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Reports of Workshops on Probe Measurements of Particles and Radiation in the Atmosphere of Titan

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PREFACE

This document consists of two reports of workshops dealing with the measurement of particles and radiation from a probe descending in the atmosphere of Titan. It had been intended that additional workshops dealing with atmospheric composition and structure measurements would be held, but these have not materialized. The workshops were held on August 11-12, 1986 (Part 1), and December 16-17, 1986 (Part 2). The proceedings were first published and distributed informally. With the solidification of plans for the Cassini mission to Saturn and Titan, it seems appropriate to present these proceedings in a more readily available document. This report presents these proceedings as first issued, with only minor editorial changes.

TABLE OF CONTENTS

PART I – REPORT OF A WORKSHOP ON THE MEASUREMENT OF PARTICLES IN THE ATMOSPHERE OF TITAN

	Page
PREFACE	v
SUMMARY	3
INTRODUCTION	3
SUMMARY RECOMMENDATIONS	4
BACKGROUND INFORMATION	5
IMPORTANCE OF AEROSOL AND CLOUD PARTICLE MEASUREMENTS	6
Physical Processes	7
Atmospheric Evolution and Surface Morphology	7
Precursors to Biological Activities	7
DESIRED INFORMATION	8
Physical and Optical Properties	8
Radiative Flux Profiles	9
Chemical Composition	11
Vertical and Horizontal Variability	11
APPROPRIATE MEASUREMENT TECHNIQUES	12
Physical Properties	12
Optical Properties	13
Gaseous and Particulate Composition	15
Horizontal and Vertical Variability	16

TABLE OF CONTENTS – PART I (CONT'D)

	Page
CONCLUSIONS AND RECOMMENDATIONS	17
REFERENCE	18
TABLES	18
FIGURES	19

TABLE OF CONTENTS

PART II - REPORT OF A WORKSHOP ON RADIATION MEASUREMENTS AND IMAGERY IN TITAN'S ATMOSPHERE

	Page
SUMMARY	23
INTRODUCTION	23
SUMMARY RECOMMENDATIONS	23
IMPORTANCE OF RADIATION MEASUREMENTS AND IMAGERY	24
EXPERIENCE WITH ENTRY PROBE RADIATION MEASUREMENTS	25
A. Introduction	25
B. Solar Radiation	25
C. Thermal Radiation	26
D. Imaging	26
DESIRED INFORMATION	27
DESCRIPTION OF APPROPRIATE MEASUREMENT TECHNIQUES	27
A. Solar Flux Measurements	27
B. Thermal Flux Measurements	27
C. Imaging Data	28
D. Suggested Instrumentation	28
CONCLUSIONS AND RECOMMENDATIONS	30
REFERENCES	31

TABLE OF CONTENTS – PART II (CONT'D)

Page

APPENDICES 33

A. AGENDA, GOALS OF THE WORKSHOP, ATTENDANCE LIST, AND MODEL SCIENCE PAYLOAD FOR THE TITAN PROBE 33

B. EXPERIENCE WITH ENTRY PROBE THERMAL RADIATION MEASUREMENTS 41

PART I

REPORT OF A

WORKSHOP ON THE MEASUREMENT

OF PARTICLES IN THE

ATMOSPHERE OF TITAN

SUMMARY

The March 1985 joint ESA–NASA Cassini mission to the Saturnian system will include an atmospheric probe to be dropped into the atmosphere of Titan for in situ measurements during descent. Because of the unique properties of the Titan atmosphere, it is necessary to consider the peculiar requirements for such measurements and applicable techniques. The proceeding of a workshop dealing with the measurement of particulate matter in the atmosphere of Titan is presented. The workshop was held in August of 1986. The proceeding was first published and distributed informally, and is presented here with only minor editorial changes. In this proceeding for the particulate matter workshop, discussions of the mission background, the importance of the measurements, and descriptions of the desired information are followed by a description of appropriate measurement techniques and conclusions and recommendations.

INTRODUCTION

A future planetary mission to the Saturnian system has been proposed jointly by NASA and ESA. This mission, appropriately named "Cassini" after the discoverer of several Saturn satellites and ring features, represents an in-depth, second-phase exploration of Saturn and the Saturnian system of satellites and rings. The Cassini mission is a natural extension of the reconnaissance, flyby exploration carried out by Pioneer 11 (1979) and Voyager 1 and 2 (1980 and 1981). The mission gives special attention to Titan, Saturn's planet-sized moon, which is blanketed by a thick opaque atmosphere suggestive of the primitive Earth. In addition to many very close passes of Titan by an orbiting spacecraft, an atmospheric probe will be deposited into the Titan atmosphere for in situ measurements during a slow, three hour descent to the surface.

The science objectives for the Titan exploration phase of the Cassini mission are summarized in Table 1. However, at the present time the appropriate measurement techniques and instruments to accomplish these scientific objectives lack complete definition. For this reason, it was deemed appropriate to convene groups of experts to discuss several of these important scientific measurements in order to develop measurement specifications and to suggest appropriate instrument concepts for future design study and development for the Titan probe mission. This report represents the results of the first of a trilogy of these scientific workshops. The three areas of in situ measurement to be discussed in these workshops are: (1) particle measurements, (2) radiation field measurements and imagery, and (3) atmospheric gas and aerosol composition. The first workshop on particle measurements was convened on August 11 and 12, 1986 at the NASA Ames Research Center (ARC) and 18 experts contributed to the following recommendations. The attendees are listed in Table 2 and the agenda for the discussion is given in Table 3.

A nephelometer has been identified as part of a strawman payload for the Titan probe to determine the physical structure and location of cloud layers. However, it appears that the current Galileo Probe nephelometer instrument design, originally envisioned for the strawman payload, will not be adequate for particle measurements in the Titan atmosphere. In addition, it has also been recognized that a comprehensive understanding of atmospheric particles in Titan's atmosphere will require more than just a measurement of the physical properties of particles (i.e., number, size, etc.) and that measurements of chemical composition, optical properties, and vertical and horizontal variability will also be required. Although chemical composition, optical properties, and variability of the aerosols were discussed, the emphasis of this workshop was on the measurements of aerosol physical properties.

The following is a report of the deliberations of the workshop and is organized for the reader with a concise summary statement of the workshop recommendations followed by more detailed discussion material on Titan and the Cassini mission, the importance of aerosol and cloud particle measurements, a description of knowledge requirements and measurement specifications, and the identification and description of appropriate measurement techniques.

SUMMARY RECOMMENDATIONS

The Workshop participants concluded that gaining comprehensive understanding of atmospheric particles in Titan's atmosphere will require more than just a measurement of the physical properties of particles (i.e., number, size, etc.) and that measurements of chemical composition, optical properties, and vertical and horizontal variability would also be required.

The Workshop participants made the following recommendations.

Four types of measurements should be made as follows:

(1) Particulate physical properties – size, number density, shape, and charge.

(2) Optical parameters – fluxes, optical depths, particle phase functions, particle indices of refraction, and particle asymmetry functions.

(3) Composition of particulates and gases associated with particulates (adsorbed, occluded).

(4) Imagery yielding the vertical and horizontal distribution of particles.

Secondly, programs should be instituted to develop the specialized instruments needed to make such measurements for special application to particulates in the Titan atmosphere.

Lastly, laboratory measurements should be made to help characterize the properties of particles expected to be present in the Titan atmosphere.

The instruments or techniques recommended for further investigation and development with associated appropriate ranges of parameters to be measured include the following.

For particulate physical properties,

(1) a particle size spectrometer is needed that has the following ranges:
haze particles—diameters of <0.2 to >2.0 μm, number densities of <1 to 10,000 cm^{-3};
cloud particles—diameters of 2.0 to 200 μm, number densities of <1 to >1000 cm^{-3};

(2) a nephelometer capable of multiple angles, multiple wavelength, and dual polarization; and

(3) a mobility analyzer capable of analyzing charges from 0 to >10 electronic charges for the above particles.

For optical parameters, a spectral radiometer is needed that has a range of:

(1) 0.4 to at least 1.0 μm (preferably 2 to 3 μm) and a resolving power >100;

(2) radiometers measuring upward and downward fluxes (and net flux) at solar wavelengths and in a broad thermal band (at about 18 μm); and

(3) radiometers to measure direct and diffuse contributions and azimuthal variations in solar scattered radiation.

For composition, the following are needed:

(1) collectors—inertial and/or electrostatic;

(2) pyrolyzers—such as thermal and laser, preferably stepwise heated to allow for thermal identification of phase changes and vapor production rates; and

(3) Analyzers—either gas chromatograph, mass spectrometer, or combination GC-MS.

For imagery for horizontal and vertical variability, the following are needed:

(1) cameras operating at visible and/or near infrared wavelengths; and

(2) cameras having field-of-view and resolution determined by maximum communications rate.

Finally, the participants of the Workshop recommend that NASA initiate, as soon as possible, definition and development activities associated with the above instruments. The current schedule for a launch of the Cassini mission in 1995 dictates the need to address, in a timely manner over the next several years, several key definition and development issues associated with the recommended instrument set. A small amount of pre-project funds spent on these instrument development issues can save the need for substantially larger funding during the tighter schedule of the actual project and is likely to enhance the performance and science value of the final measurements.

BACKGROUND INFORMATION

The Cassini mission is currently being studied jointly by ESA and NASA. It will consist of a Saturn orbiter spacecraft built by NASA and a Titan atmospheric probe constructed by ESA. If approved on schedule, the mission would receive approval to start in 1990 for a launch in 1995. The most recent post-Challenger evaluation of possible launch vehicle and trajectory options suggests that the optimum scenario is a launch by an expendable launch vehicle followed by an Earth gravity assist and subsequently followed by a Jupiter gravity assist enroute to Saturn. The total flight time for the trajectory from launch to Saturn takes about 7.5 to 8.5 years. To take advantage of the Jupiter assist, 1995 is the earliest launch opportunity and an additional opportunity exists for a launch in 1996.

