Some Recent Advances and Applications of Infrared Detector Technology at the Jet Propulsion Laboratory

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ADSTRACT

The Jet Propulsion Laboratory (JPL) has a long history in the development and application of infrared detector technology for the exploration of our planetary system. We will describe some recent applications of IR detector technology at JPL for ground based astronomy, the Earth Observing System, the Cassini Mission to Saturn and the other proposed planetary missions. The infrared detector technologies to be discussed include single element, multiplexed linear and staring arrays, using a wide variety of infrared sensing materials including InSb, InGaAs, HgCdTe (PV & PC) and SiAs.

INTRODUCTION

This paper will present a historical and technical overview of infrared detector technology and their applications at the Jet Propulsion Laboratory over the past few years. The applications have been divided into three areas, ground based astronomy, earth observing and planetary exploration. The paper intentionally focuses on work performed at JPL. There are currently two active ground based astronomy projects utilizing infrared arrays at JPL. The earth observation applications both deal with multispectral imaging, one with a Fourier transform spectrometer and the other with a dispersive system. The planetary discussion will focus on the Cassini Mission to Saturn and the potential technology to be used in a future mission to the Pluto/Charon system.

GROUND BASED ASTRONOMY

PFIRCAM

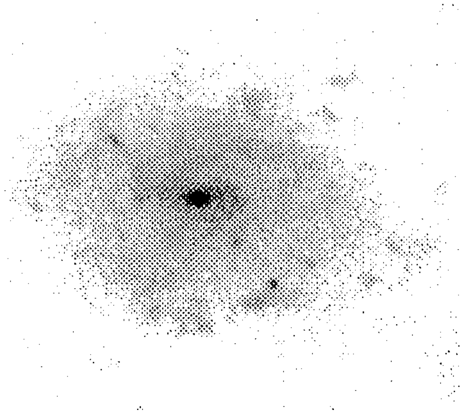
Before the advent of infrared array technology, infrared astronomers were restricted to looking at the universe with single detectors and arc second pinholes. At JPL, scientists and engineers developed their first model of the Prime Focus Infrared Camera in 1987. With its 128 X 128 array of HgCdTe detectors a field of 90''X9O" could be mapped in 100 msec. This early array, with a read noise of 1500 electrons rms, would later be replaced with a larger and quieter device. The Prime Focus InfraRed CAMera (PFIRCAM) is currently a facility instrument at the 5 m Hale Observatory. It helps to satisfy the observational needs of astronomers in the spectral range of 1 to 2.5 microns by utilizing a HgCdTe infrared detector array. The camera has a plate scale of 0,54 arches/pixel for an overall FOV of 138 x 138 arcseconds. One of the latest upgrades to the PFIRCAM has involved replacing the NICMOS2 128X128 pixel array with a NICMOS3 256X256 pixel array. The many advantages of using the NICMOS3 array include a larger FOV while at the same time allowing for an improved spatial resolution due to the smaller pixel size. Furthermore, various modifications to the detector design by the manufacturer have resulted in an overall better performing array, in particular lower read noise and improved cosmetic qualities. However, it was determined at JPL that the NICMOS3 device possesses an unstable reset level due to a charge injection mechanism associated with the reset FETs which was not present in the NICMOS2 device. Recent devices developed for the Pluto Fast Fly (PFF) By Mission and the HAWAII FPA, a 1024X1024 array, have been redesigned with the more stable reset architecture.

The focal plane array and camera optics are enclosed in a fairly large cylindrical dewar which mounts to the prime focus pedestal of the 200-inch Observatory. The data acquisition, transmission, timing, and bias electronics attach directly to the outside of the dewar as a single unit. The power supplies for these electronics also reside at the prime focus cage, but are housed in a separate unit which connects to the camera electronics via shielded cables. Image data is transmitted through a pair of coaxial cables to a high speed data receiver located near the controller PC. The receiver then transmits the data to a buffer/processor board located at the PC bus. At the telescope, the PC serves as a slave waiting for commands from the telescope computer from which observation runs are controlled. The telescope computer specifies the parameters for an observation sequence to the PC which then controls the camera through another board in its bus. Once a set of images are collected and coadded, the PC writes the resulting image to common storage, At this point other computer systems at the telescope are able to access the data.

