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OPTICAL REMOTE SENSING OF ASTEROID SURFACES FROM SPACECRAFT

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The application of optical remote sensing techniques to asteroid surfaces using ground-based telescopes has revealed most of what is known about these objects. Transporting the related instruments to the asteroids for close-up study during rendezvous or landing missions has the potential for providing large increases in our knowledge of asteroid surface structures, composition and mineralogy. Reflectance spectroscopy and multispectral mapping are the companion techniques likely to be most useful, for between the two approaches surface units can be determined. Several other techniques should be considered for providing complementary information. The state of instruction is such that no serious technical problem in developing such experiments is expected.

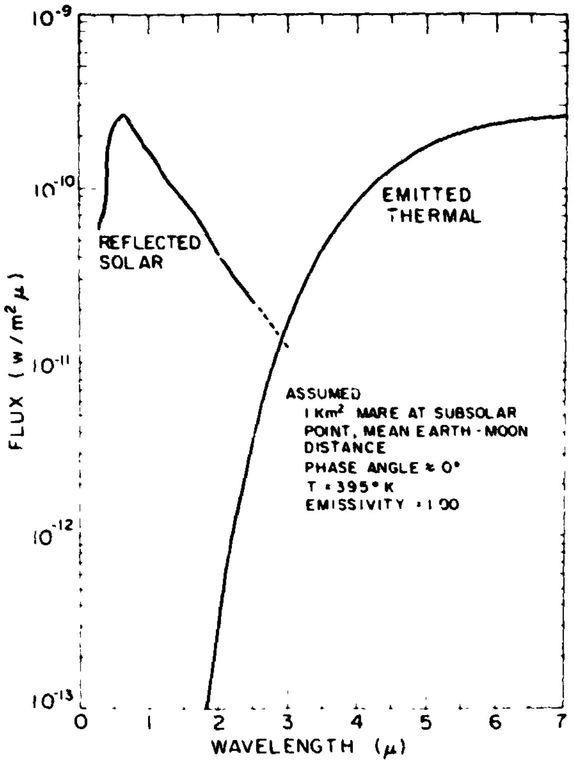
INTRODUCTION

When asteroid exploration is extended by carrying instruments near asteroids and onto their surfaces we will find measurements in ultraviolet, visible and infrared energy regions even more useful than they are now, working from the Earth's surface. A variety of techniques are available which all depend on measuring radiation reflected or emitted by surface material. This article discusses each technique briefly and points out some more obvious experiments which could be performed on flyby, rendezvous or landing missions. As always one must be cautious in assuming that all possible techniques and experiments are known. New and better methods may be discovered in the future and in fact may now exist unknown to the author.

Optical radiation coming from an asteroid consists of two components: passively scattered solar radiation at shorter wavelengths and emitted thermal radiation at longer wavelengths. Figure 1 shows the flux received at the Earth from a square kilometer of a lunar mare region at near-zero phase angle. The case for a low albedo asteroid near the Earth would be very similar. For objects farther from the Sun the wavelength at which emitted thermal radiation becomes dominant shifts to longer wavelengths, to about 4 μm at Mars and 6 μm at Jupiter.

The major techniques available for observing asteroids at optical wavelengths are tabulated in Table 1. All of these could be remotely applied from a flyby or rendezvous spacecraft and the spectroscopic techniques could be applied on the asteroid surface to study samples, as is commonly done in terrestrial laboratories.

Fig. 1. Radiation received from a 1 km^2 mare area, albedo 0.06, at the mean Earth-Moon distance (Adams and McCord, 1970).



RADIATION FROM MOON [1km^2 of more] AT EARTH

Table 1. The Major Techniques Available for Observing Asteroids at Optical Wavelengths

Technique	Wavelength Region	Property Determined	Physical Phenomenon
1. Reflectance Spectroscopy	0.1-5.0 μm	Mineralogy	Electronic Absorption
2. Emittance Spectroscopy	5.0-1000 μm		Molecular Vibration
3. IR Radiometry	5.0-1000 μm	Diameter, Albedo, Thermal Inertia	Thermal Energy Exchange
4. Polarimetry	0.1-1.0-? μm	Grain Size to Material Opacity Ratio	Specular Reflection and Scattering
5. Broadband Photometry	0.1-1000 μm	(See 1 and 2 Above) Albedo	(See 1 and 2 Above)
6. Multispectral Mapping	0.1-1000 μm	Compositional Unit Extent	(See 1 and 2 Above)

REFLECTANCE SPECTROSCOPY

Technique Description

Spectral reflectance is the fraction of incident solar radiation that is reflected from a surface as a function of wavelength. With sufficient spectral resolution and intensity precision, absorption bands often can be resolved that are diagnostic of surface composition and mineralogy (see Figure 2). For mineralogical interpretation we are concerned primarily with the wavelength dependence of reflectance and to a lesser extent with the albedo or absolute amount of reflected light, and angular dependence, or polarization of the reflected radiation.

