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Pluto integrated camera spectrometer (PICS) instrument

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ABSTRACT

We describe an integrated instrument that will perform the functions of three optical instruments required by a Pluto Fast Flyby mission: a near-lR spectrometer (256 spectral channels, 1300-2600 nm), a two-channel imaging camera (300-500 nm, 500-1000 nm), and a UV spectrometer (160 spectral channels, 70-150 nm). A separate port, aligned in a direction compatible with radio occultation experiments, is provided for measurement of a UV solar occultation and for spectral radiance calibration of the IR and visible subsystems. Our integrated approach minimizes mass and power use, and promotes the adoption of integrated observational sequences and power management to ensure compatible duty cycles for data acquisition, compression, and storage. From flight mission experience, we believe the integrated approach will yield substantial cost savings in design, integration, and sequence planning. The integrated payload inherently provides a cohesive mission data set, optimized for correlative analysis. A breadboard version of the instrument is currently being built and is expected to be fully functional be late summer.

OVERVIEW

Pluto is the only known planet in our Solar System that still awaits close reconnaissance and exploration. Observations possible from Eiarth-based platforms can provide only quite limited knowledge about the planet's composition, surface morphology, and geology and that of its only known satellite, Charon, discovered in 1978. The planet's great distance (30-50 AU), together with realistic budgetary and technological constraints, preclude the use of any but the smallest reconnaissance spacecraft with currently available launch vehicles and propulsion techniques. A NASA-sponsored Pluto Mission Development study was initiated in 1993, under which one of two envisioned cost-constrained missions, Pluto Fast Flyby (PFF), will utilize an 83 kg (dry mass) spacecraft to be launched in 1998 on an approximately 7-year cruise to Pluto[1]. The instrument described in the present article was conceived in response to a NASA Research Announcement[2] inviting innovative approaches to meet the scientific objectives of the PFF mission.

The mission science requirements call for an instrument incorporating two spectrometers, one working in the far UV, and one in the infrared, plus at least two visible-light cameras. The instrument must weigh less than 7 kg and consume less than 6 watts.

No previously existing instrument met these constraints or even came close. Our approach from the outset was to maximize the commonality between the different channels of the instrument. Thus, all channels from IR to

UV use the same primary mirror element, the heaviest mirror in the system. For detectors that require cooling, the radiator and the detector assembly form an integrated mechanical subassembly. The optical bench, the radiator, and the electronics are so designed that the various critical components will all run at their optimum temperatures. Necessarily the instrument and the materials composing it must be tolerant, over a long term, of wide ranges in the temperature of the spacecraft's environment, from around 280K on Earth, to 40-60K at Pluto. We sought to use materials that are highly dimensionally stable, chemically non-reactive, and having good structural capabilities and manufacturability. Moreover, we sought to avoid the need for a focus mechanism. The result of that set of constraints was the decision to make the entire instrument, optical and structural, of silicon carbide (SiC). Once that decision was made, there was a considerable effort invested in selecting industrial teaming partners for the effort, and the best way to design the instrument to take advantage of the strengths of SiC and avoid its weaknesses.

The 10-cm aperture size of the PICS optics is dictated by the need for a signal to noise ratio of better than 100:1 at Pluto. The range of each of the spectrometers in PICS is one octave exactly, a scientifically acceptable limitation that avoids the use of order sorting filters and simplifies the optical design, The UV system of PICS is configured to look through the atmosphere of Pluto at the Sun so that the absorption spectrum of Pluto's atmosphere can be obtained after the encounter. The electronics, all either hybrid packaged or using field programmable gate arrays, consist of six integrated circuits that can be mounted on a printed circuit board. The PICS electronics noise performance is background limited, consistent with the performance attained on such instruments as Wide Field and Planetary Camera for the Hubble Space Telescope.

An issue that was considered very early in the design of PICS was the need for an integrated science data gathering timeline in which the UV and IR spectrometers and visible-light cameras can be used in a complementary fashion, to accumulate data as the spacecraft approaches and then passes Pluto and Charon over an interval. of about 12 hours. By designing not only an integrated instrument, but also an integrated timeline, it was possible to avoid most of the sequencing difficulties and issues that had been problematical on earlier planetary missions, such as Voyager, Galileo, and Cassini. This should have a major impact in allowing the use of pre-programmed sequences and allowing a major reduction in mission operations costs.