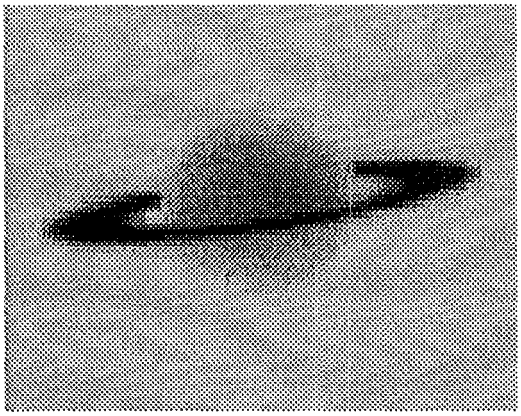
The near-infrared detector used in the camera is a NICMOS3 device developed by Rockwell International under a NASA-funded contract through the University of Arizona. It is a backside-illuminated 256 x 256-pixel hybrid focal plane array. The detector material is liquid phase epitaxy (LPE) HgCdTe grown on a sapphire substrate. The photodiode detector array is formed by ion implantation into the HgCdTe layer. The detector array is cold welded to a Silicon multiplexer readout through iridium columns. The readout is divided into four electrically isolated quadrants, each one consisting of a CMOS FET-switch array having its own output amplifier. The multiplexer unit cell architecture follows the principle of a source-follower-per-detector, which means that the detector photodiodes are connected directly to the gate of a switched source follower amplifier.

The NICMOS3 array and associated optics are housed in an Infrared Laboratories HD-8 cylindrical dewar which is approximate] y two feet tall and has a diameter of 9 inches. The dewar bolts directly to the prime focus pedestal of the 200 inch Telescope, looking down at the primary mirror. There are two optical subsystems within the dewar. Light first passes through a pair of CaF2 lenses that serve as a modified Ross corrector to remove residual coma from the image formed by the parabolic 200-inch primary mirror. Chromatic aberrations due to this lens pair are minimized because of the lenses' low magnification, Two filter wheels follow the Ross corrector, each containing eight filter positions. Each wheel has one open and one blank-off plate for dark current measurements. The thirteen remaining positions contain a number of broad- and narrow-band filters for the 1 to 2.5 m region, The broad-band photometric filters include J, H, and K (1.25, 1.65, and 2.2 m, respectively), while the narrow-band filters having 1% to 3% fractional bandwidths are centered on specific spectral lines including H2 (2.12 and 2.24 m), Brackett gamma (2.16 m), and FeII (1.64 m). After passing through this pair of filter wheels, the light enters an Offner relay, which re-images the image formed by the 200-inch primary mirror on a cold stop that rejects background radiation from the telescope. The primary of the Offner relay is Zerodin glass; the secondary of the Offner is a diamond-turned aluminum mirror with a slightly aspheric surface, A hole in the Offner secondary matches the hole in the 200-inch primary. Finally, the light is folded once and imaged onto the NICMOS3 array. The 256 x 256 pixel NICMOS3 array has 40 micron pixels that result in a plate scale of 0.54 arches/ pixel and a 138 x 138 arches field of view. Images at the center of the field are usually limited by the seeing at Palomar. There is some residual coma at the edges of the field.

The PFIRCAM has not only provided a wealth of data for astronomers at Palomar, but it has provided an indispensable test bed for short wavelength infrared (SWIR) arrays based on the NICMOS3 readout, InGaAs arrays hybridized to NICMOS3 readouts have been preliminally investigated using the camera's software and electronics. As well artifacts in the performance of the NICMOS3 readout have been observed and proposed corrections are under development for use in future JPL instruments, Below are two images acquired with PFIRCAM.