On the way to Saturn, the Cassini spacecraft will have an excellent opportunity to fly by several types of asteroids. Upon reaching Saturn, an orbit is established by a propulsion manuever which takes place following a slight, but significant, gravity assist by a close flyby of Titan on the in-bound fall toward Saturn. At apoapsis of the first orbit, a second small propulsive maneuver raises periapsis so that the spacecraft will re-encounter Titan near the completion of the first orbit. During this second approach to Titan, about 10 days prior to encounter, the atmospheric probe is targeted and released for a near vertical entry into the atmosphere of Titan. The spacecraft then manuevers to receive relay communications from the descending probe for the three-hour descent to the surface.

Much of the atmosphere traversed by the probe will be accessible to remote sensing from the orbiter because of the expected low opacity. Thus, the in situ measurements made by the probe will take on exceptional significance, both in providing precise data at one location on the satellite and in furnishing "ground truth" for extension of the orbiter measurements to the rest of the satellite.

The ballistic configuration of the probe is such that it rapidly decelerates from an initial entry speed of about 7 km/sec to subsonic speeds (about 260 m/sec) at an altitude of about 200 km above the surface. At this point, the high-speed decelerator is discarded and a parachute is deployed which is sized to permit the slow descent to the surface. During the descent, in situ measurements are made of the structure and composition of the atmosphere and clouds. Probe descent profiles of the predicted velocity, altitude, and ambient atmospheric pressure and temperature for one model atmosphere are shown in Figure 1.

An assessment study of the baseline, pre-Challenger disaster probe mission has been recently completed (Ref. 1). This study was submitted to ESA in the fall of 1985. A Phase-A study of the probe was approved by the ESA advisory councils and governing body and will start in 1987. Meanwhile, it is important to proceed with the definition of key probe instruments to obtain better instrument descriptions for the future Phase-A studies.

IMPORTANCE OF AEROSOL AND CLOUD PARTICLE MEASUREMENTS

The key objectives for the probe mission as defined by the Joint Science Working Group are given in Table 1. Of these, we see that improved knowledge of the properties of the haze and clouds in the atmosphere could have a bearing on a number of these objectives. Even surface properties are affected by the haze and clouds, in that aerosol particles descending to the ground may <u>form</u> the surface, on those parts of Titan that are not covered by the hypothesized oceans of liquid ethane. In addition, expanded knowledge of aerosol properties may affect our ability to study other atmospheric phenomena; for example, studies of the general circulation would be greatly aided if we could find a wavelength region in which the haze revealed absorption features with sufficient contrast to allow feature tracking.

But the immediate reasons to study the aerosols in the atmosphere are to understand their physical and optical properties, their vertical and horizontal distributions, and their compositions and origin. The former are required if we are to construct an adequate model for the radiation balance, in conjunction with information on the vertical profiles of pressure and temperature. In addition to the photochemical smog, we expect the atmosphere to contain condensation clouds of ethane and methane. The altitudes at which these occur and their horizontal distribution can in turn tell us about the Titanian equivalent of the hydrologic cycle while we learn about cloud physics in an alien environment. The composition and origin of the haze particles leads to considerations of the chemical evolution of Titan. We want to know whether certain pathways toward complexity are favored and if so, why. We also want to understand what level of chemical complexity has been produced and whether any of this chemistry has any relevance either to the origin of life on Earth, or to primordial production of the organic material we find today in meteorites and comets as well as on the surfaces of some of the satellites in the outer solar system.

Physical Processes

The distribution and properties of cloud and aerosol particles in the atmosphere of Titan play a central role in many important physical processes. The small aerosol particles high in the atmosphere have low albedos and absorb most of the sunlight incident on Titan. The absorbed solar energy determines the temperature structure of the upper portions of Titan's atmosphere. The total optical thickness of the small photochemically produced aerosols, together with the thickness of any possible condensate clouds in the lower stratosphere and troposphere, determine the amount of solar energy reaching the surface and available to power the small greenhouse effect which maintains Titan's surface temperature. The condensate cloud particles in the troposphere provide an important source of thermal opacity at infrared wavelengths where atmospheric gases are transparent, and so are critical in maintaining the thermal structure of the lower atmosphere.

The thermal structure of the atmosphere is also influenced by the wind field. The driving force for the winds is the net radiation heating or cooling of different atmospheric regions. The cloud and aerosol particles play key roles in determining the radiative flux divergences that provide the forcing function for atmospheric dynamics.

The aerosol and cloud particles also play an important role in the chemistry of the atmosphere. The small, high-altitude aerosol particles are thought to be produced in photochemical processes that begin with the photodissociation of methane and lead to higher hydrocarbons. Some of these higher hydrocarbons can form solid aerosol material directly (such as polyacetylenes) and some can condense from the vapor at lower atmospheric levels. In both cases, coagulation to larger particle sizes and sedimentation out of the atmosphere results in a loss of this material and affects the path of the subsequent chemistry. Also, the presence of particulate material in the atmosphere can act to catalyze certain chemical reactions on the surface of the particles.

Atmospheric Evolution and Surface Morphology

The sedimentation of particulate material out of the atmosphere of Titan is an important link in helping to explain the processing of the material out of which the satellite is formed, and may be important in determining the nature of the present surface of Titan and the evolution of its atmosphere over the history of the solar system. The nature of any exposed solid surface on Titan is likely to be determined by the slow deposition of polymeric hydrocarbon particles which fall out of the atmosphere and the (possibly more rapid) raining down of condensed methane, ethane, and other hydrocarbons.

Precursors to Biological Activities

There is considerable interest in the extent to which organic chemistry has proceeded on Titan in view of the importance of presumably similar processes in producing the initial material from which living organisms were formed on the Earth. Fundamentally, the study of exobiology is highly dependent on detailed knowledge of the reactions of the biogenic elements (C, H, N, P, S) and their compounds in the various natural environments of the solar system. It is felt that understanding these natural chemical processes will aid in elucidating early chemical evolution and the origin of life on Earth or on any hospitable body in the universe. Titan is of particular interest because of the evidence of substantive organic chemistry taking place in the atmosphere at this time. While Titan's atmosphere is a relatively poor model of the early Earth in that the temperature is quite low, there is virtually no water, and there is significantly less oxygen, it does allow study of organic chemistry that is so important to exiobiology on a global scale. Such information would go far toward improving models of Earth's early atmosphere and the chemical processes leading to the appearance of life.

DESIRED INFORMATION

As is described above, knowledge of the particulate matter in Titan's atmosphere is of interest in determining its connection and role regarding energy balances in the atmosphere and on the planetary surface, considerations of atmospheric and planetary surface evolution, including surface composition and characteristics, and as a possible precursor to biological activity. To characterize the particles and aerosols sufficiently to cogently investigate these roles, we must have measurements of their physical and optical properties, chemical composition, and the vertical and horizontal distribution of particles and clouds within the atmosphere. From these in situ measurements we obtain direct knowledge and a great deal of indirect knowledge which, together with remote measurements from the orbiter spacecraft will allow inferences regarding the fundamental processes of interest.

Physical and Optical Properties

The desired knowledge of the microphysical properties of the aerosols and cloud particles as a function of altitude above the satellite surface includes particle size distributions, particle indices of refraction, particle shape and structure, and electric charge. All of these measurements are desired from the parachute deployment altitude of about 200 km down to Titan's surface.

Particle size distributions, N(r), i.e., the number of particles of characteristic dimension r (e.g., radius for spherical particles) per unit size interval between r and r + dr, such that the total particle density is $N = \int_a^b N(r)dr$, should be determined for at least several overlapping size and density ranges of particles. The range a,b expected to be characteristic of the smaller aerosols extends from <0.1 to >1.0 μm with associated particle densities ranging from <1 to about 10^4 cm^{-3}. Sizes of cloud particles are expected to be in the range of <2 to >200 μm with particle densities of <1 to about 10^3 cm^{-3}.

A good deal of uncertainty exists concerning the complex refractive index of the expected aerosol and cloud particles. Some data are currently available on the expected cloud species (i.e., methane and ethane) and laboratory experiments have been performed on aerosol materials produced under simulated laboratory conditions (i.e., the so called "tholins"). These data suggest a wide range of values of index, $n = n(1 + ik)$, ranging from about $n = 1.29$ and $k = 0$ to >0.03 for methane at visible wavelengths to values of $1.4 < n < 2.0$ and k up to 0.28 for "tholins" over a span of wavelengths from the visible to the infrared. The desired range of measurements should be broad enough to encompass at least these limits, i.e., $1.25 < n < 2.0$ and $0 < k < 0.3$, for at least two wavelength ranges; (1) the visible to near infrared and (2) a wideband infrared range centered at about 18 μm. Measurements at infrared wavelengths out to 100 μm could be useful.

Shape and structure of both the aerosol and cloud particles is largely unknown. The smaller aerosol particles that constitute the pervasive haze are probably irregular in shape and may have a variety of shapes including filamentary, spongy, or approximately spherical configurations. Fortunately, because of their expected small size, their exact shape may be unimportant for radiation transport considerations. Cloud particles may be composed of liquid or solid methane and ethane in a variety of configurations. It would be useful to know "shape factors," i.e., ratios of minor to major particle dimensions to establish the physical state of the particles. An additional and perhaps more important measurement is a determination of the radiation-scattering asymmetry factors, $g = \int P\cos(\theta)d\theta$ (where P is the angular scattering phase function), used in radiation transport calculations.

The electrical charge of the particle is of importance in controlling particle growth as well as possibly influencing other atmospheric processes. Recent calculations have suggested that particles in the Titan atmosphere may be significantly charged. It is thus of interest to attempt to determine the electrical charge of particles, especially for aerosol particles, in the range of about 0 to 10 electronic charges or 0 to 1.6×10^{-18} coulombs per particle.