It is suggested that all of the data be stored on a 2-gigabit solid state recorder, which can then be played back to Earth after the encounter. The scenario is basically to approach the planet, perform the encounter, and during that time take all the information and output it into the solid state recorder, so that the sequence is not constrained by any bit rate limits on the down link. The data then can be down linked to Earth in the most efficient manner at that point as determined by the PFF project.

PICS OPTICAL SYSTEM

The PICS optical design consists of a two-color camera, an infrared imaging spectrometer, and an extreme ultraviolet imaging spectrometer. These systems share a single off-axis Gregorian telescope as shown in Figure 1. The two camera systems occupy the same field position, to which the spectrometer fields are adjacent. The optical system parameters are given in the accompanying Table 1.

Telescope System

The primary and secondary mirrors for the telescope are off-axis sections of rotationally symmetric aspheres, to enable fabrication by diamond turning with post-polishing. Light from the primary mirror is focused directly onto the entrance slit of the UV spectrometer. A fold mirror reflects the fields for the camera and infrared spectrometer to the aluminum-coated concave secondary mirror. An advantage of the off-axis telescope design is that it provides better image contrast than on-axis designs, in which obscuring secondary mirror diffracts light into the outer rings of the Airy pattern.

Camera System

The light from the telescope secondary is folded across the telescope to the focal plane assembly, where two CCDs are located. There a dichroic beamsplitter cube splits the light to the two focal planes. Two field flattening lenses in front of the CCD focal planes correct the telescope's field curvature. Raytrace results show that diffraction-limited performance is achieved over both CCD fields of view with this design.

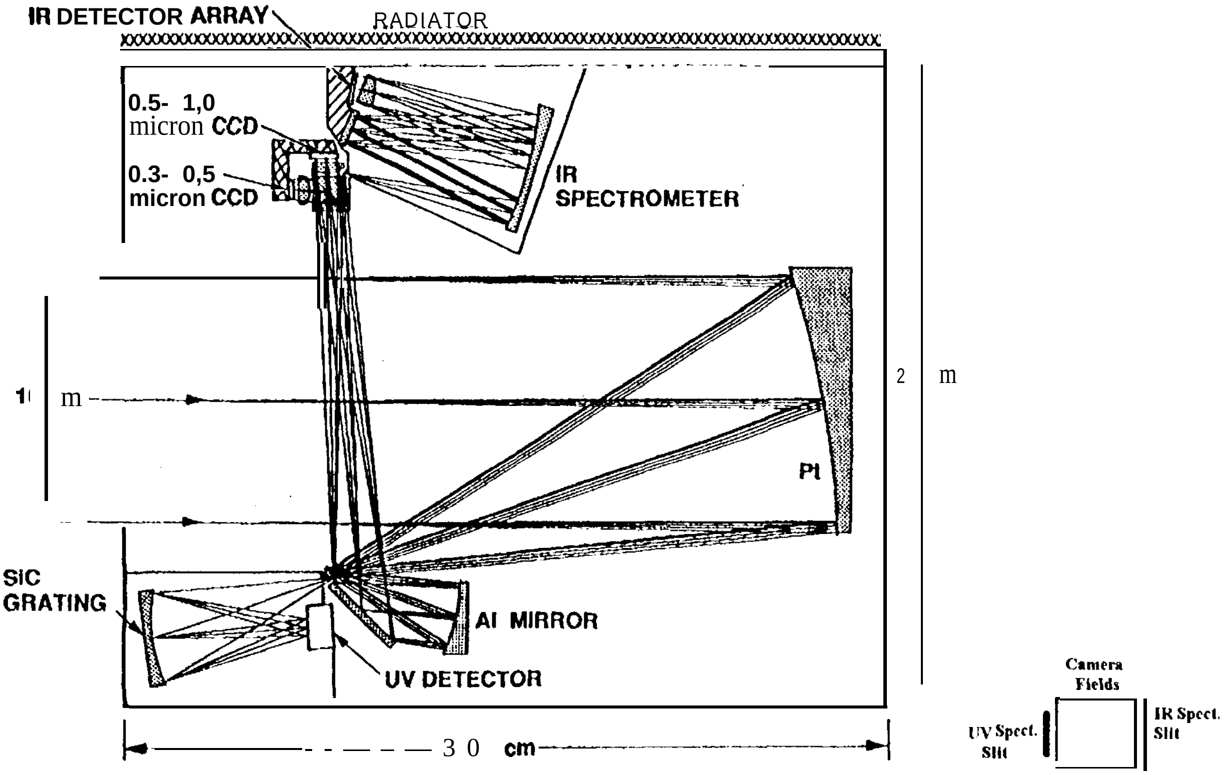

Fig 1. PICS optical system layout. Inset at right shows FOV configuration.

