability.

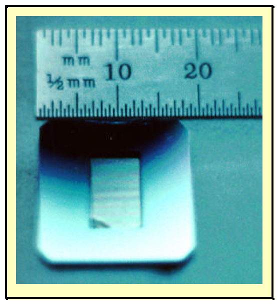


Figure 6. The LVF -- about 6.4 mm x 2 mm in size, is bonded to a Si frame for mounting purposes.

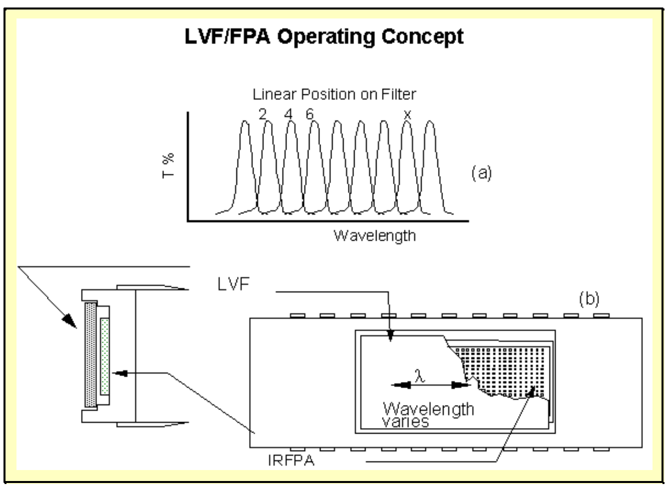


Figure 7. LVF operating concept. (a) shows the LVF's transmission function varying linearly with position from 7.5 µm at one end to 14 µm at the other. (b) side and top view of the LVF placed 0.2 mm over the FPA.

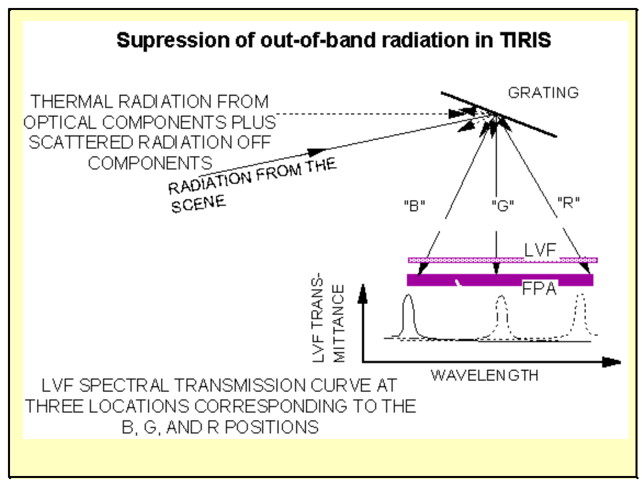


Figure 8. Suppression by the LVF of out-of-band near field thermal radiation emitted by the foreoptics.

2.4. Electronics

The TIRIS sensor and electronics are controlled by a PC which also contains a frame grabber to acquire data from the FPA. The entire electronics to operate the FPA and interface it to the frame grabber was custom designed, Fig.10.

The PC communicates with the focal plane electronics via a parallel I/O interface. All the clock rails and bias levels required to operate the FPA are generated using DACs. The timing patterns to operate the focal plane are loaded into an FPGA from a PROM. The PROM also provides the FPGA with the necessary frame grabber timings such as the pixel, line and frame validation clocks. Pixel readout is software controlled. A gray code is required to sequentially address a row of pixels from 1 to 64. Alternative readout procedures are possible by modifying the addressing scheme. At present, the parallel interface provides the user full control over the clock and bias level settings and the readout scheme. However, the FPA and frame grabber timing patterns can be modified only by replacing the PROM. A future EEPROM based design will permit modification of timing patterns also from the computer.

To allow noise reduction via correlated double sampling (CDS) or subtractive double sampling (SDS), each row is read twice, once after incrementing the gray code, and a second time after a reset signal is applied to the row. Data are read in 20 parallel channels corresponding to the FPA's 20 columns. Each channel leads to an analog chain where suitable gains and offsets are applied to the data so as to fully utilize the entire dynamic range of the A/D converters. Every three data channels are then multiplexed to a single A/D converter. Seven ADCs are used to digitize all 20 columns of pixels at 12-bit resolution. As a result, we obtain 7x3 = 21 columns of data from the focal plane. The last column does not contain real data and is an artifact of the multiplex readout process. Each A/D converter is then sequentially given access to a bus that is connected to the frame grabber. CDS or SDS are then performed in software.

