INFRARED FOCAL PLANE ARRAYS FOR PLANETARY SPACE MISSIONS: A PROSPECTUS*

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ABSTRACT

A representative set of requirements for infrared detector arrays suitable for future remote sensing missions to the outer planets is developed. Using the Galileo (Jupiter) mission as a starting point, objectives and constraints applicable to a Saturn - Titan dual probe mission are stated. An advanced mapping spectrometer utilizing 128 × 128 element infrared detector arrays is described. By using detector arrays in preference to discrete photodiodes, the instrument is capable of higher spatial resolution; yet the detectivity requirement is reduced by a factor of four relative to the comparable Galileo instrument.

INTRODUCTION

More than a dozen future planetary missions are under current study within NASA, from solar probes to Neptune probes, including an assortment of comet and asteroid missions and orbiters about several outer planet satellites. Most of these missions afford the opportunity to perform significant infrared investigations. To assess whether significant technological advances will be required to develop satisfactory instrumentation for these missions, informed judgments regarding the experimental goals have been made. By considering reasonable spacecraft-imposed constraints on the instruments, this analysis is extended to develop the performance requirements for the detector.

To develop a prototypical instrument concept in which to evaluate detector performance requirements, the Saturn Orbiter Dual Probe Mission[1] was chosen. This 1987 mission consists of a Saturn orbiter and two entry probes released from the orbiter targeted at Saturn and its largest satellite, Titan. This mission choice results in severe sensitivity requirements for an infrared instrument because of the great distance between Saturn and the sun. Having developed an instrument concept for this mission, the focal plane array requirements are derived and compared to those of the Near Infrared Mapping Spectrometer currently under development.

It is recognized that other types of infrared experiments may be proposed for these missions and their requirements may be significantly different. The purpose of this work is to establish a reasonable set of order-of-magnitude development goals based on an experiment concept that has demonstrable scientific merit. It should follow that the requirements pertaining to related instrument types can be extracted from the work by analogy.

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PROTOTYPE INSTRUMENT CONCEPT

The Advanced Mapping Spectrometer (AMS) developed for this study is an extension of the concept embodied in the Near Infrared Mapping Spectrometer (NIMS) currently being built for the Galileo mission to Jupiter. Spectral mapping is understood to mean the simultaneous acquisition of spatially and spectrally resolved data as indicated schematically in fig. 1. Infrared area arrays suitable for use in the Near Infrared Mapping Spectrometer were not sufficiently advanced to meet the performance requirements and to be qualified for spaceflight in time for the January 1982 launch. A simpler focal plane covering the spectral range 0.6 to 5.2 μm, consisting of fifteen indium antimonide photodiodes and two silicon photodiodes was designed.[2] For the AMS, first order considerations suggest that filling the focal plane by means of detector arrays would provide a more efficient instrument; that is, virtually all of the energy reaching the focal plane would be collected, resulting in an improvement in signal-to-noise ratio which scales with the square root of the number of detector elements.