Infrared Imaging Spectrometer

The infrared imaging spectrometer slit is off-axis with respect to the CCD fields, as indicated in Figure 1. This enables the light for the infrared imaging spectrometer to be split off after the dichroic cube by a small mirror (a small aluminized prism bonded to the cube).

A significant challenge in the spectrometer design was to make it compact enough to be cooled as part of the cold focal plane assembly, thus contributing low thermal background. This is difficult to do because it requires a short focal length system providing good image quality over the 256 by 256 infrared detector array. The design developed is related to the Czerny Turner family[3], and has an overall length of 7 cm. The major aberration of this type of design for short focal length systems is the extreme field curvature, which is different in the spatial and spectral directions. This was compensated by an off-axis segment of a spherical field-flattening lens. The spectrometer contains a plane grating with 110 grooves/mm. Raytrace results show that the spot sizes are less than 20 microns over the focal plane, thus giving good performance with 40 micron pixels.

Ultraviolet Imaging Spectrometer

The need for sufficient system transmittance in the far ultraviolet spectrometer was the major driver in developing its design configuration. Reasonable transmittance was achieved by sharing only one reflection with the other systems, namely the telescope primary mirror, which is platinum-coated to provide far ultraviolet reflectance. The grating in the ultraviolet spectrometer is silicon carbide coated to provide good reflectance.

The entrance slit for the ultraviolet imaging spectrometer is located at the telescope's primary mirror focus. Its field position is off-axis with respect to the visible camera's field of view. The spectrometer consists of a toroidal grating (1400 grooves/mm) which focuses the light onto the microchannel detector. The microchannel plate has a 7 cm radius of curvature. Raytrace results show spot sizes slightly less than the detector size (nominally 0.1 mm) over the focal plane.

Table 1
PICS Payload Performance Requirements

	Uv	Vis(Blue)	Vis(Red)	IR
Wavelength Range	70-15011111	300-500 nm	500-1000 nm	1300-2600 nm
Aperture diameter	10 cm	10 cm	10 cm	10 cm
Effective Focal Length	20.0 cm	75.0 cm	75.0 cm	75.0 cm
F/#	2.1	7.5	7.5	7.5
Detector Array Size	10X80	1024 x 1024	1024 x 1024	256 x 256
Pixel Size (mm)	100	9.0	9.0	40
FOV(deg)	0.34	0.6 x 0.6	0.6 x 0.6	0.78
IFOV (mrad)	500	10	10	53.3
Plate Scale (mrad/mm)	5	1.33	1.33	1.33
Spectral Resolution	1.0 nm			10 nm
Sampling Interval	0.5 nm			5 nm
SNR	Photon Noise limited	Photon Noise Limited	Photon Noise Limited	Photon Noise Limited
Typical Exposure Time	30-3000s airglow 0.1 s solar occult.	$\geq$ 1 sec	$\geq$1 sec	$\geq$3 secs

PICS STRUCTURAL CONFIGURATION

The structural configuration of' PICS, developed in collaboration with SSG of Waltham, Massachusetts, is shown in Figure 2, The instrument consists of a single telescope and an electronics chassis. The telescope has a triangular shaped tubular optical bench housing three highly integrated optical systems: a UV imaging spectrometer, a two-color CCD camera, and a near-IR imaging spectrometer. The triangular shaped tubular construction offers a leverage in achieving a lighter and stiffer optical bench, in which the off-axis telescope optics and detectors can be conveniently integrated and aligned externally except for the primary mirror and Sun-port pickoff mirror.

While all the optical elements and detectors of the UV spectrometer and visible camera are mounted directly on the 150K telescope optical bench, the 90K IR spectrometer is packaged in a stand-alone subassembly (the IR bench). The IR bench is mounted to the telescope via three pre-stressed fiberglass band supports providing thermal isolation. The fiberglass supports are arranged in such a way that the IR spectrometer's entrance slit is athermalized relative to the telescope optical bench.