The material on the surfaces of solar system objects typically occurs as randomly oriented fragments. When observed in reflected solar light, the particulate material returns two components of radiation: (1) a specular component, which consists of first surface reflections and is described by Fresnel's laws for absorbing dielectrics; and (2) a diffuse component, which is composed of light that has entered at least one grain and has been scattered back into space toward the observer. It is the diffuse component that contains the most compositional information.

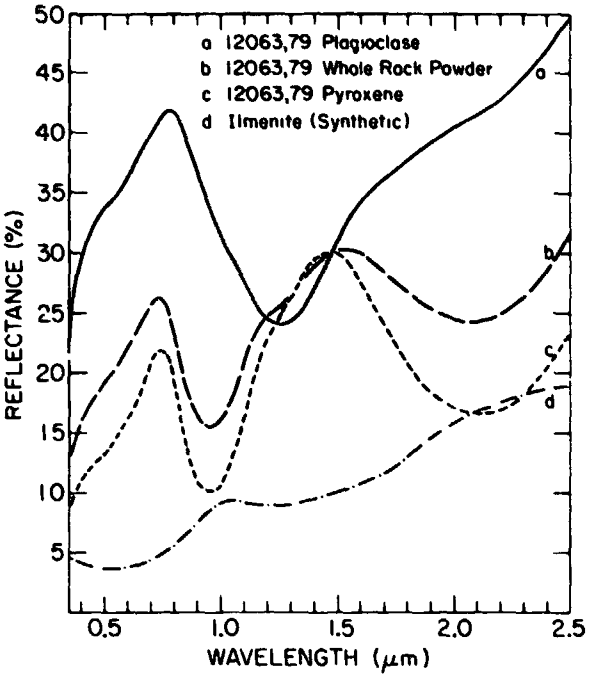
The absorption bands that appear in reflectance spectra are due primarily to (1) electronic transitions and charge transfers by d-shell electrons in transition metal ions (Fe^{2+}, Ti^{4+}, Cr^{3+}, etc.), (2) overtones of molecular vibrations, (3) photoelectronic emission, and (4) photoconduction. The wavelength positions of the absorption band centers depend on the types of ions present and on the dimensions and symmetry of the sites in which the ions are situated. These two factors to a large extent define the mineralogy of a sample. Note that reflectance spectroscopy is a method of remotely sensing *mineralogy*, in contrast to γ-ray spectroscopy and x-ray fluorescence, which remotely sense *elemental composition*.

Reflectance spectra are interpreted using a combination of laboratory and theoretical techniques. Laboratory spectra of a large number of chemically analyzed terrestrial, lunar, and meteoritic minerals and rocks have been analyzed, and their spectra have been studied as functions of particle size, phase angle, mixing ratios, and mixing heterogeneity. Interpretations of absorption bands are based on ligand field theory (interelectronic transitions), molecular orbital theory (charge transfer transitions), band theory (photoconductivity and photoemission), and theories of molecular vibration. Relative modal abundances are determined analytically by comparing the relative strengths of bands contributed by the constituent minerals, and using assumptions about relative grain sizes and homogeneity. Simple comparisons with catalogs of laboratory spectra are not adequate and may be misleading.

For many objects in the solar system, such as the Moon and Mars, telescopic spectra for a large number of locations can be obtained and petrologic units identified. Determination of unit petrology requires high spectral and spatial resolution; however, the spectra often can be characterized in terms of intensities at few diagnostic wavelengths, which can be mapped in two dimensions (using multispectral imaging techniques) to determine the spatial extent of petrologic units.