IRAS Faint Source

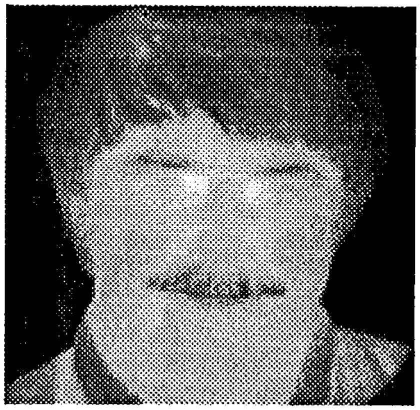


Saturn Br-Gamma

MIRLIN

The Mid-InfraRed Large-well Imager, or MIRLIN, is a stand alone camera system developed for mid-infrared (5-26 micron) ground base astronomy. The camera is housed in an Infrared Laboratories helium cooled dewar with a 10 inch work surface. The field of view of the system is 20 arcseconds at the Hale telescope or 0.15 arcseconds/pixel. At the NASA IRTF the FOV is calculated to be about 1 arcminute or 0.5 arcseconds/pixel. The camera is equipped with a set of filters to provide coverage from 5-26 microns. The set of filters includes M, N, Q, Q-short, Q-long, the 6-filter 10 micron silicate set, the 7-filter narrow-band 20 micron set and a 7-14 micron circular variable filter (CVF) with 1 % resolution. The optics of the camera have been designed to require a change only in the diameter of the cold stop for operation on either telescope. This change is accomplished with a mechanical slide. The nominal operating temperature for the infrared detector array is 7 Kelvin. The hold time for the dewar has been measured in excess of 24 hrs.

The camera and its actuators are controlled by a 486 PC equipped with a DSP board slaved to a SUN SPARC station. The waveforms for the array are generated from the DSP board and shipped to the main camera electronics for buffering and level shifting. The main electronics houses the array biases and 16 preamplifiers and ADCS with 14 bit resolution. The control system is completely autonomous which allows the system to move freely between telescopes. MIRLIN uses a 128X128 Si:As BIB array mated to a silicon readout based on a direct injection architecture. This application is particularly well suited for this architecture because of the large signal currents involved in this application. The full well of the device is in excess of 30 million electrons and expected integration times are on the order of a few milliseconds to a few thousand milliseconds. The read noise of the device has been measured in the laboratory to be 1100 electrons RMS. 'Ibis read noise implies that the system will be photo noise limited for a well depth of just 4% of the full well. The device is also shown to be linear to 1% up to 65% of the full well. Below is an image acquired by MIRLIN.



An Infrared Astronomer @ 7.8 microns

EARTH OBSERVING INSTRUMENTS

AVRIS/SISEX/HIRIS/SEIS

Solar reflectance imaging spectroscopy was pioneered at JPL with its first instrument in the field, the Airborne Visible Infrared Imaging Spectrometer (AVRIS). AVRIS is an imaging spectrometer developed at JPL for use in remote sensing studies across a broad spectrum of scientific disciplines, including botany, hydrology, oceanography and atmospheric science. The instrument and facilities were developed over the period of 1984 to 1987, and the instrument has enjoyed successful operation to date. JPL has pursued the development of earth orbiting imaging spectrometers since that time starting with SEIX and the High Resolution Imaging Spectrometer (HIRIS) up to the current design, the Small Earth Imaging Spectrometer (SEIS). The AVRIS spectrometer is built around a CE 256 X 1 InSb array multiplexed through a Reticon linear CMOS multiplexer. This array has sufficient performance to enable significant science return in an aircraft environment. The requirements of an earth orbiting push broom imaging spectrometer, like HIRIS, has led to the development of a new class of infrared detector readouts. The HIRIS readout developed at the Rockwell International Science Center meets or exceeds all the previous HIRIS requirements. This readout developed under a NASA funded project for the development of an infrared imaging spectrometer for an EOS platform will provide a read noise of 100 electrons rms at a data rate in excess of 8MHz.