One of the innovative features of the PICS telescope design is the use of monolithic material, SiC, for both the structural and the optical elements. SiC is an emerging technology for future instrument design since it offers (1) high specific stiffness allowing for thinner and lighter design, (2) the optical performance of glass, but with a much higher strength and fracture toughness, (3) a good thermal stability at cryogenic temperatures, and (4) dimensional stability over the life of the mission,

The entire telescope assembly is mounted onto a warm (approximately 300K) electronics chassis kinematically via three Vespel bipeds for thermal isolation. The electronics chassis directly under the telescope optical bench provides the detector electronics the shortest possible wire length. The electronics chassis serves as a transition structure to the spacecraft mounting surface. Vibration and shock isolation will be achieved with commercial mounts using silicone elastomer.

INTEGRATED RADIATOR/DETECTOR MOUNTING

The severe mission constraints of power, mass, and cost impose new technologies for a successful mission. The requirement of $\leq$90K detectors on the IR scanner dictates use of a cooling device since the rest of the spacecraft most likely will be held slightly below Earth ambient temperature (0°C). A multistage radiative cooler best fits the mission environment for PICS assuming that the detector power dissipation is reasonable (10 milliwatts or less).

To best fit within the mission constraints, the radiator is integrated into the instrument design and not a separate additional component as has often been done in the past. The IR detector radiating surface is an outward facing component of the instrument enclosure. The optical design is configured in such a way that the IR detector mounts directly onto the inner surface of the radiator. The support structure for the detector/radiator subassembly is part of the optical bench and provides the necessary thermal isolation. The configuration is such that the detector can be made easily accessible for ground testing and possible last minute detector replacement.

The IR radiator must be uniquely oriented with respect to the spacecraft to eliminate radiative energy in puts from the dominant heat sources -- the spacecraft and Sun. A shade will be necessary to prevent the radiator field of view from containing warm parts of the spacecraft. In consideration of the mass constraint, a compromise must be made between detector temperature and shade mass.

The instrument is capable of being radiatively and conductively isolated from the spacecraft to the greatest extent possible. The instrument is designed to be attached to the spacecraft with a fiberglass structure to minimize the conductive heat leak while meeting the mechanical integrity requirements. The instrument should be positioned on the spacecraft so as to prevent the IR radiator from viewing any warm portion of the spacecraft. A shade attached to the instrument could prevent heat from the relatively warmer antenna dish from impinging on the detector radiator. All non-radiating surfaces will be covered with multilayer insulation (MLI) to minimize the radiative heat transfer.

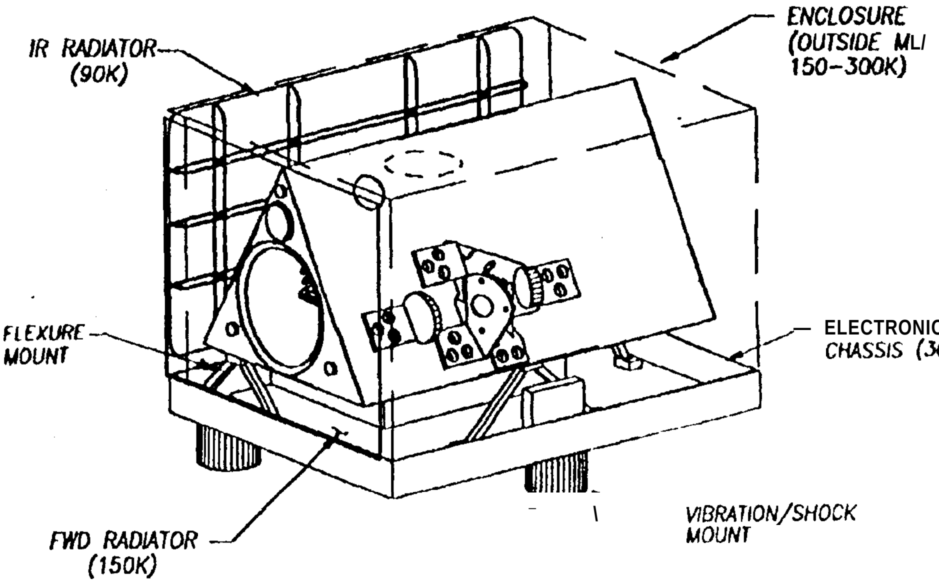

Fig. 2. PICS structural configuration.

The instrument is divided into three temperature zones to accommodate the required component temperatures.

Optics Temperature Zone

The optics will be maintained at about 150K to minimize the heat radiated from the optical elements to the IR detector and to provide a relatively cool background for the IR detector radiator. Along with the optical elements and CCDs, this temperature zone includes the optical bench structure. Since there is little or no heat dissipation in this zone, the temperature will be maintained by a balance between the heat leakage from the warmer electronics zone and the heat radiated from the surface of the instrument facing Pluto (optical port side).