Problems can arise to make the application of reflectance spectroscopy difficult or impossible. For example, observations can be affected by low light levels and poor spatial resolution. Furthermore, solar system objects have their surface optical properties modified by one or more alteration processes, which have to be understood before accurate interpretations can be made. The optical properties of soils can be strongly altered by masking agents, such as agglutinitic glass on the Moon and Mercury, vegetation and clouds on Earth, and windblown dust on Mars. To a lesser extent, polarization effects and reflection geometry can also complicate interpretations.

Fig. 2. Spectral reflectivity of Apollo 12 basalt powder 12063 and plagioclase and pyroxene separates from the same rock. Ilmenite is a synthetic sample (Adams and McCord, 1971).



These limitations notwithstanding, the technique has been successfully applied using ground-based telescopes; the compositions of nearly 100 asteroids have been determined; the pyroxene composition, titanium content, soil maturity and mare basalt types have been determined for units across the lunar surface; the abundance, type, and water content of ferric oxides in the martian soils have been measured; and the presence of H_2O on the Galilean satellites, and the rings and satellites of Saturn has been detected. Spacecraft experiments should extend the ground-based work and acquire basic information about the composition of solar system bodies.

Instrument System

Remote Measurement. Flyby, orbiter and rendezvous missio[illegible] asteroids require spectrometers of some sort with telescopic foreoptics to gathe[illegible]ght and project an image of a surface spot. Several spectrometers have been developed for ground-based telescopic observations. These include multi-discrete interference filters (0.3-2.5 μm), single detector spectrometers (0.6-5.0 μm), and interferometer spectrometers (1.0-2.5 μm). Several broadband photometers have also been used.

Two instruments have been designed for spacecraft use. A cross disperson eschell spectrograph using linear arrays of detectors (0.35-5.0 μm) has been designed for the LPO mission and a modified version was proposed for the Galileo mission. This instrument gives very wide spectral coverage for only one or a few spatial elements (because of optical aberrations).

A second instrument is being designed and built to fly on the Galileo mission. It will be a single dispersion spectrometer using linear arrays of detectors aligned along the slit image, rather than along the spectral dispersion as for the other system. This instrument has narrower spectral coverage (because of order overlap) but it has the ability to image up to 30 or so spatial elements simultaneously.

These two instruments represent the two extremes of design for dispersion spectrometers. Combining the advantage of each has been attempted but not achieved.

An interferometer spectrometer was flown on the Mariner 9 Mars mission but the spectral range did not reach to short wavelengths where electronic absorptions are well developed. A similar system modified to reach to ∿1.2 μm was proposed for the Galileo mission. A problem with the interferometer spectrometer approach in general is the close mechanical tolerances required to work at visible and near infrared wavelengths and the unnecessarily high spectral resolution and resulting decreased sensitivity that must be accepted in current designs.

Circular variable filter (CVF) spectrometers have been suggested and they are attractive because of instrument simplicity. But simultaneous measurement of more than one spectral channel is not allowed and this greatly reduces measurement efficiency. For bright surfaces and rendezvous missions one might be able to use such a device.

Considerably more development of these instrument concepts is needed to obtain appropriate devices for actual missions. Different missions will require different devices. Important parameters affecting design are: surface brightness (distance of object from Sun, distance from object, spatial resolution, surface material albedo), integration time spent on one surface spot (ground track speed, spatial resolution), and aerial coverage desired (type of object, total time spent at object).

In Situ Measurement. A landing mission could involve some sample analysis. In this case a reflectance spectrometer could be used to make detailed mineralogical analyses, just as is presently done in terrestrial laboratories. No such instrument has been designed (although many models exist for laboratory use) and problems of light sources, calibration and sample manipulation may exist.