The original, August 1986, HIRIS requirements were loosely based on the SISEX design. Later that year the Imaging Spectrometry Science Advisory Group defined the requirements for an EOS space platform borne imaging spectrometer, HIRIS. For example, it was determined that a spatial resolution of 30m or less was required to match the gap-phase disturbances in forest ecosystems, or to chartreuse environmental gradients such as nitrogen cycling, The requirement for spectral resolution at the time of this study was driven by geology in the 1 to 2.5 micron region for which 10 nm sampling is sufficient. Recent data from AVRIS has demonstrated that vegetation may also be characterized in this region with this sampling interval. Ground coverage requirements and orbit altitude required the HIRIS instrument and focal planes to have a high data rate of > 8 Mpixel per second. System design considerations and the current state of technology drove HIRIS to be a passively cooled instrument, leading to an attainable focal plane temperature of 130 Kelvin,

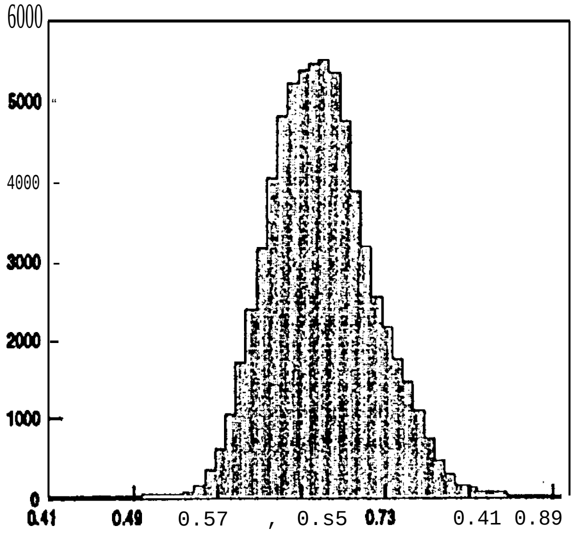
In order to meet these requirements, JPL embarked on an eight year development program with the Rockwell International Science Center (RISC), funded by the HIRIS project to develop infrared arrays for this EOS application. Initially the SISEX arrays, which used a direct injection architecture, were found to have poor frequency response at the HIRIS signal levels. A switch FET architecture based on the multiplexer from EG&G Reticon was found to have poor read noise performance and overstressed the short wavelength infrared detectors at these temperatures resulting in poor uniformity. Improvements in the switch FET approach or the source follower per detector approach as it is now called resulted in a RISC device with very low read noise. This NICMOS FPA, which is described in detail above was too slow and suffers from poor performance at elevated temperatures due to the reverse bias characteristics of the RISC PACE-1 HgCdTe detector material. By 1991 the NICMOS readout and its infrared detector array were becoming a mainstay of the SWIR imaging community. These detector interface schemes are not optimum for EOS imaging spectrometer applications which require high speed and low noise at low photon backgrounds.

A final detector development began in 1992 with the goal of proving a new readout design which could meet all of the HIRIS goals. The approach would be to develop a readout which would operate the PACE 1 SWIR detectors at very near zero reverse bias. The zero bias approach for optimization of detector performance had been understood for some time but the engineering of such readouts was difficult. In 1994 RISC delivered two HIRIS readouts based on the Capacitive Transimpedence Amplifier (CTIA). These devices exhibit breakthrough performance. All the program requirements of HIRIS were met.