Radiative Flux Profiles

Measurement of solar and thermal flux profiles directly traces and reveals the role of atmospheric particles in basic atmospheric processes, and also indirectly yields information on the distribution and nature of the particles. The flux profiles are determined to a large extent by the distribution, size, and composition of the particles, so that, measurements of these profiles can lead, not only to an understanding of the processes controlling the thermal balance of Titan's atmosphere, but can be used indirectly to determine the vertical distribution and optical properties of the particles. The opacities (actually the diffuse scattering and transmission properties as well as the direct absorption) of the cloud and aerosol particles to solar and thermal radiation as functions of altitude and wavelength from the ultraviolet to the far infrared are needed. Information regarding variations with latitude is also required in light of the Pioneer and Voyager data which show increased absorption in the polar regions and significant differences between Titan's northern and southern hemispheres. Much of this information regarding spatial variations would have to be obtained from the orbiter. The direct determination of the profile of particle opacity at the probe entry site serves as valuable "ground truth" for verifying the inversion methods used to extract some of this information from remote data obtained by the orbiter at many locations over the satellite. For this reason, if possible within mission constraints, it would be highly desirable to obtain remotely sensed data of the probe entry and descent site from the orbiter simultaneously with the probe entry and descent data.

Radiative flux measurements can be used to constrain many important optical properties of cloud and aerosol particles, including the single-scattering phase function of the particles and the profiles of optical depth and single-scattering albedo of the particles with altitude. Further, the flux measurements determine these particle properties at each wavelength at which measurements are made. If measurements are made over a broad range of wavelengths, then the variations of particle optical depth with wavelength can be used to limit the size of the particles. The variation of scattering efficiency with wavelength also provides some constraint on the real part of the refractive index. The single-scattering albedo versus wavelength data can also be used to constrain the value and variation of the imaginary part of the refractive index with wavelength, a quantity which may be useful for constraining the composition of the particles.

It is possible that no value for the real part of the refractive index gives the observed variation in scattering efficiency factor with wavelength for the observed number densities, size, and optical depth profile when the particles are assumed to be spherical. In fact, considerable evidence exists to suggest that the smaller particles in Titan's atmosphere are in fact nonspherical. The flux estimates would at least yield the correct scattering efficiency factors as a function of wavelength which would be available for comparison with calculations using laboratory measurements of nonspherical particles for the purpose of constraining the shape of the particles.

Current models for the haze particles in Titan's atmosphere indicate that the total optical depth of these particles above the surface is relatively small, roughly two to four at red wavelengths. This means that the rotation of the field of view of a detector, as produced, for example, by the rotation of the probe or by mechanical means, will produce variations in the observed downward solar flux with azimuth relative to the azimuth of the sun (unless the probe descends exactly at the subsolar location and/or the detector field-of-view is centered on the probe axis). The azimuth variation in the radiation field results from the shape of the single-scattering phase function and the variation in scattering angle of incident sunlight during a probe rotation about its axis. This variation will persist until the total optical depth above the probe is so great that singly-scattered light is a small component of the multiply-scattered radiation (slant optical depth to the probe >10). Even for a local solar zenith angle of 20°, the range of scattering angle during the probe spin increases to 40°, covering the region containing the expected forward diffraction peak of the aerosol particles, and will nicely constrain the size of these particles. Further, azimuthal variation will continue down into the region where clouds of condensed methane, ethane, and/or other hyrocarbons are expected to occur near the lower stratosphere and troposphere, permitting the presence and size of these particles to be clearly differentiated from the small, nearly isotropically scattering, haze particles seen at higher altitudes.

When discussing the usefulness of flux measurements for thermal balance studies, it is convenient to consider solar and thermal fluxes separately. In the case of solar fluxes, the downward flux exceeds the upward flux at each level, and the difference in the net flux (which is directed downward) at two altitudes is the amount of solar energy which has been absorbed by the intervening layer of atmosphere. For the thermal fluxes, the upward flux generally exceeds the downward flux at each level, and the difference in the net thermal flux between two altitudes is the amount of thermal energy lost by the layer. Averaged over the planet, the profiles of thermal and solar net flux differences in each layer should be quite similar, with the net gain of solar energy nearly balancing the net loss of thermal radiation at each level. When the balance is considered at a particular location on the planet, the local net solar gain will generally not balance the local net thermal radiative loss, and the difference between the two provides a local net heating or cooling rate which provides forcing for atmospheric dynamics.

In summary, it is desirable that upward, downward, and net fluxes be measured at both solar (0.4 to 1.2 μm) and broadband thermal wavelengths (at a mean expected wavelength of about 18 μm). Spectral radiometric measurements of reasonable resolution (resolving power >100) should be made for a wavelength regime of about 0.4 μm to at least 1.0 μm and preferably out to 2 to 3 μm to help identify absorbing species and wavelength regions of interest. In addition, the solar measurements should include a provision for measuring the azimuthal variations in the downward streaming solar radiation field at known azimuth angles from the sun.

Chemical Composition

In order to further our understanding of the particles and aerosols that exist in Titan's atmosphere, we need to know what they are composed of, how they are made, and what their ultimate fate is. Elemental, molecular, and, to some extent, isotopic composition of the aerosol is desired and both the presence and concentration of species are of interest. To obtain the answers to the above questions, it is necessary to determine the chemical composition of the particles as well as of the atmosphere in which they are formed. Although measurement of the composition of atmospheric gases was not part of the scope of this workshop and this report, it is important to study these gases as well as the particles and aerosols because aerosols and particles are formed in and from the atmosphere and, in addition, the gases in the atmosphere will be dissolved in and adsorbed on the aerosols.

For the gaseous components of the atmosphere, three types of measurements are important. First, in addition to direct measurement of the major expected atmospheric components N_2 and Ar, detailed measurements of the light gases, beyond those of the Voyager results, are required. These measurements should include direct determinations of the abundances of the trace species CO, CO_2, and H_2, and searches for Ne, Kr, and O_2. Second, similar measurements of the organic species should be made including direct determinations of the hydrocarbons and nitriles. The measurements should be made for species already known to be in the atmosphere as well as searches for other molecules, such as acetonitrile which are predicted by theoretical models and laboratory simulations. Analytical sensitivities of parts-per-billion are required as some species (e.g., cyanogen and carbon dioxide) have already been detected at this level and many compounds, as yet undetected, that may form or be incorporated in the aerosols may not exist above this concentration. Third, direct measurements of the $^{13}C/^{12}C$ and D/H ratios are needed as these isotopes may be indicators of the processes by which the more complex organic molecules are formed and an indication of the reservoir from which the atmosphere was originally derived. Precision for these ratios of about 1 part per thousand should be sufficient here. If possible, the above measurements should be made at various altitudes in the atmosphere, as the composition may vary due to the influences of different chemical processes above and below the tropopause.

Essentially, similar kinds of measurements need to be made of the aerosol composition, except that the kinds of molecules to be searched for are likely to be more complex. Based on theoretical models and laboratory simulations of the chemistry in Titan's atmosphere, the components of the particles in the upper atmosphere may range from simple (several carbon atoms) condensible organic compounds to polyacetylenes and polyethylenes. More specifically, the types of compounds expected include alkanes, alkenes, alkynes, nitriles, and amines. Sensitivities of a few parts-per-million of the sample mass should be sufficient to determine most compounds of interest. As for adsorbed or occluded gases, determinations of the composition of the aerosols and gases at various altitudes would be helpful in identifying the sources of these materials. Finally, information about the composition of particles with respect to their size would be very useful in that at least two types of particles, chemically produced aerosols (the hazes) and condensed droplets (the clouds) have been postulated to exist in the atmosphere. The aerosols may be condensation nuclei for the droplets.

Vertical and Horizontal Variability

Both the vertical and horizontal variability of the distribution of aerosols and cloud particles is of scientific interest. An indication of the vertical distribution is, of course, determined be the direct measurements made on the descending probe. The horizontal variablity (i. e., the patchy nature of the general cloud cover) can be determined only by a downward looking imaging system to image the cloud cover below the probe from an altitude of, perhaps, about 20 km to the surface. A spatial resolution of, perhaps, 100-200 m should be sufficient. The image should be as large as is possible and supportable by the communication limitation.

APPROPRIATE MEASUREMENT TECHNIQUES

Physical Properties

It is highly desirable that the required measurement capabilities be implemented using an in situ approach. A combination of measurement techniques will be required. These should include, at least, particle sizing spectrometry, nephelometry, and, if possible, particle charge measurements. In concept, several of these instruments may be incorporated into the same package, or may be used in tandem or with other experiments. For example, light scattering nephelometry might be incorporated with the particle size spectrometer, or a particle charge analyzer combined with an electrostatic collector used for particle composition analysis. Particles may be measured one at a time (no more than one particle in the sampling volume per measurement period) in order to avoid ambiguities in data interpretation or in an ensemble mode (many particles in a sampling volume) to ensure simplicity and reliability.

The particle size spectrometer, however, should measure particles one at a time rather than in an ensemble. The bulk of the size range, say up to 10 μm, may be measured using light scattering. One common technique involves the measurement of the total amount of light scattered by a particle from an incident light beam into an annulus defined by angles extending from as small as possible to perhaps 10° to 15° in the forward direction. A suggested approach for larger particles involves imaging or "shadowing" the particle onto an array of detectors whose response with and without a particle present defines the particle's dimensions. Several optical viewing volumes of different sizes must be defined to optimize the collection of both larger (and less frequent) as well as smaller (and more frequent) particles. Shapes of the larger particles may be inferred from the detector array response. For smaller particles, shape or asymmetry may be investigated by observing light scattered by each particle at a variety of angles extending from about 70° to 130° from the forward direction, and at least one forward and one backward scattering angle. The real part of the refractive index can also be derived on a single particle basis from analysis, using scattering measurements at optimum viewing angles, principally in the backward direction, and independently derived size information. The imaginary component of the refractive index is best inferred from combined measurements of atmospheric energy deposition (net flux divergence) and particle size distribution. Measurements made using light beams at several wavelengths and orthogonal polarization provide valuable supplementary information that is especially useful for helping to determine the sizes, shapes, and indices from scattering data, and in resolving ambiguities.