EMISSION SPECTROSCOPY

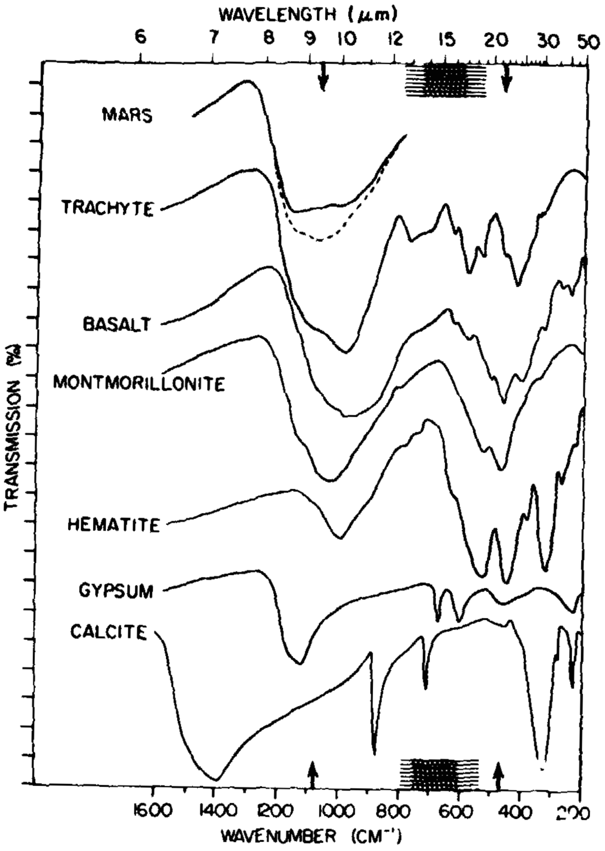
Technique Description

A planetary surface element reaches a certain temperature according to a complex set of energy-balance conditions involving geometry and Kirchoff's laws. The major source of energy is solar radiation which is absorbed by the surface at visible and near infrared wavelengths (Figure 1). A minor but possibly detectable amount of energy may originate in the planet's interior. Some emitted thermal radiation is reabsorbed by other parts of the surface within the field-of-view of the emitting surface element.

The ability of a surface to radiate depends partly on the optical properties (index of refraction and extinction coefficient) of the material, and these properties vary with the wavelength of radiation emitted. Solids are composed of atoms and molecules bound in a crystal lattice. With their associated bonds, these form oscillators which vibrate at preferred frequencies. Near the preferred vibrational frequencies, bands (called reststrahlen bands) appear in the emission spectrum of the solid (Figure 3). For silicates the Si-O bond is responsible for a strong emission near 10 μm, for example. These bands can be diagnostic of composition.

Unfortunately, these emission bands usually can be seen only for surfaces with large particle sizes (100 μm). However, at a wavelength slightly shorter than but related to the reststrahlen band, the index of refraction of the emitting material becomes equal to that of the surrounding medium. At this wavelength (Christiansen frequency) no scattering occurs at particle boundaries and the maximum possible radiation escapes to space. It has been shown that the Christiansen frequency varies predictably with composition and this approach has been used to study lunar and terrestrial samples.

Fig. 3. Transmission spectra of rocks and mineral ground to 0-5 μm and suspended on a mirror. Curves have been separated vertically for clarity. Peak transmission near 8 μm (250 cm^{-1}) is typically about 90% for the rock spectra, and ordinate divisions are 10%. Shaded region of the spectrum is obscured by martian CO_2 lines in Mariner 1971 spectra. Recalculated Mariner 1971 nonpolar spectra are shown here. Vertical arrows indicate position of polar radiance maxima, near which we also expect the nonpolar transmission minima (Logan *et al.*, 1975).



Instrument Systems

Remote Measurements. Several spectrometers of the designs (but with different detectors) described under a previous section have been built and used on ground-based telescopes. The spectral range covered is restricted to the 10 μm and 20 μm terrestrial atmospheric windows.

A CVF spectrometer (2-14 μm) was flown to Mars on the Mariner 6 and 7 missions and an interferometer spectrometer (4-50 μm) was flown to Mars on Mariner 9.

In this spectral range the interferometer spectrometer becomes a more practical alternative because of the increased wavelength of radiation observed. The detectors become more difficult to handle because of the need for cooling to near 0°K. Considerable development of both the techniques and the instrumentation is required to make available a dependable experiment.

In Situ Measurement. As in the case of shorter wavelength reflectance spectroscopy, emission spectroscopy can be applied on landing missions to analyze samples. Spectroscopy at these energies is a standard laboratory technique, as at shorter wavelengths, and instrumentation is equally undeveloped. Probably the *in situ* measurements would be made in transmission rather than emission so that sample preparation becomes a serious problem.

IR RADIOMETRY

Technique

The temperature of an illuminated planetary surface is controlled by insolation (surface area presented to incoming sunlight), surface albedo (amount of sunlight absorbed), and temperature of objects within the field-of-view of the radiating surface element. After sunlight is cut off (*e.g.*, eclipse), the relative importance of subsurface heat exchange increases rapidly as the surface cools. From the solution of the heat-conduction equation one finds that the surface material properties K (thermal conductivity), ρ (density), and C (heat capacity), in the functional form $(K\rho C)^{1/2}$ (called the thermal inertia), control the rate of cooling of a surface, but the temperature of objects in the field-of-view of the emitting surface also has an effect.