Electronics Temperature Zone

The electronics will be maintained at 230K to 270K, A mechanical extension of this zone is located near the CCD detectors, allowing mounting of the preamplifiers close to the detectors to minimize noise. The electronics will be mounted on a plate located between the optical bench and the spacecraft. This plate will be thermally attached to the warm electronics radiator which, in turn, is coplanar with the optical opening and shares its field of view, Since the structure and the majority of the box is included in the optics temperature zone, this electronics and the plate onto which it is mounted will be radiatively and conductive isolated from the structure which is at the optics zone temperature. The temperature of the electronics zone will be held as low as possible within the electronics component limits, to minimize heat leakage into the other temperature zones, as well as to minimize the long term outgassing products that could condense onto the colder optics and detectors, and to minimize the power needed for temperature control.

Detector Temperature Zone

The IR detector subassembly will be maintained at a temperature of ≤90K by directly mounting to the IR radiator plate; the entire plate will be mounted to the optics subassembly with a fiberglass band support system to minimize heat conduction. The attachment of the cold IR detector/radiator subassembly to the 170K optical bench subassembly forms a two-stage radiative cooler for cooling the IR detector. The fiberglass band support system not only provides conductive thermal isolation, but is designed to maintain its relative position with respect to the optics over the complete temperature range.

ELECTRONICS

Electronics for the Pluto visual, UV, and IR imaging subsystem draw heavily upon JPL's experience gained during the design of WFPC-I and WFPC-II, Galileo SS1, SXT, and the Cassini 1SS, However, state-of-art electronics packaging such as hybrids and gate arrays are employed to minimize mass and size. CMOS gate arrays and the judicious selection of analog components will optimize the power requirements.

Three electronic modules provide the control, timing, and signal processing required by the imaging subsystem. The instrument Control and Input/Output (ICIO) module have been implemented in a CMOS gate array. Detector timing, integration control, detector readout, command and data interfaces are implemented within the ICIO functional block. CCD drive level translation, bias, and preamplification are provided by the Clock Drive (CD) hybrid. Three CD modules are required, one for each CCD detector in the two visible channels and the UV channel. Clock buffering and pre-amplification for the IR array is provided by a discrete subset of the CD electronics. Output signals from the detectors are multiplexed to the Signal Chain (SC) hybrid. The SC module provides all required gain, clamping, and sampling prior to converting the detector video output signal to digital data. In addition to the signal conditioning circuitry, this module contain the 8-bit low power analog-to-digital converter.

To assure mission success, redundancy is designed into the flight imaging subsystem electronics. Power will be provided by a dual bus system. The focal plane instruments (CCD and HgCdTe) will be partitioned such that in the event of a power failure, at least two of the instruments will survive. A standby (powered-down) SC and ICIO are incorporated to provide a backup capability for the instrument. If a failure occurs in the signal processing or control this backup circuitry will be turned on and multiplexed into the data path. With the backup circuitry in operation the instrument performance will not be compromised,

In order to meet science goals, detector pixels will be processed at a 300 KHz rate. It is estimated that the electronics for the instruments will require 4 watts at the 300 KHz processing rate. This power estimate does not include power supply loss factors or the power for the high voltage required by the UV microchannel plate.

PICS INFRARED FOCAL PLANE

Mission Requirements

The science requirements for the infrared imaging spectrometer channel of the PICS instrument, and the strict limits on instrument mass and size, impose several difficult demands on the 1 R focal plane. These demands include:

- *capability for SNR > 100 in all spectral channels.* The extremely low levels of reflected sunlight at the Pluto system, along with the small telescope aperture, demand a focal plane with high quantum efficiency and low read noise. Any decrease in focal plane performance will require longer integration times, leading to higher S/C stability requirements, or a reduction in the SNR.

- *high spatial and spectral resolution.* The need for 10 mn resolution at wavelengths from 1.3 to 2.6 mm, as well as -4 km ground spatial resolution at closest approach, coupled with the pushbroom design chosen for the imaging spectrometer, demand at least a 256x256 staring IR focal plane. A pixel pitch between 30 and 40 microns is required to match the IR spectrometer field of view with the visible camera's FOV.