In addition to the single particle scattering instrument described above, a second, backup instrument involving light scattering from an ensemble of particles should be included. Such an instrument could furnish information on mean particle sizes, cloud layering, and particle density variations with altitude and rough determinations of particle shape, density, and indices. This instrument should have a sampling volume large enough to incorporate a representative sampling of the particle size distribution during each sampling period. A minimum suggested set of scattering angles includes three forward and one backward scattering angles at <5°, 15°, 45°, and >175°. Data from measurements at angles of 70°, 90°, and 120° are also desirable. Orthogonal polarization at several wavelengths for the incident light should again be used, if feasible.

Currently available particle charge measuring technology will require considerable development for application to this mission. Present day mobility analyzers measure electrical charge by electrostatically deflecting particles from a moving gas stream and measuring collected charge as a function of location along the flow. Development of such a technique for this mission might be considered, perhaps in connection with the development of an aerosol collection apparatus for a particle composition experiment. Other techniques used for very highly charged aerosols involve the induction of signals into a pickup coil or apparatus by the passage of the charged aerosol stream. It is doubtful, however, that this method will be applicable for the predicted charge levels of Titan aerosols.

As part of the development of instruments for these measurements, it may be necessary to consider the controlled ingestion of a sample for measurement or collection. It is important that the acquistion of the sample not disrupt the ambient particle flow and that the particles ingested into the sample volume be representative of particles in the ambient atmosphere. The in situ methods discussed above require analytical and experimental investigations of the atmospheric flow about the moving probe vehicle. At any given position near the body, atmospheric flow about the probe may seriously distort particle size distributions from those existing in the ambient atmosphere. These distortions will vary as a function of distance from the probe, location on the probe, and probe velocity. The simplest solution to this problem is to attempt to design the experimental equipment to sample volumes in relatively undisturbed flow regions far enough from the probe surface and/or to design the descent vehicle to provide access to sampling volumes in relatively undisturbed flow. In addition, very careful aerodynamic design of inlets and sampling devices is also required.

Optical Properties

To accomplish the goals of the above described measurements requires net flux radiometers measuring upward and downward fluxes in a broad thermal band (centered at about 18 μm) and at solar wavelengths. Computations, assuming horizontal homogeneity of the optical medium, have shown that only simple measurements of the upward and downward fluxes as a function of altitude are required, rather than the entire form of the radiation field, to determine the profiles of optical depth and single-scattering albedo. This is true for even small optical depths where there is a strong dependence of the radiation field on the solar zenith angle. The requirements for accurate flux measurements increase if the single-scattering albedo is near one. However, the haze particles on Titan are quite dark throughout the visible range, and measurements good to a few percent are adequate to determine the single-scattering albedo to good accuracy (to a few percent of one minus the albedo).

The expected downward flux levels as a function of wavelength for several altitudes are shown in Figures 2(a) and 2(b) for typical models of Titan's atmosphere. These flux levels are adequate to permit measurements at good spectral resolution (resolving power of 100) throughout the solar region. Figure 3 shows the expected variation of both the upward and downward flux levels as a function of altitude in a narrow spectral band near 0.75 μm for these typical models of the Titan atmosphere. Note that the upward solar flux is only some 10% of the downward flux, and we do not have the sometimes troubling situation of having to measure the small difference between two large numbers to determine the net solar flux. The models in the figure were computed for three different optical depths of a methane condensation cloud between 25 and 46 km altitude. Note the variation in the decrease in upward and downward fluxes through the methane clouds of various thicknesses.

The measurement of net thermal fluxes, however, generally poses a much more serious problem than the corresponding measurement of solar fluxes. The thermal fluxes generally do not vary so much over the planet as do solar fluxes. For Titan, the atmospheric temperatures are quite low throughout the atmosphere (below 90 K in the troposphere, between about 70 and 170 K in the stratosphere), and the thermal flux in either the upward or downward directions is relatively low. The difference between values, the net flux, is even smaller.

The wavelength dependence of the optical depth structure derived from the upward and downward flux measurements can be used to constrain the size of the particles. For this purpose, it is important to include wavelengths sufficiently long that the particle size parameter, defined by particle circumference divided by wavelength, is smaller than about 10. Several values between 1 and 10 are preferred. If the size parameter is larger than 10 for all the measurements, all that can be determined is that the particles are large compared to the longest wavelength of the measurement. The radius of photochemically produced haze particles is expected to be about a few tenths of a micron over a wide vertical range of the atmosphere, and measurements at wavelengths between 0.4 and 1.0 μm give size parameters in the range from about 1 to 5, thereby nicely constraining the particle size.

On the other hand, the possibility of condensate clouds of methane or ethane suggest the possibility of significantly larger particles, perhaps as large as many tens of microns in radius, which would require measurements at much longer wavelengths for optical depth variations to be useful constraints on particle size. The extension of flux measurements to the thermal infrared would be necessary for this technique to provide good determinations of particle size. This may not be altogether impossible. For example, the Galileo Probe Net Flux Radiometer has been designed to measure upward as well as net (and therefore also downward) fluxes in a cold atmosphere by using relatively broad spectral filters. The extent to which a similar approach would be useful for Titan remains to be investigated in the light of Titan's even colder atmosphere.

Perhaps the best constraint on the size of possibly large condensate particles (at least the best available from measurements of the ambient radiation field) would result from measurement of the azimuthal variation at small scattering angles of the direct solar beam penetrating into the top of the condensate cloud. Measurements of the azimuthal structure at a wavelength near 1 μm between a few degrees and about 20° of the solar direction may permit determination of particle size between about 1 and 20 μm radius. Of course, if condensate clouds are very patchy, measurements of the azimuthal structure may primarily reveal details of this patchy structure and may be useless for the determination of the size of the large particles.

In order to measure the azimuthal variations, it is useful for the instrument to be capable of determining the intensity peak at the azimuth of the sun and of measuring the intensity at several known azimuths relative to the sun. The solar flux radiometer (LSFR) on the Pioneer Venus mission included such a mode of operation utilizing the rotation of the descending probe. Such an instrument should perform even better on Titan than it did on Venus due to the extended, optically thin region of haze between altitudes of 50 and 300 km in Titan's atmosphere. Another approach may be to effectively rotate the field of view of the detector to define the acceptance angles relative to the sun.

Gaseous and Particulate Composition

In order to achieve a comprehensive understanding of the chemical processes and the current chemical and physical state of the particulates or aerosols of Titan's atmosphere, it will be necessary to concurrently obtain detailed inventories of the local gaseous atmosphere. The aerosols may act as a sink for the atmospheric species in that they may be selectively soluble in or adsorbed onto the organic phases of the aerosols. As an aerosol particle drops deeper into the atmosphere and eventually to the surface, it will become first colder and then subsequently warmer, first increasing and then decreasing the adsorption of local gases. Knowledge of the gaseous content of the aerosols may aid in characterization of these likely very complex organic materials in the atmosphere.

In order to obtain a gaseous inventory of the local atmosphere, two principal instruments should be used: the gas chromatograph (GC) and the mass spectrometer (MS). The GC and the MS can be viewed as complementary instruments for gaseous analysis. Alone, neither device provides a complete analysis. They accomplish a much more complete chemical analysis when used in parallel than either alone. For example, the GC readily separates and identifies molecules of the same molecular weight, e.g., CO, N_2, C_2H_4. However, the GC treats isotopes as a single chemical species, e.g., all Ar isotopes (mass = 36,38, 40) are determined as Ar. Further, simple GC's generally have only modest capability in conclusively identifying separated species, e.g., organics through C_6, because retention characteristics are the prime means of identification. Several components of such complex mixtures may have similar retention times. On the other hand, the MS readily determines individual isotopic masses, e.g., each argon isotope is independently measured. However, simple molecules of nearly equal molecular weight are not easily resolved without the use of very high resolution instruments, e.g., to fully resolve CO from N_2, a resolution of one part in 2800 is required. For increasingly complex molecules, the measurement of "cracking patterns", i.e., mass fragments derived from the original molecular species, are used to resolve molecular ambiguities. However, as the sample becomes more complex (as with mixtures of organics) the resolution problems become more severe because of interference from other molecular species and their associated mass fragments. Thus for complex samples, the GC and the MS are mutually supportive. The GC can identify and quantify the organics $\leq C_6$ and provide quantitative values for total rare gases, while the MS can determine isotopic ratios and aid the GC identification of organics $>C_6$.

Another instrument that is a candidate for gaseous analysis of planetary atmospheres is the combined GC/MS. A fully developed instrument of this type for flight application is not available at this writing. This instrument has many of the benefits of the parallel configuration, as well as some significant drawbacks. Unfortunately, to produce a functionally useful flight instrument, both the GC and the MS portions of the instrument are usually required to make significant compromises which reduce the benefit of the combined system to some degree. It is beyond the scope of this report to detail these problems here. It is clear, however, that the development of a GC/MS which minimizes or solves all the current problems would make such an instrument a very favorable candidate for analysis of complex, organic-containing atmospheres.

In order to obtain a detailed inventory of the aerosols in Titan's atmosphere, they must first be captured and then subjected to chemical analysis. Samples should be collected and analyzed at at least several altitudes. Additionally, it would be valuable to obtain size differentiated aerosol fractions for analysis. Because of the expected low columnar mass loading of haze aerosols, the collection device used will have to be highly efficient over a range of altitudes. It must also be capable of readily processing the sample at high temperatures, and require a modest share of spacecraft resources. Several collection schemes have been studied which would be adaptable to available analytical instruments. These include flat disk impactors, filters, wire impactors, electrostatic devices, and combinations thereof. Initial studies tend to favor wire impactors designed to hold particles electrostatically. The wire impactor shows the highest efficiency (most material collected per unit time per unit area) of the devices studied and could be used to collect and analyze size differentiated fractions if the spacecraft resources were available. In addition, due to its low thermal mass, the wire impactor requires relatively low power input for thermal treatment of collected samples.