Infrared radiometry is the measurement of flux emitted from a surface, perhaps at several broad spectral bands, from which an effective temperature can be derived. Temperatures of an illuminated surface, alone, usually reveal little about the surface except albedo and illumination geometry. When condensates are present some compositional information can be inferred by considering freezing temperatures. Temperature changes during illumination changes such as an eclipse can give additional information from the measurement of thermal inertia.

Instrument System

A large number of IR photometers are in use making ground-based measurements of flux in several broad spectral bands for a wide variety of objects including asteroids. Also, a number of instruments have been flown on spacecraft. Development of such instruments is not difficult given the work already done. One area of difficulty is the detector cooling required to achieve the best sensitivity.

POLARIMETRY

Technique

Reflected radiation can be analyzed into its two orthogonal planes of polarization, one perpendicular ($I_\perp$) to the plane of scattering and one parallel ($I_\parallel$) to this reference plane. The plane of scattering is defined by the source, surface, and observer. The polarization (P) of the reflected radiation is defined as

$$\%P = \frac{I_\perp - I_\parallel}{I_\perp + I_\parallel} \cdot 100$$

Polarization has usually been measured as a function of the angle between source, surface, and observer, or "phase" angle. There is generally a maximum polarization near a phase angle of 110°, diminishing to zero near 20°. A 90° shift in the plane of polarization occurs at small phase angles resulting in a small "negative" polarization which again approaches 0 at 0°.

In the laboratory, the polarization versus phase-angle curve has been shown to be a combined function of opacity (composition), particle size, and surface structure. Within moderate limits, an empirical relation has been shown to exist between the slope of this polarization curve and the geometric albedo of a particulate surface. The negative polarization at small phase angles is characteristic of surfaces covered with some form of dusty semi-opaque soil.

Through computer modeling techniques a recent theoretical analysis of the way light is reflected and scattered from a particulate surface has allowed a better understanding of the physics and optics behind the observed polarization (see Wolff, 1975). This analysis showed that the polarization versus phase curve is the result of several factors, such as the complex refractive index of the particles (determined by composition and defining opacity), porosity of the soil, amount of shadowing, and particle size. For example, if the basic structure of the soil is known or assumed constant over a region, then the observed polarization curve is largely a function of the opacity of the particles and can be used as a measure of albedo within the limits defined by the model.

Instrument System

Systems using crystal or polaroid analyses and single detectors are in common use on ground-based telescopes. Spacecraft polarimeters have been flown as part of imaging experiments. Polaroid filters are inserted in the optical path to measure polarization.

MULTISPECTRAL MAPPING

Technique Description

The basic study of a planetary surface involves defining the boundaries and extent of surface units and characterizing them in terms of physical features, lithology or chemical composition. Multispectral mapping is an effective method for determining the spatial extent of geologic units on a planetary surface. Ground-based telescopic studies of the Moon have been carried out for more than 60 years, but spacecraft missions to objects other than the Earth have seldom included multispectral mapping experiments. Developments in two-dimensional detector technology and image processing techniques are stimulating activity in this field. Increased understanding of the optical properties of planetary surface materials is making multispectral maps more meaningful.

Multispectral mapping is defined here as not just the acquisition of images at several wavelengths but also the processing of images obtained through at least two different spectral bandpasses to produce a single image encoding color information. Physical processes causing color differences across planetary surfaces have recently become much better understood and color differences are becoming a dependable parameter for defining and characterizing geologic units. As discussed above, the reflected and emitted spectra of planetary surfaces contain absorption or emission features which are related to compositional properties. In some cases, the understanding of t . surface-material optical properties has reached such a level that direct correlation of optical parameters can be made with compositional parameters. For example, the slope of the reflectance spectrum between 0.40 and 0.56 μm for mature lunar mare soil is directly correlated with TiO_2 content. Basaltic mare units can be distinguished based on titanium content. By mapping the spatial distribution of the slope of the reflectance spectrum using multispectral imaging techniques, a map of titanium content in the mare soil, and thus a map of some mare basalt geologic units, can be obtained. Other optical and compositional parameters are correlated, but this case illustrates the point.