- *radiation hardness.* The major source of radiation is not from the sun or trapped radiation belts, but from the spacecraft's phrtonium-powered RTG power units. The small spacecraft size dots not allow the RTG to be suspended away from the spacecraft on a boom (as in Voyager, Galileo, and Cassini). Hardening of the Silicon CMOS focal plane readout is necessary to help avoid degradation in performance. Current estimates are that the focal plane array will be subjected to 20 krads, mostly in the form of neutrons, on the journey to Pluto. To help alleviate radiation damage, the instrument can be warmed up to anneal out trapped charges. The option of adding shielding requires additional mass; the PICS design calls for the focal plane to be as robust as possible without incurring mass penalties.

- *relatively high operating temperature.* The small mass and volume envelope that PICS must fit into eliminates active coolers; small passive radiators must supply the cooling needed by the focal plane. The PICS integrated cooler is designed to provide 10 W cooling power at 90K, the lowest temperature practical within the spacecraft constraints. To allow the IR focal plane array to have low dark current at these temperatures, the cutoff wavelength of the photo diode array must be matched to the longest wavelength of interest (2.5 pm).

. *strong heritage to proven IR focal plane arrays.* If no existing focal plane could meet all these requirements, a design goal was to base the PICS IR focal plane array on an existing design and make as few modifications as necessary to fulfill the instrument objectives.

Table 2
Comparison of **NICMOS-3** and **anticipated PICNIC readouts**

	NICMOS-3	PICS
Format	256x256, 40 µm pitch	same
cutoff wavelength	2.5 pm	same
quantum efficiency	60% (1-2.5 µm	same
read noise (after CDS)	-30 electrons	<15 electrons

Focal plane architecture

The PICS focal plane readout represents an evolutionary advancement on the very successful Near Infrared Camera and Multi -Object Spectrograph (NICMOS-3) readout developed by the Rockwell Science Center, Thousand Oaks, Ca. This focal plane was created for the NICMOS instrument[4], a Hubble Space Telescope second generation replacement package. NICMOS-3 focal planes[5], with 2.5 mm cutoff MCT diodes, have been utilized for several years now in ground-based astronomical cameras at the world's leading observatories. This experience, along with continued developments at Rockwell, provided a solid base for creation of a focal plane design to meet the stringent PICS goals. Table *6* lists the current NICMOS-3 specifications and performance, as well as the anticipated performance of the PICNIC readout.

The PICS readout is based on silicon CMOS circuitry. The PICNIC die, unlike the NICMOS-3 readout, is being fabricated at a foundry with a radiation hard CMOS process, and the unit cell has been designed with radiation hardness features. The 20 krad specification imposed by the spacecraft will be met easily by the chosen CMOS process. The current mission scenario allows the focal plane to bc 'warm' (~300K) during most of the voyage, except for checkout periods. This warming anneals out radiation damage duc to ionizing particles, without degrading the performance of the focal plane array, Since the instrument will only be cold during the final phase of the journey, the PICS team anticipates very little degradation duc to ionizing radiation.

To meet the high detectivity demanded for reaching SNR >100 with the small optical system, a very low read noise is desired, The NI CMOS-3 already achieves low read noise (-30 electrons, input referred) but can be improved. Also, onc annoying aspect of the NICMOS-3, referred as the 'reset anomaly', will be eliminated. The reset anomaly involves the instability of the output level immediately after the reset pulse is removed; several non-destructive reads of the focal plane, without data collection, arc required at the beginning of the integration, and correlated double sampling (CDS) is necessary to reach the low read noises reported. The cause for this behavior is known, and the PICS unit cell, with onc transistor removed from the NICMOS design, is designed to be free of this anomaly. The change benefits the focal plane in several ways: a lower read noise (modeled to bc 10-15 electrons after CDS), greater operating efficiency (no dead time on useless reads), and the option of reading the array uncorrelated (estimated noise -100 electrons), for situations when long integrations will permit" high SNR without CDS, permitting a reduction of two in the data storage requirements. The dic yield may also be enhanced by the simpler unit cell architecture. A secondary benefit of lower read noise on the focal plane is the loosening of pointing and stability demands on the spacecraft.

The PICS focal plane will fulfill all of the requirements demanded by the infrared imaging spectrometer, the Pluto spacecraft, and the mission. It represents a good match between utilizing existing 'off-the-shelf' technology and incorporating experience, ncw ideas, evolutionary progress, and mission specific features that reduce risk to the instrument and the spacecraft, while providing the highest science content possible. It can be expected that the imaging spect rometer of PICS represents a ncw class of instrument that will bc adaptable to a wide range of outer planet and asteroid exploration.

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