The analysis of the collected aerosols is probably best performed by some means of stepwise heating followed by periodic chemical analysis of the evolved volatiles. Stepwise heating is indicated because the aerosols likely contain adsorbed gases, volatile organics, and complex non-volatile organics. A properly selected temperature sequence should allow the identification and quantification of each of these chemical groups. Pyrolysis—thermal breakdown (at temperatures of ≈ 500-600 C)—would be the final stage allowing the determination of the composition of the complex species.

Analysis of the evolved volatiles would be best conducted by using the same analytical instrument set as used for the atmospheric analysis, i.e., GC and MS. Such analyses would best be conducted by sharing a single sample from a collection and thermal processing facility. The analyses would be conducted as a subset of the atmospheric analysis at two or, at the most, three altitudes during the descent. Measurements at three altitudes translate to probably 12-15 analyses for each instrument if some size discrimination collections are conducted. While using the same instruments for aerosol analysis and for atmospheric analysis will reduce the total number of each type of analysis, it is likely to be the only way that both analyses can be conducted, due to the physical limitations of available space, weight, power, and bit rate. Again, a GC/ MS would be a candidate if it is available.

Horizontal and Vertical Variability

One of the major goals of the Cassini mission to Titan is to determine the nature and structure of the satellite's surface. A descent imager has been included in the strawman payload complement of the probe to accomplish that goal. In addition, the probe communication system has been sized to be capable of transmitting about 10 Kbit/sec during the last 70 km of the descent to support that imaging requirement. It is the recommendation of the workshop participants that the same imaging system be used to image the horizontal variability of the cloud layers below 70 km above the surface very effectively.

The calculations shown above (see figs. 2(a) and (b)) have indicated that there is sufficient light shortward of 1μm reaching the surface of Titan to accomplish such imaging. It is therefore recommended that the feasibility of using an imager with a conventional CCD array detector be examined for the cloud and surface imaging requirement. In addition, there is probably sufficient light available near the surface in several near infrared bands near 2 μm. Therefore, it is also recommended that an examination be made of the feasibility of using either a linear array or a CCD array of InSb detectors for imaging in the near infrared.

CONCLUSIONS AND RECOMMENDATIONS

1. We recommend that four types of in situ measurements of particulate properties and effects be made in the atmosphere of Titan with instruments on board the descent probe. The recommended measurement groups are listed below. Applicable techniques for the recommended measurements have been discussed in the previous sections.

(a) Particulate physical properties including size distribution, number density, mass, shape factors, complex indices of refraction, and electrical charge.

(b) Optical properties of the particulate matter and the effects of their interaction with solar and thermal radiation in the atmosphere. These measurements include upward and downward fluxes as a function of wavelength covering the solar spectrum and the infrared region characteristic of the expected atmospheric temperatures, net flux and the vertical gradients of the net flux, and phase functions for the particle as a function of altitude. In addition, the spectral characteristics of the ambient radiation should also be measured using a moderate resolution scanning radiometer, and the azimuthal variation at small scattering angles of the direct solar beam at a wavelength near 1 μm should also be measured. From these data, the single-scattering albedo of particles (or the complex indices of refraction), optical depths, particle size, and asymmetry factors can be inferred.

(c) Composition of the particulate matter at a number of altitudes including the measurement of the presence, composition, and concentration of molecular, elemental, and limited isotopic components of the particles and the gaseous species associated with adsorption or occlusion. In addition, the molecular, elemental, and limited isotopic composition of the surrounding atmosphere must be measured in order to obtain an understanding of the origin, evolution and eventual disposition of the particulate matter.

(d) Vertical and horizontal variability of the particles and clouds as seen from the descending probe by a visible or near-infrared imaging device.

2. We recommend that development programs be instituted to develop instruments to implement the measurements recommended above, taking into account problems particular to Titan's atmospheric environment and constraints of the proposed Cassini mission. The current schedule for a launch of the Cassini mission in 1995 dictates the need to address, in a timely manner over the next several years, several key definition and development issues associated with the recommended instrument set. A small amount of pre-project funds spent on these instrument development issues can prevent the need for substantially larger funding during the tighter schedule of the actual project and is likely to enhance the performance and science value of the final measurements.

3. We recommend that laboratory measurement programs be developed and supported to help characterize the properties of particles expected to be present in the Titan atmosphere. Techniques for both generating such particles and measurements of their properties should be considered.

REFERENCE

1. "Cassini - Saturn Orbiter and Titan Probe", ESA/NASA Assessment Study, ESA Ref: SCI(85)1, August 1985

Table 1. Cassini Titan Science Objectives

(1) Determine the abundances of atmospheric constituents (including any noble gases); establish isotope ratios for abundant elements; constrain scenarios of the formation and evolution of Titan and its atmosphere.
(2) Observe vertical and horizontal distributions of trace gases; search for more complex organic molecules; investigate energy sources for atmospheric chemistry.
(3) Measure winds and temperatures; investigate cloud physics, general circulation and seasonal effects in Titan's atmosphere.
(4) Determine the physical state and the composition of the surface; infer the internal structure of the satellite.
(5) Investigate the upper atmoshere, its ionization, and its role as a source of neutral and ionized material for the Saturn magnetosphere.

Table 2. Attendees of the Workshop on the Measurement of Particles in the Atmosphere of Titan

Boris Ragent, ARC, Chairman	Christopher McKay, ARC
Tobias Owen, SUNY/Stony Brook	Glenn Carle, ARC
Byron Swenson, ARC	Owen B. Toon, ARC
Robert Knollenberg, PMS, Boulder	Vern Oberbeck, ARC
James Wilson, U. of MN	Rudi Pueschel, ARC
James Rosen, U. of WY	Jon Bader, ARC
Martin Tomasko, U. of AZ	Raymond Reynolds, ARC
Gerald Grams, GA Tech.	Thomas Scattergood, SUNY/ARC
Shelly Pope, U. of AZ	Dean O'Hara, SJSU/ARC

Table 3. Agenda for the Workshop on the Measurement of Particles in the Atmosphere of Titan

Workshop Objectives	B. Ragent
Description of Cassini Science Goals	T. Owen
Description of the Cassini Mission and Titan Probe System	B. Swenson
Review of Atmospheric Particle Models	O. B. Toon
	M. Tomasko
	S. Pope
In-House ARC Development Activities	V. Oberbeck
Tentative Measurement Specifications	B. Ragent
Discussion	All
Report of Workshop	All
Recommendations	
Report Outline	
Writing Assignments	

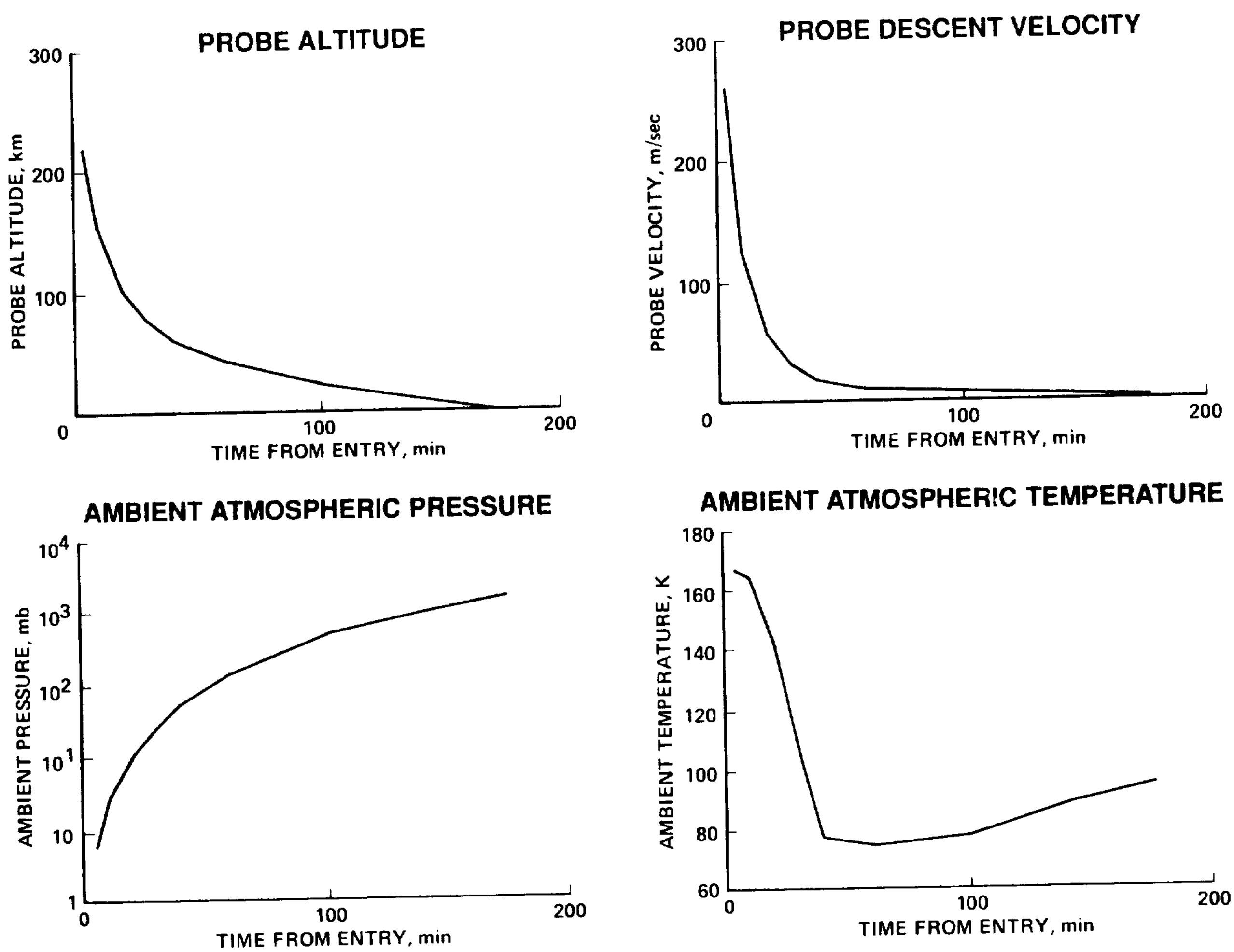

Figure 1. Probe descent profiles.