The wavelengths at which a surface is imaged must be chosen with great care in order that the color maps bring out geologic and geochemical features and so that the color images can be interpreted in terms of known physical processes affecting the optical properties. Poorly chosen bandpasses lead to massive data reduction exercises and result in poor unit discrimination. The differences in color properties which signify compositional differences are often small (0.1-10%). The precision of measurement required to map the appropriate optical parameters in two dimensions has strained the available technology.

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DISCUSSION

MORRISON: Some remote sensing techniques are a lot more productive than others and a lot more likely to fly on a mission if we have one. Could you comment on which ones you think are more important?

McCORD: I would list reflectance spectroscopy and multispectral mapping as the main spacecraft techniques for optical remote sensing. I think mineralogy is an important property, and the distribution of units on the surface of a body is important for determining how that body evolved. Emission spectroscopy may turn out to be important as well. It is less well understood and has not been practiced nearly as much. There is a problem in that for the particle size distribution we find existing on the Moon, the emission features are essentially washed out. There are complementary features called Christiansen peaks which do show up. Very little laboratory work has been done on these. Finally, mapping the temperature of the surface is less interesting to me than determining composition

MATSON: Emission spectroscopy is sensitive to a different set of minerals than reflectance spectroscopy. Radiometry is more oriented toward texture and morphology of the surface.

McCORD: If you have a fairly rapidly spinning asteroid, radiometry will be sensitive to physical properties, like exposed rock versus regolith, rather than chemical properties.

MORRISON: Basically, the radiometry is sensitive on a distance scale of millimeters to centimeters, which you don't otherwise probe.

McCORD: Polarimetry is again oriented toward small-scale physical rather than chemical properties.

ARNOLD: This list has all the techniques which you and others have applied from the Earth. What can you learn about a body in general when you are close-up rather than through a telescope?

McCORD: There are two definitions of what close-up is. One is in orbit or in rendezvous at some distance. There one wants to take the geological approach of defining and characterizing units. With multispectral mapping, one would be defining the extent of units and with the spectroscopic techniques, one would be characterizing units in terms of mineralogy. If one knows the extent and characteristics of the units on the surface, presumably one could work out an evolutionary history using the approaches of classical geology. But I would like to go further and say these techniques can be applied *in situ*, the second case. If one had a lander, one would want to carry a reflectance and emittance spectrometer and analyze the material on the surface just as you do in the laboratory. These are very powerful laboratory techniques for mineralogical analysis.

ANDERS: How long would it take you to map an asteroid the size of Ceres if you had an instrument in orbit? Also, could you resolve a 1 km crater and characterize any exposed bedrock?

McCORD: The answer to the second question is a matter of resolution. One kilometer resolution from 1000 km is easy, and if you move closer and keep the focal lengths of your optics the same, you can get much higher resolution.

VEVERKA: If you are orbiting these objects, the orbital velocity is very low, and there are no severe problems with smear. Ten meter resolution is possible.

McCORD: That's right. So characterizing a 1 km crater would be easy. Now the first question was coverage and that depends on what kind of resolution you want. For the Lunar Polar Orbiter mission, we're talking about mapping with a single spot of about 1 km and doing the entire Moon surface in a year. A different instrument being built for the Galileo mission maps spatial elements simultaneously but with fewer spectral elements. Both instruments work at about the same speed.

MORRISON: The Moon is a factor of ten larger than Ceres in surface area, so for a typical 60 day rendezvous time, you could spectrally map all of Ceres at 1 km. Perhaps you'd want higher resolution for selected areas, too.

FANALE: It is within the capabilities of these instruments to do a very exciting experiment to give a detailed map of the distribution of the water and OH on the surface of these objects.

MORRISON: Could I ask one of you involved with the Galileo imaging to comment on the degree to which the CCD imaging system can accomplish the spectral mapping goals and relieve the pressure somewhat on the kinds of instruments McCord has discussed?

CHAPMAN: The CCD has a broader spectral coverage than other cameras that have been flown but not as broad as is needed for good mineralogy. We don't have a CCD camera that goes out to 5 μm.

VEVERKA: I think the other problem is that obviously you are likely to have a limited number of filters on a CCD camera. You do not have the ability to do the kind of spectral characterization we want.