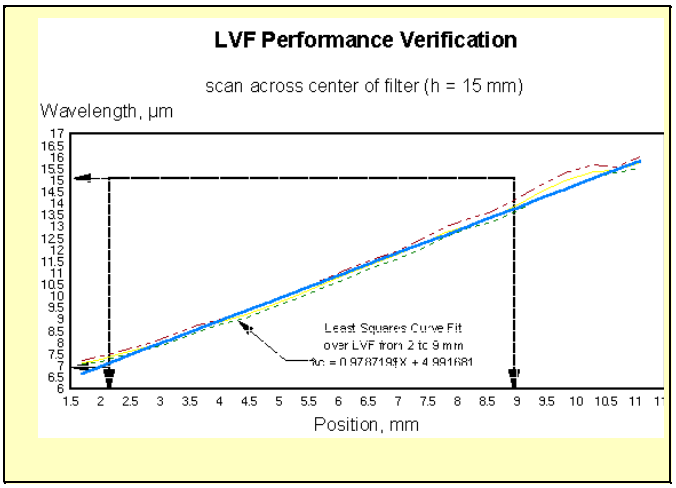


Figure 9**.** The LVF's transmission function is matched to the grating's dispersion.

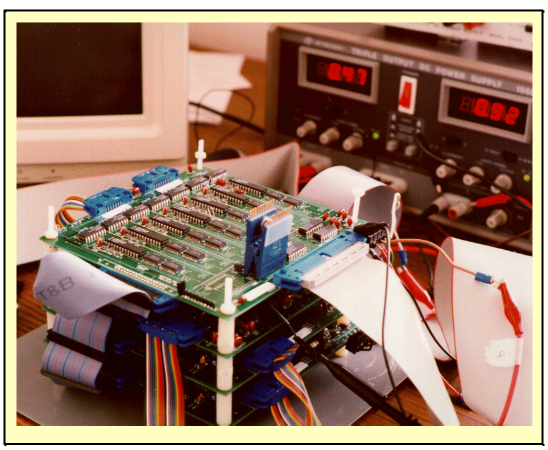


Figure 10. Prototype TIRIS-I electronics.

3. TIRIS-II DESIGN

TIRIS-II is the second generation LWIR imaging spectrometer design based on lessons from TIRIS-I laboratory prototype. The primary areas of improvement are as follows:

- The FPA was switched from the older generation PATHS to a newer HYWAYS Si:As device, made by Hughes, that is also based on a 64x20 architecture.

- The dewar was redesigned to afford more flexibility and enhanced performance: (i) a 10K radiation shield was added in addition to the 80K shield, (ii) an 8-position, 10K cold filter wheel was added to allow the insertion of band pass filters, ND filters, pinholes, or a blank for the purpose of testing, calibration[11] and characterization (Fig. 11), (iii) Two micrometer feedthrough were incorporated to allow full control for the adjustment of the LVF in both translation and rotation, to completely register it with the FPA pixels (This fine alignment is needed for the proper positioning after the thermal contraction of various components during cool down to 10K), Fig 12.

- A larger cryocooler was installed with a capacity of about 3 Watt at 10K. This was necessary because of the various feedthroughs incorporated into the dewar for LVF and filter wheel control, which increase the overall heat load.

- The electronics design for FPA control/data acquisition have been extensively redesigned. The TIRIS-I goal was to test and evaluate various design approaches. With TIRIS-II the goal is to refine and produce the highest quality possible signal to noise ratio.

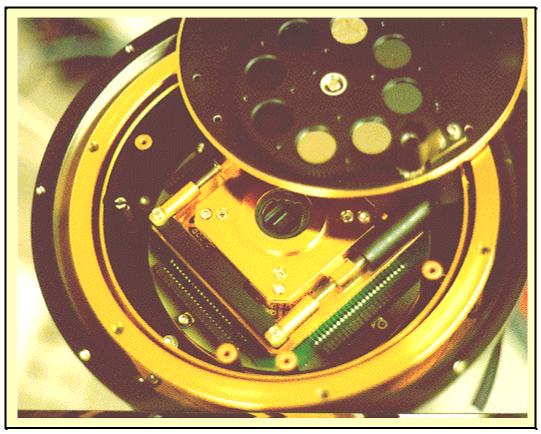


Figure 11. Filter wheel mounted onto the 10K radiation shield (shown in open position above the LVF holder and FPA).