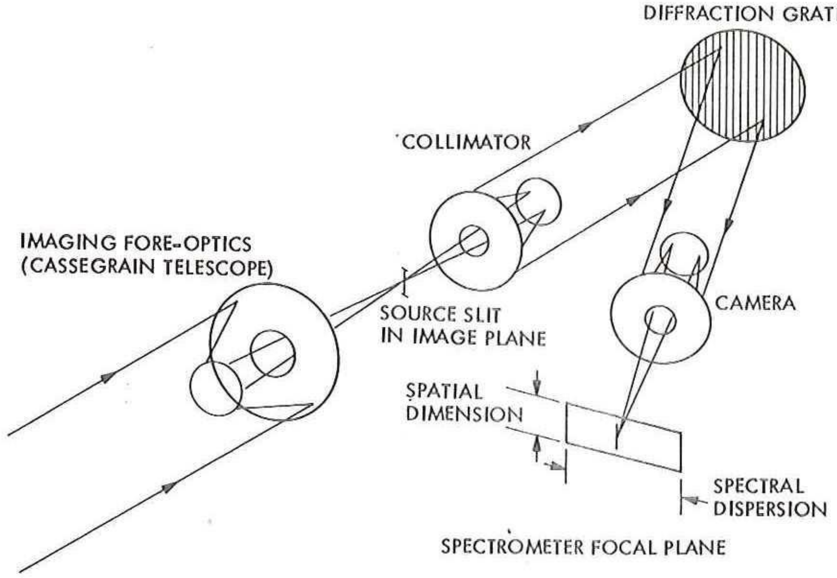

Figure 1. Optical Arrangement for Spectral Mapping

The experiment objectives for multispectral imaging missions to the outer planets have been discussed elsewhere.[3,4] For a study of the dynamics of dense planetary atmospheres, a resolution approaching the atmospheric scale height is required. For Saturn, an instantaneous field of view per picture element of 10 km is implied. Geochemical mapping of satellite surfaces at resolutions of 5 - 10 km could satisfactorily distinguish major province boundaries; however, resolution of a few hundred meters would be required to characterize a Titan landing site. Laboratory measurements and spectral observations indicate that a spectral resolution of 0.03 μm will suffice for outer planet missions. Astronomical observations provide less help in selecting the spectral range. Laboratory data indicates diagnostic absorption features for both minerals and gases extending to beyond 15 μm.[5,6] The choice of spectral range is left open in this study.

The constraints imposed by the spacecraft, developed using the Galileo mission as a point of departure, are given in table I. Although outer planet missions are severely weight constrained, it is assumed that the allocation for the AMS could grow, thereby allowing a larger aperture. Based on improvements in communication equipment[7] and the use of

TABLE I. CONSTRAINTS IMPOSED BY THE SPACECRAFT

Item	NIMS	AMS
Weight	10 kg	25 kg
Optical Aperture	22 cm	33 cm
Raw Data Rate	11.9×10^3 bits/s	10^5 bits/s
Focal Plane Temperature	80 K	70 K

data compression and advanced coding[4] a high raw data rate capability is projected. Improvements in radiative cooling capabilities are costly in weight. A modest improvement of 10 K for focal plane and instrument housing temperatures is assumed.

With a set of experiment objectives and spacecraft constraints, an instrument concept may now be developed. Assuming a detector element size of 100 μm, a one meter focal length objective would produce an angular field of view of 0.1 mrad per detector. This resolution would produce 100-m footprints from a range of 1000 km, appropriate for the mapping of landing sites on Titan. At greater range the surface could be mapped at lower, but acceptable, resolution.

Constraining the spectral resolution to 0.03 μm per detector element, a range of 3.84 μm can be covered with 128 elements. Three arrays are mosaicked in the direction of the spectral dispersion as shown in fig. 1 to increase the spectral range. Assuming an encoding precision of 10 bits per sample, each 128 x 128 array generates 163,840 bits per readout. By selecting a frame time of two seconds for each 128 x 128 array, a data rate of 81,920 bits per second is generated. The instrument parameters are given in table II. The noise bandwidth of 0.25 Hz corresponds to the two-second readout time. A signal-to-noise ratio of 100 is chosen as appropriate for the spectral analysis of the data.

TABLE II. ADVANCED MAPPING SPECTROMETER FUNCTIONAL DEFINITION

Parameter	Value
Optics	
Focal Length	1.0 m
Diameter	33 cm
Spectrometer	
Dispersion	0.3 μm/mm
Background Temperature	150 K
Focal Plane	
Array Size	128 x 128 (3 Arrays)
Element Spacing	100 μm
Spectral Range	To Be Defined
Temperature	70 K
Spatial Resolution	0.1 mrad
Spectral Resolution	0.03 μm
Signal Chain	
Integration Time	2.0 s
Data Rate	82×10^3
Encoding Precision	10 bits/sample
Noise Bandwidth	0.25 Hz
Signal-to-Noise Ratio	100

FOCAL PLANE PERFORMANCE REQUIREMENTS

The spectral radiance reflected from a planetary body is given by

$$R_\lambda \text{ (reflected)} = \left(\frac{\alpha^2 D^2}{4R^2}\right) T_\lambda S_\lambda \phi\rho_\lambda \Delta\lambda \tag{1}$$

where α is the angular dimension of the projected pixel field of view; D, the optical aperture; R, the distance from the sun; T_λ, the instrument optical transmission; S_λ, the solar irradiance; ϕ, the planetary phase function value; ρ_λ, the geometric albedo of the surface; and $\Delta\lambda$, the wavelength interval. The thermally emitted radiation is given by

$$R_\lambda \text{ (emitted)} = \left[\frac{2\pi c^2 h}{\lambda^5\left[\exp\left(\frac{hc}{\lambda kT}\right) - 1\right]}\right] \frac{\alpha D^2}{4} T_\lambda \varepsilon_\lambda \tag{2}$$

where c is the speed of light; h, Planck's constant; k, Boltzmann's constant; T, the surface temperature of the body; and ε_λ, the spectral emissivity. To achieve a given signal-to-noise ratio W, the required detectivity D* is given by

$$D^*_\lambda = \frac{WA^{1/2}(\Delta f)^{1/2}}{R_\lambda} \tag{3}$$

where A is the detector area and Δf is the signal bandwidth. In the cases considered below the reflected and emitted radiation are considered separately. In a sampled system the signal bandwidth is related to the detector integration time, τ by