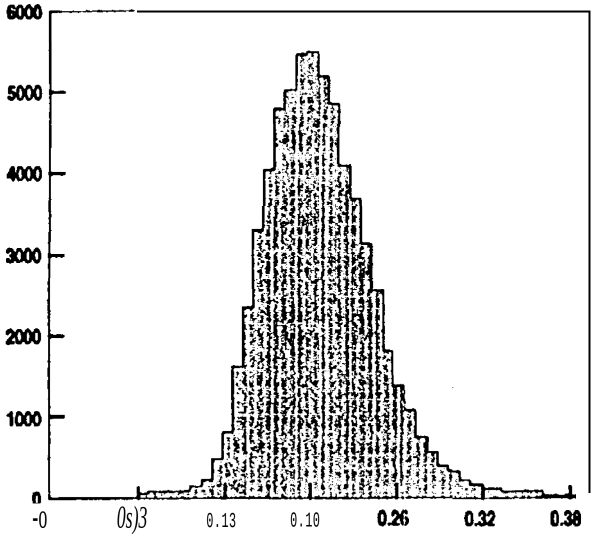
The HIRIS arrays are PACE-1 256X 256 arrays with CTIA based unit cells. A Rockwell pipelined switched-FET Architecture allows low power dissipation and reduced amplifier glow while simultaneously achieving a low noise and data rate>= 9MHz. Important readout characteristics are summarized in the table on the following page.

Format	256X256 pixels/ 40 micron pitch
Power Dissipation	Variable - <100mW nominal
Full Well	1.6E6 e-Low Gain/l e5e-High Gain
Nominal Read noise	100 e- rms
Data Rate	>8 MHz
Detector	PACE -1 HgCdTe

Data taken at RISC for the HIRIS array is shown below in the form of quantum efficiency (QE) and read noise histograms.



QE Histogram

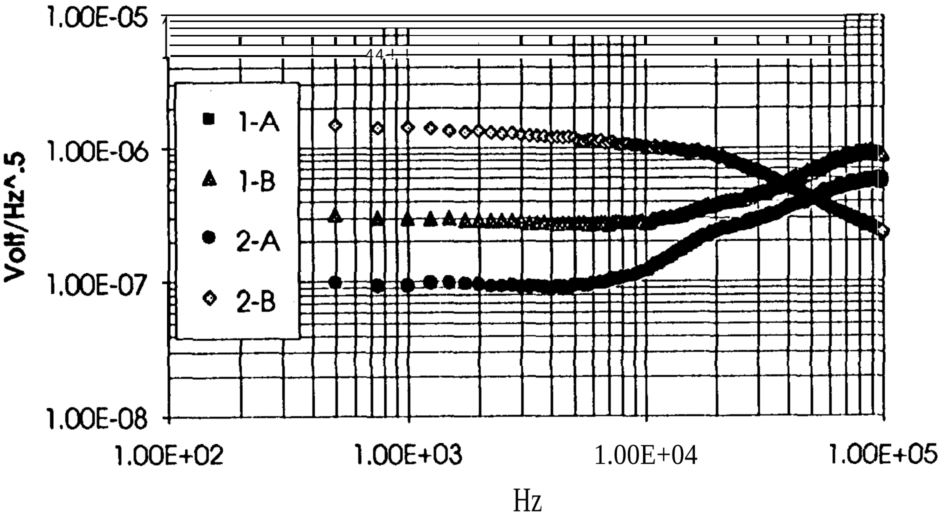


Read Noise Histogram [mV]