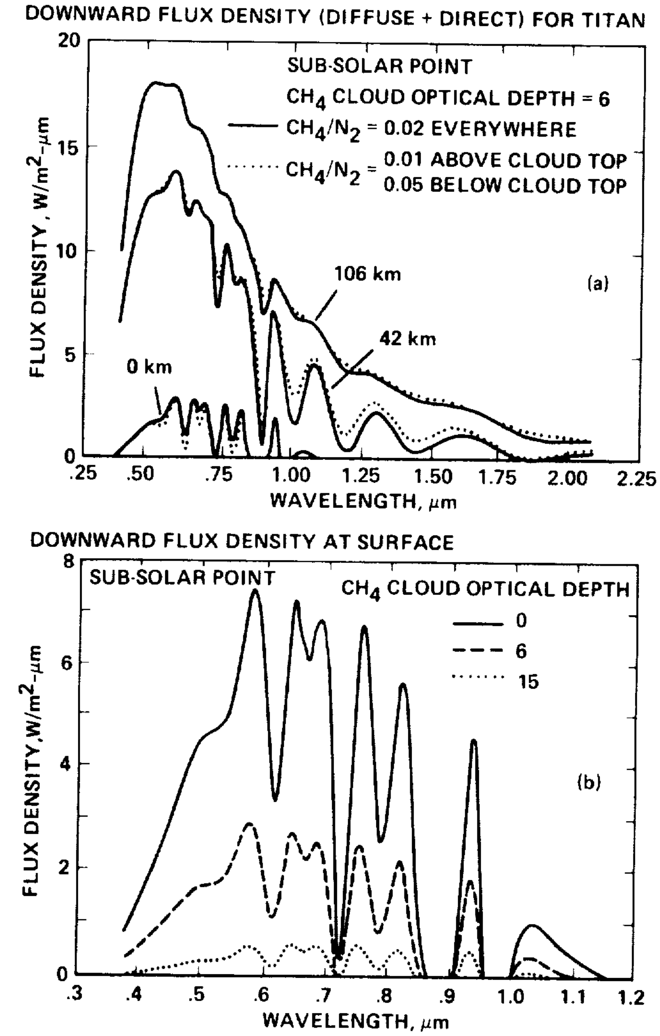

Figure 2. Calculated downward fluxes as a function of wavelength. (a) Calculated fluxes at three altitudes; (b) calculated fluxes at the surface.

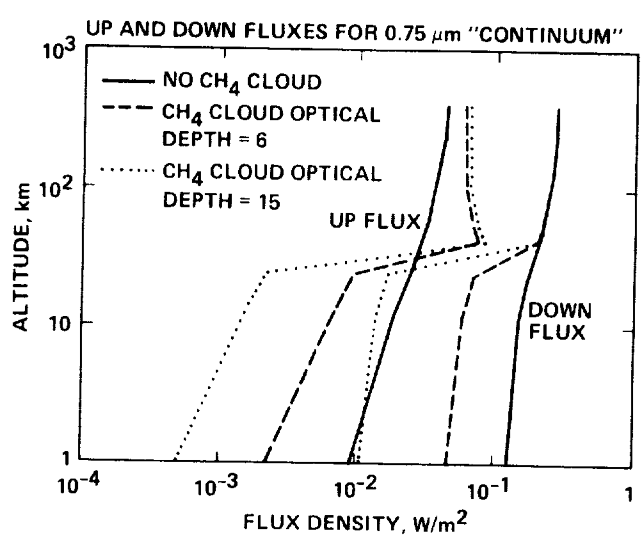

Figure 3. Altitude dependence of calculated up and down fluxes for various CH_4 cloud optical depths.

PART II

REPORT OF A

WORKSHOP ON RADIATION

MEASUREMENTS AND IMAGERY

IN TITAN'S ATMOSPHERE

SUMMARY

The planned 1995 joint ESA–NASA Cassini mission to the Saturnian system will include an atmospheric probe to be dropped into the atmosphere of Titan for in situ measurements during descent. Because of the unique properties of the Titan atmosphere, it is necessary to consider the peculiar requirements for such measurements and applicable techniques. The proceeding of a workshop dealing with the measurement of radiation in the atmosphere of Titan is presented. The workshop was held in December of 1986. The proceeding was first published and distributed informally, and is presented here with only minor editorial changes. This proceeding for the workshop on radiation measurements and imaging contains a discussion of the importance of radiation measurements and imaging, and presents a summary of experience with such measurements made from entry probes. These are followed by a description of appropriate measurement techniques and conclusions and recommendations.

INTRODUCTION

A workshop dealing with radiation measurements and imaging in the atmosphere of Titan was convened at NASA Ames Research Center on December 16 and 17, 1986. This workshop was the second in a series dedicated to attempting to define better the types of measurements and requisite instrumentation required to document effectively the atmospheric and surface properties of Titan. The data are to be obtained from a descending probe, as part of the Cassini mission to Saturn and Titan. This document is issued as an addendum to the proceedings of the first workshop (See Part I of this report), and readers are referred to those proceedings for background and overlapping information on the desirability and utility of radiation measurements and imaging. The list of attendees, agenda, goals of the workshop, and a listing of a strawman "Model Science Payload" for the Titan probe (as originally proposed by a joint ESA-NASA committee) are given in Appendix A.

This report is an edited compendium of contributions from the attendees of the Workshop and the editors express their appreciation to all contributors.

SUMMARY RECOMMENDATIONS

The Workshop participants conclude that the measurement of radiation in Titan's atmosphere requires the development of several instruments specifically designed for the required measurements rather than totally imitative of previous designs. Specifically, instruments (1) to measure the spectral deposition of solar energy, (2) to measure direct and diffuse solar fluxes in several wavelength bands, (3) to measure broad-band infrared fluxes, and (4) to image the clouds and surface of Titan (at several wavelengths) should be developed. Solar flux measurements and imaging emerge as capable of potentially yielding the least ambiguous data, whereas measurements in the infrared, although extremely useful, may be more difficult because of the expected small fluxes.

Atmospheric inhomogeneities may cause problems in interpreting much of the data, especially in the lower atmosphere where non-uniform condensation clouds may be present. Imaging at these altitudes and down to the surface should be helpful here, as well as inherently useful for cloud and surface studies.

Furthermore, the need for a well planned instrument test program and facilities capable of testing over the entire expected range of signals and environmental parameters, including radiation fluxes, temperatures, and atmospheric flow conditions, was strongly emphasized as essential for a successful program.

The workshop participants recommended that studies be initiated aimed at developing the required instrumentation. In this connection it appears, conceptually, that several instruments might well be integrated into a single package.

IMPORTANCE OF RADIATION MEASUREMENTS AND IMAGERY

Radiation measurements are crucial to understanding several fundamental physical processes in a planetary atmosphere. The thermal balance of the entire atmosphere is determined by the penetration and absorption of sunlight and the emission of thermal radiation. While measurements from outside the atmosphere of the spherical bolometric albedo can indicate the total amount of sunlight absorbed, the vertical structure of the atmosphere depends on where this energy is absorbed and how it is transported vertically and horizontally around the planet. This requires measurements of the solar heating and thermal cooling rates with altitude. The solar heating and thermal cooling rates will integrate to the same values over the surface of the planet (in the absence of an internal energy source), but these two rates will generally vary significantly with altitude and location on the planet. The differences provide the forcing for atmospheric circulation, a process which modifies the amount and distribution of atmospheric haze, and, in turn affects the penetration and escape of solar and thermal radiation. The production of the photochemical haze is also controlled by the radiation field. Finally, through their dependence on radiative opacity, measurements of the radiation field indirectly indicate the presence and mixing ratio of atmospheric trace gases and the size and number densities of atmospheric aerosols.

In the troposphere, condensation clouds of methane, ethane, or other hydrocarbons are possible. These clouds could be very inhomogeneous, similar to conditions in the troposphere of the Earth. In this region of the atmosphere, images of the clouds would be extremely useful for revealing the extent to which measurements along the probe entry trajectory might differ from conditions a short distance away. From some altitude below the clouds, the ground would be clearly visible. Images of the ground would reveal much about the relationship between the solid planet and the atmosphere. The presence of solid ground with vertical relief, craters, drainage features, extensive oceans, or possible icebergs would be of great interest. Further, spectral information on the reflectivity of the surface seen in the images would add valuable compositional information.

EXPERIENCE WITH ENTRY PROBE RADIATION MEASUREMENTS

A. Introduction

Solar and thermal radiation measurements by atmospheric entry probes can provide direct information on the radiative forcing of atmospheric motions and thermal structure, as well as valuable constraints on the vertical distribution of minor gases and suspended particulates. The vertical divergence of net radiative flux density at a given level defines the radiative power deposited per unit volume at the same level. Radiative heating and cooling rates calculated from the deposition profile are balanced over the long term by advection or latent heating. Given the atmospheric thermal structure, the net flux density in moderately strongly absorbing bands can be used to infer the vertical distribution of the absorber. Although the above comments refer to both solar and thermal radiation measurements, the practical problems in making the measurements are quite different for these two spectral regions. Measurement of the flux and deposition of solar radiation has been highly successful both on Venera (Moroz et al., 1980) and the Pioneer Venus Sounder Probe (Tomasko et al., 1980). However, the measurement of planetary radiation at thermal wavelengths has proven to be fraught with difficulties, the most important of which are discussed in the context of Pioneer Venus and Galileo experience (see Appendix B).