$$\Delta f = \frac{1}{2\tau} \tag{4}$$

To evaluate these equations, values for the optical properties of the outer planets and satellites are required. In a detailed analysis it would be necessary to utilize spectroscopic measurements for the wavelength-dependent quantities; however, for the purposes of this work average quantities or analytic functions were used, which are in reasonable agreement with reported values in the infrared regions of the spectrum. The solar irradiance is given by a properly normalized 5900 K Planck distribution. A single value of 0.25 has been used to characterize the instrument optical transmission at all wavelengths. Saturn and Titan albedos and temperatures are taken from the references.[8,9] Required detectivity curves for the two instruments at both Saturn and Titan are given in fig. 2. The double curves in the reflected solar spectrum (short wavelength) result from the choice of two phase angles, 0 and 75 degrees.

A comparison of the required detectivities for the two instruments at selected wavelengths is given in table III. The immediate conclusion is that the detectivity requirements for the advanced instrument are lower by a factor of four than those of the NIMS design. The largest contribution to the lowered requirement is the significantly decreased noise bandwidth which derives from the large increase in the number of detectors in the focal plane (multiplex advantage). A number of factors also contribute to the differences in requirement, including optical aperture, detector area, spectral resolution, and spatial resolution.

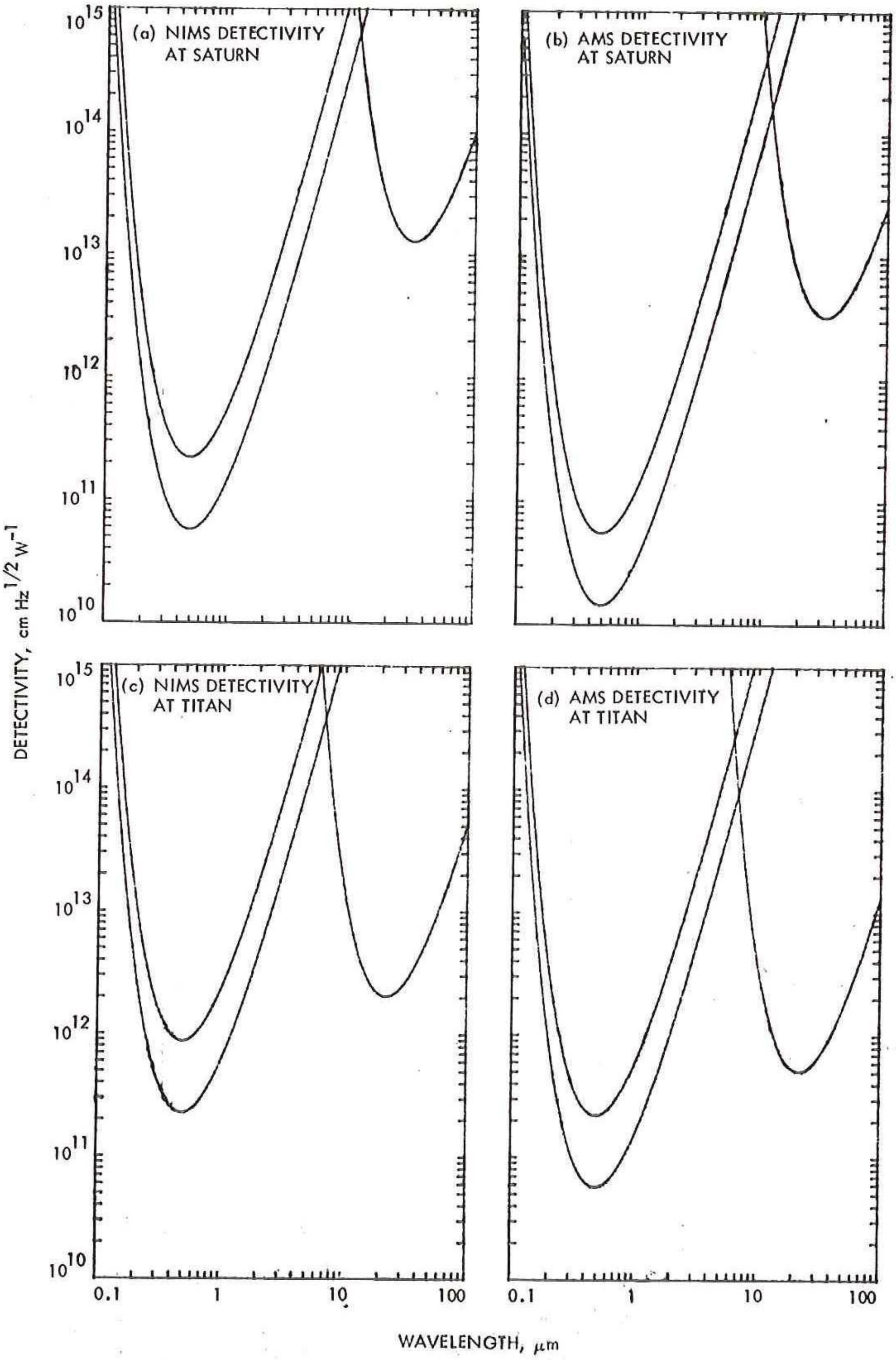

Figure 2. Required Detectivity for NIMS and AMS Detectors at Saturn and Titan

TABLE III. COMPARISON OF REQUIRED DETECTIVITIES*

Wavelength (μm)	Detectivity ($cm\ Hz^{1/2}\ W^{-1}$) Saturn NIMS	Saturn AMS	Titan NIMS	Titan AMS
3	1.6×10^{13}	4.0×10^{12}	6.6×10^{13}	1.7×10^{13}
5	1.0×10^{14}	2.6×10^{13}	4.2×10^{14}	1.0×10^{14}
10	(2.0×10^{15})	5.0×10^{14}	(1.6×10^{13})	4.3×10^{12}
20	(2.4×10^{13})	6.5×10^{12}	(2.1×10^{12})	5.1×10^{11}

*Numbers in parenthesis refer to wavelengths for which the NIMS instrument was not designed. The specified detectivity of the NIMS detectors is 2×10^{13} cm $Hz^{1/2}$ $watt^{-1}$ at 5 μm. Performance at 3 and 5 μm is based on 75 degree phase angle observations.

Another focal-plane performance requirement assumed in developing the Advanced Mapping Spectrometer concept is the two-second integration time. In the simplest concept the signal integration would occur on the focal plane. A more complex alternative would involve multiple readouts of the focal plane with signal averaging occurring away from the focal plane. For arrays of this size, such an alternate approach would necessitate high internal data rates, large memory, and (possibly) relatively fast computing. Because of these difficulties, the goal of integration on the focal plane is chosen. The requirements for detector arrays developed in this analysis are summarized in table IV.