AES/TES

The Tropospheric Emission Spectrometer (TES) is a Fourier Transform spectrometer designed to study atmospheric chemistry. 'Consistent with the EOS mission objectives, the general goal of TES is to map the three dimensional distribution of gases important to tropospheric chemistry, tropospheric-biosphere interactions and tropospheric-stratospheric exchanges on a global, regional and local scale. The Airborne Emission Spectrometer (AES) instrument is an aircraft instrument and should be viewed in the same light as AVIRIS is to HIRIS. TES is currently selected to fly on the EOS Chemistry platform to be launched in 2002. The AES is currently being flown over various land and water areas for a number of customers. The interferometer has four detector assemblies which cover the 2,3 to 16.7 micron region. TES may image downward to provide geographically located spectra or image the limb to provide simultaneous spectra in 2.3 Km vertical slices. The detectors for TES are currently under study, but are baselined to be similar to the detectors for AES. AES covers the 2.3 to 16.7 micron band with four detector/dewar assemblies. All the detectors are operated at 65 Kelvin. The three optical bands from 2.3 to 11.5 microns each have a four 100 X 1000 micron HgCdTe PV detectors, the long wave band uses HgCdTe PC detectors in the same format. The basic configuration for each of the PV detector preamplifiers is a

Transimpedence amplifier (TIA) with a differential JFET pair, feedback resistor and capacitor. The plots below shows the dark noise spectra for each band. The noise performance, shown below, closely matches published models for detector coupled TIAs.



AES Detectors; 1-A(PV, 5.5 microns), 2-A(PV, 10.5 microns), 1-B(PV, 11.7 microns), 2-B(PC, 17 microns)