B. Solar Radiation

Measurements of the solar radiation fields have so far been made only in the atmospheres of Venus and Earth. In the case of the Earth, considerable attention is given to obtaining a proper average over the large vertical and horizontal inhomogeneities. Measurements of both direct and diffuse radiation are useful as well as any knowledge of particle phase functions and underlying albedo inferred from data obtained by other means. Not only must diffusing plates or hemispherical collectors generally be used to give the proper weighting of the radiation field with zenith angle, but measurements must be repeated many times at many locations to average over changing local conditions. This is especially important for the Earth since water and ice clouds are poor absorbers, flux divergences are usually small, and the subtraction of large numbers to obtain a small number produces a noisy result. The clouds on Venus seem to exhibit more continuous cover than is the case on the Earth, and are locally less patchy. Measurements have been made of the upward, downward, and net flux in broad spectral bands by the Pioneer Venus mission and with greater spectral resolution by the Venera missions (see, for example, Tomasko et al. 1980, and Moroz et al. 1980). As mentioned, considerable care must be used in the measurement of the upward and downward fluxes so that their difference can be obtained with sufficient accuracy. The net flux is the total amount of sunlight absorbed below the altitude of the measurement. The difference in the net flux at two levels is the amount of solar energy absorbed by the intervening layer of atmosphere, and will be poorly determined if the measurement errors in the individual upward and downward measurements are comparable to their difference. For Venus in visible wavelengths, the difference between upward and downward fluxes is about 10%, several times larger than the roughly 2% accuracy in the relative upward and downward measurements typically attainable when separate detector systems are used for upward and downward viewing. In principle, more accurate measurements are possible when the same detector system is rotated to view both upward and downward. Such an approach has been used on the Venera missions.

For a mission to Titan, several factors indicate that solar radiative flux measurements will be easier to make than in the atmospheres of the Earth or Venus. Firstly, throughout the greater part of the descent, the atmosphere of Titan is filled with small, photochemically produced haze aerosols. These particles are present from great altitudes to the base of the stratosphere. In this region of the atmosphere, vertical motions of the atmosphere should be slight, and the cloud should be much more similar to the relatively homogeneous smog on Venus than to patchy condensation clouds in the Earth's troposphere. Secondly, these smog particles in Titan's atmosphere are known to be extremely absorbing at visible wavelengths; the visible geometric albedo of Titan ranges from less than 0.1 at blue wavelengths to a maximum of about 0.3 in the red wavelengths. This means that the atmosphere absorbs most of the sunlight incident on the planet, and that the relative difference between upward and downward fluxes will be much greater than on Venus or in the Earth's nearly nonabsorbing water clouds. The expectation of reasonable horizontal homogeneity and absorbing haze particles should make solar flux measurements on Titan relatively straightforward, at least above altitudes at which possibly inhomogeneous condensation clouds are encountered.

C. Thermal Radiation

Aside from the Earth, thermal net flux measurements have so far only been attempted on the Pioner Venus mission. In the Venus atmosphere the principal constituent (carbon dioxide) absorbs strongly at thermal wavelengths. Consequently, the difference between the upward and downward flux is extremely small and measurements of the net flux require cancellation of the instrument asymmetries to a high order of accuracy. Despite several problems, postflight instrument calibration measurements and models produced reasonable thermal flux results from the flight measurements. An instrument similar to one flown on the Pioneer Venus mission is planned for the Galileo entry probe of Jupiter. The experience gained on the Venus mission has been crucial for the successful design and operation of the Jupiter instrument. A description of the difficulties involved in the cases of the Venus and Jupiter instruments is given in Appendix B.

On Titan, the main atmospheric constituent (nitrogen) can provide an important source of thermal opacity at some wavelengths due to collision induced absorptions. In addition, the thermal flux levels are very low due to the cold temperatures (between some 70 and 150K). It remains to be seen whether a thermal net flux instrument is practical for a Titan entry probe mission. A thermal instrument for Titan would be limited to a few very broad channels, yielding total net flux, and perhaps net flux in a band where particle opacity might be important. It seems likely that other techniques may be more sensitive for measurements of the presence and abundance of trace gaseous constituents.

D. Imaging

To date, no imagery has been attempted from a probe during its descent in a planetary atmosphere. Imagery has been performed from landed unmanned probes, for example, from the Viking Mission Mars and the Venera Mission Venus landers.

DESIRED INFORMATION

The following list summarizes the desired information that may be obtained from radiation measurements and imagery in the atmosphere and of the surface of Titan.

(1) The most basic information needed is about the deposition of solar radiation in the Titan atmosphere as it varies with altitude, and the reradiation of longwave radiation as it varies with altitude.
(2) Information on the spectral variation of the information needed in (1).
(3) Optical depths (gas + particulates) in wavelength bands defined by (2).
(4) Specific information on vertical column content of gaseous and particulate absorbers and nonabsorbers.
(5) The morphology of inhomogeneous structures composed of particulates such as clouds, including a description of both vertical and horizontal variations.
(6) Haze and cloud particle size distribution and composition.
(7) Surface reflectance with spectral and spatial resolution.

DESCRIPTION OF APPROPRIATE MEASUREMENT TECHNIQUES

A. Solar Flux Measurements

The profile of the absorption of solar radiation as a function of altitude is needed for thermal balance studies. These measurements need to cover the spectral range where significant solar energy is contained, from about 0.3 to about three microns in wavelength. It is also important in understanding the mechanisms responsible for the heat balance of the atmosphere to know the wavelengths at which energy is being absorbed. Sufficient spectral resolution should be used to resolve the methane absorption bands in the red part of the spectrum. Finally, the upward and downward solar flux, in addition to the net flux, should be measured so the optical depth structure of the clouds can be determined. It is useful to separately measure the downward direct flux as well as the sum of the direct and diffuse downward flux for additional information on the cloud structure.

B. Thermal Flux Measurements

Here the integrated net thermal flux from about three to several hundred microns should be measured if possible. The divergence of the thermal net flux gives the radiative cooling rate as a function of altitude. The sum of the thermal cooling rate and the solar heating rate gives the net radiative heating or cooling of the atmosphere, which provides the forcing for atmospheric dynamics. If a sufficient signal-to-noise ratio is available at the low temperatures on Titan, a few narrower bands could be used to determine the thermal opacity of the cloud and aerosol particles at infrared wavelengths where they are expected to make important contributions to the total opacity.

C. Imaging Data

Two types of imaging data would be quite useful. An attempt should be made to image the horizontal structure of any condensation clouds in the troposphere to determine the nature of the variations in the cloud coverage at sites other than along the entry trajectory of the probe. Several images having a wide angular field of view centered roughly 45 degrees below the horizon seem reasonable. If images could be obtained in a methane band of intermediate strength as well as in a continuum region, it might be possible to range specific cloud features seen in the images.

The second type of imaging data should be of the surface. The image should have a wide field of view to provide information on the variations in surface conditions over as wide an area as possible. Some portion of the image should contain relatively high spatial resolution if possible. Finally, the image should have spectral information on the reflectivity of some of the regions seen in the images, preferably from a spectrometer sighted with the imager. If permitted by the telemetry rate, imaging data in a few separate spectral channels would be useful for the construction of a color image.

D. Suggested Instrumentation

Direct/Diffuse Solar Radiometer– This instrument should be capable of measuring total, diffuse, and, hence, direct, radiation over a hemisphere in at least several wavelength bands in the visible and near-IR spectrum. We may conceptually consider a specially designed, hemispherically collecting (and/or a diffusing flat plate collector configuration), together with an oscillating shader to occult the direct solar beam. Motion of the occulting shading device relative to incident solar radiation might be accomplished by internal mechanical means or probe rotation. Ideally, this instrument should be capable of measuring both downwelling radiation and upwelling radiation in near simultaneity so as to determine the net flux at each altitude. Subtraction of the net fluxes at two altitudes then yields the energy deposited in that altitude range in the measured wavelength band. It is probably not necessary to employ an occulting device to measure the upwelling radiation, and, for regions of strong atmospheric absorption, it may even not be necessary to measure upwelling radiation to obtain approximate net fluxes. During the probe descent, measurements should be made as frequently as is consistent with available data rates.

Solar Scanning Radiometer– This instrument is intended to measure the spectral distribution of the energy in the ambient radiation as a function of probe altitude. It may be considered as a separate instrument, or combined with the above instrument to form a single integrated package. The spectral resolution should be sufficient to easily resolve the various methane bands and cover the range from about 0.3 to 3.0 microns, requiring a measurement bandwidth of the order of 0.01 microns in the visible and near infrared. Data rate limitations and the large number of channels required to adequately document a spectrum may limit the possible number of spectra reported. It is highly desirable that the spectral variation of both total and diffuse fluxes be determined so as to obtain spectral variations of optical depths with altitude.

Multispectral Infrared Radiometer– Net flux measurements in at least one wide spectral infrared band (say 3.0 to 200 microns), and, desirably, several narrow band channels, are required to derive radiative cooling rates and thermal opacities. Hemispherical measurements of up- and downwelling fluxes are desired, but practical considerations usually dictate that data be obtained at only one (or at most a few) angles, and that the integrated fluxes be derived using assumptions about the angular dependence and symmetry of the radiation field. For the case of single angle measurements, angles of 45 degrees with respect to the zenith and nadir are to be preferred. A description of a typical instrument designed specifically for the Jupiter Galileo Probe, together with a discussion of some of the difficulties and pitfalls involved in the design of such an instrument, are given in Appendix B.

Imager– The design of the imager depends to a significant extent on the data rate the probe is able to support. If a data rate of 1000 bps is available for roughly the last hour of the descent, some 4×10^6 bits could be transmitted. If each pixel were represented by 8 bits and no data compression were used, 5×10^5 pixels or about ten 200×200 images could be transmitted. Several of these roughly ten images should be images of the clouds taken at higher altitudes. In this case too few total images are transmitted to permit the use of different color filters. However, some estimates for the probe telemetry rate are higher, and some data compression is possible. If the rate is such that the number of pixels that could be transmitted is large enough, then the use of three or four color filter bands become attractive. These might include a modest methane band as well as three broader bands to permit a color reconstruction. Care should be taken that the shortest wavelength channel is sensitive enough to respond to the amount of solar energy that reaches the ground.