TABLE IV. SUMMARY OF FOCAL PLANE ARRAY REQUIREMENTS

Array Format	128 x 128 elements
Element Dimension	100 m square
Detectivity at 5 μm	1.0×10^{14} cm $Hz^{1/2}$ W^{-1}
20 μm	6.5×10^{12} cm $Hz^{1/2}$ W^{-1}
Integration Time	2 s
Operating Temperature	70 K

CONCLUSIONS

There has been no firm specification of spectral range. As has been pointed out, there is useful information throughout the entire infrared region of the spectrum. The transition from reflected solar to emitted thermal radiation occurs in the region from 7 to 10 μm for the Saturn system; however, this transition shifts to lower wavelength for planets and satellites nearer the sun. Under these conditions it is clearly appropriate to presume that differing detector array implementations will be needed for short- and long-wavelength experiment objectives. Realistically, the cutoff wavelengths will be determined by the detector material and implementation approach selected.

The required detectivities shown in this paper are high. This is a particular concern because many military applications are background limited; thus there is not a large demand for high detectivity arrays. On the more encouraging side, the multiplex advantage offered by arrays has been shown to result in increased performance (higher spatial resolution);

yet the detectivity requirement is eased in comparison to the mechanically scanned set of discrete diodes (NIMS). The requirements shown here, while they do not exceed theoretical limits, are comparable to some of the best results reported for 5 μm diodes. This is a clear indication that considerable effort must be expended to insure that the multiplexing circuitry not appreciably increase the detector noise levels.

Given the goal of two-second integration time on the focal plane, it is apparent that hybrid infrared detector arrays must be selected in preference to monolithics. At 77 K monolithics, which store and transfer the charge within the infrared detecting material, have short thermal charge-up times, which limit integration times to a few milliseconds at best. The use of a silicon Charge Coupled Device (CCD) as the storage device is preferable because this limitation can be removed or reduced by one of several postulated approaches. The signal plus background flux levels must still be accommodated, and this will necessitate careful design.

The requirements for array format and element dimension are somewhat arbitrary. To achieve a useful multiplex advantage, it is necessary to increase the number of elements in the focal plane significantly. The format size stated is consistent with goals of other users and was chosen for that reason. The factor which will determine the element dimension is the complexity of the circuitry needed to couple the infrared detectors with the CCD wells.

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