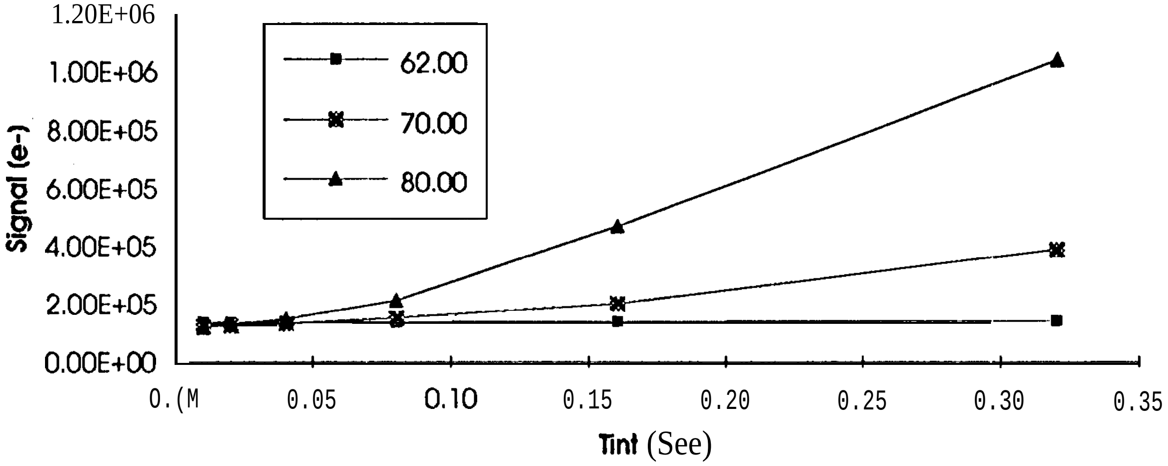
PLANETARY MISSION

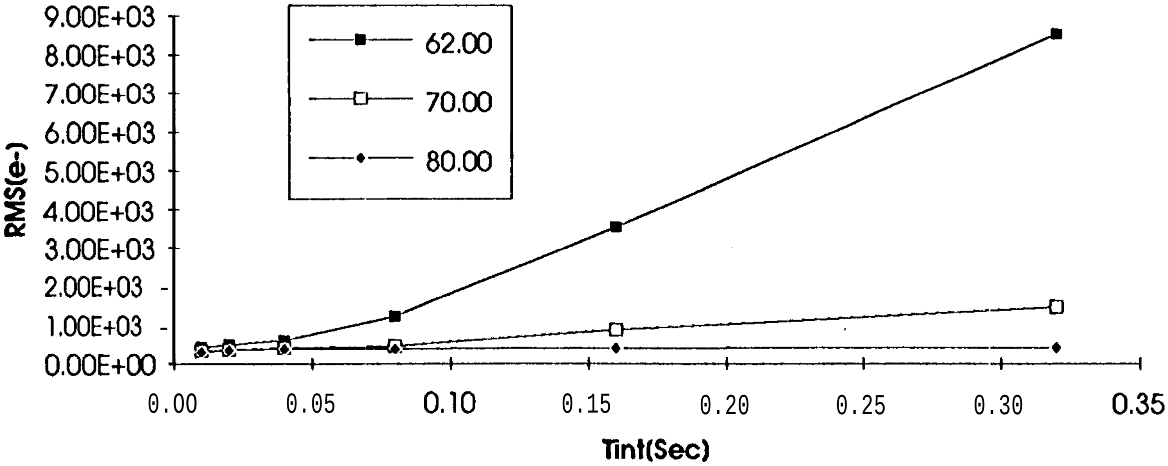
VIMS - Saturn

The Visible Infrared Mapping Spectrometer (VIMS) is scheduled to arrive at Saturn on the Cassini spacecraft in 2007. The VIMS will be the first CMOS multiplexed infrared detector array to visit another planet, The VIMS focal plane draws heavily from its predecessors, the AVIRS array and the Near Infrared Mapping Spectrometer NIMS detector assembly which is currently enroute to Jupiter and recently returned data from the Shoemaker/Levey comet impact. The primary infrared objectives for the VIMS are to determine the chemical and mineralogical composition of the dark material on the Saturnian moons Lapetus, Hyperion, and Phoebe, the distribution of volatile NH3, CH4 and CO, the composition and structure of Saturn's ring system, its clouds and atmosphere.

The infrared channel subsystem of VIMS includes the telescope and fore optics, the spectrometer and the infrared detector assembly. The telescope is a diffraction limited system at f/3.5. It is a Ritchey-Chretien Cassagain configuration with a 22 cm aperture. A scanning secondary provides imaging over a 32 mrad FOV. Light from the telescope enters the spectrometer slit and is collimated and spectrally dispersed over the 256 pixels of the linear detector array with integral order sorting filters (OSF). The OSF includes three broad band pass filters and one linear variable filter (LVF) segment, The focal plane is built by Cincinnati Electronics Corporation under contract to the Jet Propulsion Laboratory. The detector array is a 1X256 element array of 103 X 200 micron, InSb photodiodes on a 123 micron pitch. The detectors are iridium bump bonded to a ceramic fanout board with bias resistors and bypass capacitors. The photodiodes are stitch bonded to a CMOS readout fabricated in Honeywell Inc.'s RICMOS process. The readout unit cell is based on a differential cascode amplifier with a modified CDS processor. The focal plane is housed in a Kovar base with a Kovar lid which is laser welded in a helium purged atmosphere.

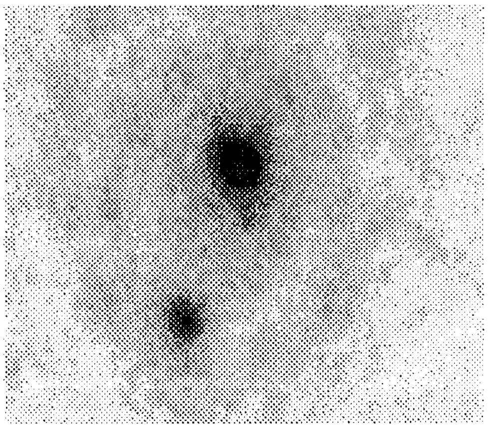
The detector assembly has been thoroughly tested at JPL with good results. The focal plane and filters perform as required to meet the instrument's projected S/N performance, although markedly better noise performance is obtained at operating temperatures below 67 Kelvin, due to excess noise in the photodiode dark currents. The first of three detectors to be delivered to JPL has been fully tested. The array noise and dark current for 62, 70 and 80 Kelvin are presented in the following charts.