To this end, care has been taken to keep all the bias and data lines isolated from the clock lines until they are brought together at the focal plane. The manganin wires carrying signals and data in TIRIS-I have been replaced by micro-coaxial cables with the sheaths grounded. This feature significantly reduces noise and cross talk between digital clocks and analog signals. All analog and digital circuitry have been completely isolated and the only point of contact between the two is at the A/D converters. Instead of 7 A/D converters used in a 3-1 multiplex mode, 20 parallel 12 bit flash A/D converters are used to digitize the data. The timing patterns have been carefully adjusted so that no clocks switching occurs when the A/D converters digitize the data. All clock signals have been filtered so that they now resemble rounded trapezoids. This minimizes high frequency noise produced by clock ringing. All clock lines have also been suitably terminated to minimize ringing. The analog chain that gains and offsets the data before passing it on the A/D converters also filter the data with a rapid roll-off at a frequency of twice the pixel clock rate. The current data rate is set at 1000 frames per second. A prototype design of the electronics hardware has yielded noise levels < 1 mV. CDS is performed in software while SDS can be performed directly in hardware. We anticipate that the final system will have noise levels of the order of a few 100 μV resulting in a field operating system with at least 10 bit dynamic range.

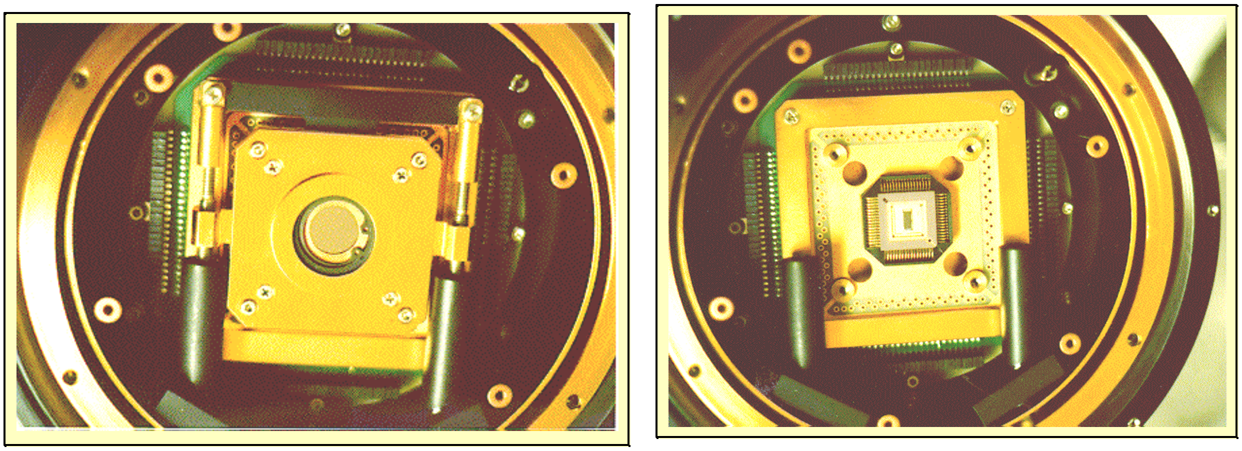


Figure 12. TIRIS-II system. HYWAYS FPA in sensor (right) and LVF holder with manipulator levers (left).

4. APPLICATIONS

Most molecules possess spectral features in the IR that can be used for their detection and identification. As mentioned at the beginning of this paper, one of TIRIS's applications is the detection of organic compound and plumes in the atmosphere. These may be related to pollutants, chemical warfare agents, drug manufacturing byproducts, volcanic plumes and much more. Some description of an algorithmic approach to signal processing is given in another paper presented in this SPIE conference.[12] In addition, IR imagery also has broad applications in land management use, target detection, the tracking of thermal plumes discharged into water bodies from cooling towers of power plants, etc. Some discussion of algorithmic techniques for classification can be found in ref. 13.

5. SUMMARY

This Paper outlined the status of the TIRIS system which is the first demonstration of the use of uncooled optics in a LWIR imaging spectrometer. TIRIS is currently undergoing laboratory characterization and calibration. In addition, laboratory measurements of gas detection are also underway. Finally the algorithmic basis is also under development.

Additional background and updates to this work can be found on the WWW.[14]

ACKNOWLEDGMENTS

The work in this paper has been performed under DARPA contract # DASG60-94-C-0088. The FPA was provided by the USAF Phillips Laboratories.

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14. Recent development and expanded coverage can be found on the WWW at http://www.techexpo.com/opto-knowledge.