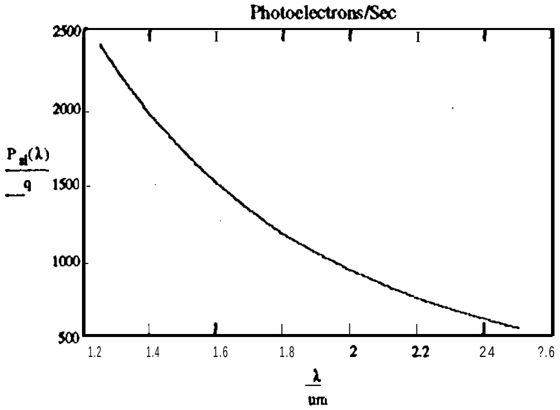




]PICS - Pluto

The Pluto/Charon system is the only known planetary system in our solar system yet to be visited by an Earth probe. A NASA sponsored Pluto Mission Development was begun in 1993, which envisioned a 1998 launch to Pluto. The Pluto Fast Flyby mission objectives as specified in the NASA RA require an infrared spectrometer. JPL has met the challenge of designing a lightweight, low power imaging spectrometer which will meet the demands of the PFF Mission. At the heart of the instrument is an SWIR detector array made by RISC and funded by NASA/JPL through Code C. The challenge of spectral imaging at Pluto is primarily driven by signal. At 30 to 40 solar distances, Pluto is a very faint broad band image and an even fainter multispectral image.


HST Image of Pluto/Charon



Signal Photoelectrons/ Sec at Pluto

For these low signal levels an infrared array with very low read noise levels is required.
The current NRA for the Pluto Fast Fly By Mission carries as its baseline detector the Rockwell NICMOS3 IRFPA. The primary forcing function for this choice is that this array is currently the only commercially available .8 to 2.5 micron, low noise (30 e- rms), area array. A close examination of this array leads to the conclusion that it is not ideally suited for the Pluto mission. Additionally, these nonidealities include the array's noise performance, its reset anomaly, its radiation susceptibility, and its useful optical band pass.

Radiometric analysis of the PFF Mission currently demonstrates that the NICMOS3 array will be significantly read noise limited at all but the shortest wavelengths for reasonable integration times (5 -30 WC). In order to obtain the shot noise limit, an array with 15 electrons is more desirable and would provide a S/N ratio of 100 at all wavelength with a 20 second integration. Currently proposed modifications of the NICMOS3 device could attain these performance levels. This modification could also eliminate the reset anomaly which renders the low noise triple sampling mode of the NICMOS3 IRFPA unusable and at the same time lower the read noise, This reset anomaly also reduces the effective full well of the device by 30-40 ‘%.

The predicted total dose environment for the IRFPA has been determined. The predicted levels of exposure may render the currently available version of the NICMOS3 IRFPA inoperable. This effect is solely a result of the process used to fabricate the current NICMOS3 CMOS multiplexer. The readout chosen for the PFF must be fabricated in a radiation tolerant (to the level of the predicted dose) process, The infrared sensitive material used on the NICMOS3 IRFPA is PACE-1 HgCdTe. The currently available devices are fabricated with a Hg/Cd mix providing a 2.45 to 2,54 micron cut-off wavelength, The shape of the response curve is very steep at the cut-off half power point. Given considerations of likely response nonuniformities, which have not been measured, the current NICMOS3 IRFPA would not be suitable for science at 2.5 microns. If the PFF JR Spectrometer is to operate over the .2 to 2.6 micron decade, a HgCdTe array tuned to a 2.7 micron cut-off will be required.

ACKNOWLEDGMENTS

We have reviewed three focus areas of infrared technology development at JPL over the past few years, and have presented some historical insight leading to the recent development of infrared array technology, Not all areas of development have been mentioned, most notably excluded are the space-based astronomy applications. The author would like to thank all those who have laid the foundation for infrared development at JPL and M. Ressler for his contribution of the MIRLIN camera.

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