Comments and Suggestions for Additional Instrumentation– In general, experience with measurements of radiation in the Earth's atmosphere has indicated that the design of instruments should be as simple as possible consistent with obtaining the desired data. Also, because of the rather severe limitations on probe weight, volume, and power, it is important to use relatively simple instrument concepts whenever possible and to consider combining instrument capabilities. A solar flux spectrometer could be combined with an optical imager in a single package and we believe that such a possiblity should be investigated. It may be possible to use a single two-dimensional detector array to record the imaging data as well as separate spectra of the upward and downward solar flux. The sensitive range of silicon detectors from 0.4 to 1 micron covers most of the range over which solar energy is likely to penetrate to significant depths in Titan's atmosphere due to the strong methane absorption bands between 1 and 3 microns and the decreasing fraction of solar energy found at these longer wavelengths. The spectrometer should have a resolution sufficient to resolve the methane absorption bands at red wavelengths. Because of the relatively large difference expected between upward and downward fluxes (about a factor of ten) it seems possible to use separate optics and separate portions of the detector array to record the fluxes in these two directions. In drawing conclusions, it is necessary to be aware of the fact that the direct solar beam will contribute significantly to the downward flux throughout the stratosphere due to the small optical depths estimated for the photochemical haze in this portion of the atmosphere. Measurements of the direct downward solar flux are useful for determining the optical depth of the aerosols above the probe, and, if possible, measurements of the solar aureole would give useful information on the size of the aerosol particles above the probe (see Part I of this report for a discussion of the indirect information about particle properties contained in the internal radiation measurements). The data rate for the Cassini mission is capable of supporting a vertical resolution in the flux measurements of a fraction of a scale height.

It is also desirable that several (at least two) narrow angle field-of-view photometers viewing off-zenith (pointing, for example, at 30 and 60 degrees from the zenith) be included. One wavelength is sufficient but it should be the same as one of the wavelengths used in the visible to near IR net flux sensor. This measurement is simple, but valuable, because it will provide additional constraints on the parameters used in model calculations of the radiation field.

Experience in the Earth's atmosphere has also shown that cloud or surface albedo inhomogeneities cause difficulties in attempting a straightforward analysis of flux divergence by simple differencing of net flux observations, and that imagery may be essential to avoid serious pitfalls. Finally, the focussing effect of clouds may produce unusually anomalous readings of solar flux when sun, cloud edge, and instrument are in line.

CONCLUSIONS AND RECOMMENDATIONS

We recommend that four types of in-situ measurements of radiation be made in the atmosphere of Titan with instruments on board the descent probe. The recommended measurement types are listed below.

(1) The spectral intensity of the direct, diffuse, and total radiation in the visible and near infrared (0.3 to 3.0 micrometers) as a function of altitude in the Titan atmosphere.

(2) The net flux in at least several wavelength intervals in the range of 0.3 to 3.0 micrometers.

(3) Imagery, presumably looking downward, of the clouds from at least the lower atmospheric cloud region to the surface. A number of images of the surface should be taken from an altitude of about 10 kilometers to the surface in several wavelength bands in the visible and near infrared wavelength regions, if possible.

(4) Net flux measurements in the infrared for a number of wavelength intervals, including at least one wide band channel extending from 3.0 to several hundred micrometers. Other wavelength bands in the infrared should be chosen for their usefulness in clarifying the effects of atmospheric species, considering the expected atmospheric temperatures. The possibility and efficacy of such infrared net flux measurements should be carefully evaluated based upon current technology and experience with the Pioneer-Venus and Galileo instruments before final designs are fixed.

In addition to the above measurements, variations of the radiation field with azimuth and zenith angles should be measured at several angles using small angular resolutions, in order to verify homogeneity of the fields and to validate model calculations.

We recommend that development programs be instituted to develop instruments to implement the recommended measurements, taking into account problems peculiar to Titan's atmospheric environment and constraints of the proposed Cassini mission. The current schedule for a launch of the Cassini mission in 1995 dictates the need to address, in a timely manner over the next several years, several key definition and development issues associated with the recommended instrument set. A small amount of pre-project funds spent on these instrument development issues can prevent the need for substantially larger funding during the tighter schedule of the actual project and is likely to enhance the performance and science value of the final measurements.

As mentioned above the design of a combined imager/solar radiometer seems possible and quite attractive for a Titan entry probe mission. It could contribute very valuable information on a broad range of important problems. These include the vertical profile of the size, number density, and optical properties of aerosols; the solar heating profile for thermal balance and dynamic studies; and the morphology of the tropospheric clouds and of the surface. Additional compositional information on the surface is obtained from the combination of the images and the visible reflection spectrum of the surface.

In view of the broad capability of such an instrument, we recommend that NASA support the design and development of a combined imager/scanning radiometer and net flux radiometer as well as separate simpler instruments that would be ready in time for the Cassini mission. Also, in view of the importance of these measurements we recommend that a simple solar radiometer backup instrument be flown in addition to any more complicated instruments. Note that while a few radiometers have been flown on past probe missions, no imaging radiometer with the capabilities required for the Titan mission has yet been built. While the design considerations are relatively straightforward, development should begin early to obtain instruments that best meet the specified requirements and yet fit within the narrow envelope available for probe instruments.

There is no question that thermal flux measurements would also be very useful on a Titan entry mission. We believe that the technical approach for the thermal instrument is sufficiently different from that needed for the solar radiometer/imager that a separate instrument is probably required for thermal flux measurements. We recommend that NASA fund a study to determine whether a modification to an instrument like the Galileo Net Flux Radiometer is feasible for a Titan entry probe mission. While the interest in the thermal flux measurements is high, the technical difficulties seem significantly greater than for the solar radiometer. It is important to begin early to consider whether thermal flux measurements are feasible on a Titan probe.

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APPENDIX A

AGENDA, GOALS OF THE WORKSHOP, ATTENDANCE LIST, AND MODEL SCIENCE PAYLOAD FOR THE TITAN PRBOE

AGENDA

Workshop on Radiation Measurements and Imagery in Titan's Atmosphere
December 16-17, 1986
NASA Ames Research Center

Tuesday, December 16, 1986

Time		
0900-0910	Welcome and Workshop Objectives	B. Ragent
0910-0920	Logistics Payment, Agenda, Dinner	B. Swenson
0920-0940	Description of Cassini Science Goals	T. Owen
0940-1000	Description of Mission and Probe Systems	B. Swenson
1000-1120	Review of Atmospheric Models and Radiation Calculations	R. Samuelson B. Toon M. Tomasko
1120-1230	Lunch	
1230-1400	Participant Presentations	All
1400-1700	Discussion of Measurement Objectives, Problems, and Techniques	All

Wednesday, December 17, 1986

Time		
0900-1200	Discussion of Workshop Recommendations	All
1200-1300	Lunch	
1300-1500	Report Outline and Writing Assignments	All

GOALS

As a member of the Workshop on Radiation Measurements and Imagery in Titan's Atmosphere, participate in the group meeting during December 16 and 17, 1986 in the following manner:

1. Review the background of the Cassini atmospheric probe mission to Titan including the basic science goals and objectives, the proposed mission and system description, current models of the Titan atmosphere, and the tentative scientific and engineering specification for experiments to measure radiation and imagery from the probe (table 4).
2. Discuss and develop a consensus option on the scientific measurement specifications for desired radiation measurements and imagery, appropriate techniques of measurement, instrument design concepts, and the instrument support requirements and interface with the probe.
3. Submit written responses to the Chairman's assignments as required.

ATTENDANCE LIST

TITAN WORKSHOP ON RADIATION AND IMAGERY

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Table 4. Model Science Payload (Probe)

	Mass (kg)	Power (W) Aver.	Power (W) Peak	Data Rate (bps) Min	Data Rate (bps) Max	Data Rate (bps) Impact/surface	Characteristics
1. Atmospheric Structure Instrument (ASI)	3.8	6.3	13.0		18	18	Pressure sensors (10^{-3} to 1.6 bars), temperature sensor (70k to 200k). Test axes accelerator unit (3g to 50g)
2. Nephelometer (NPH)	4.4	13.5			10	0	Cloud particle size measurement (0.2 to 20 μm). Laser source, forward and backward scatter detectors. Requires boom extension after probe entry.
3. Neutral Mass Spectrometer (NMS)	12.0	40.0		98	195	98	Determine chemical composition of gas and condensed phases. Mixing ratio of atomic and molecular mass 10-200, sensitivity 1 ppm.
4. Gas Chromatograph (GC)	3.0	8.0	20.0	98	195	98	Complementary to NMS technique.
NMS and GC Combined (GCMS)	13.0	36.0	45.0	32	500		Chemical composition and mixing ratio 10^{-8} for atomic and molecular mass 1-250 amu. Gas inlet near apex of probe fairing.
5. Aerosol Collector Pyrolyzer (ACP)	4.7	40.0	60.0		50	0	One high altitude collecting device at high probe speed. One low altitude collecting device at low probe speed (FAN). Coupled to GC and MS for analysis. Collecting devices to be extended outside boundary layer.
6. Near Infrared Spectrometer (NIRS)	3.0	8			35	35	Dual beam grating spectrometer. Optical assembly directing beam either to retroreflector (gaseous path meas.) or to cooled plates (conc. frosts). Spectral range 2.5 to 14 μm linear array detector.

Table 4. Model Science Payload (Probe) (concluded)

	Mass (kg)	Power (W)		Data Rate (bps)			Characteristics
		Aver.	Peak	Min	Max	Impact/ surface	
7. Descent Imager (DI)	3.0	7		500 at 10km	1000 at 1km	0	Downward pointing telescope; focal length 8 cm. Spectral range 1 to 8 µm. Operates during the last 10 km of descent. Requires spin.
NIRS and DI Combined Near Infrared Descent Spectro-Imager (NIRDSI)	4.0	8	16	200 at 10km	200 at 1km	16	Two small telescopes (upwards and downwards). Spectral range 2.5 to 5 µm FOV 12°. Detector 64 element array, 8 bit grey scale.
8. Lightning and Radio Emission Detector (LRD)	2.2	2.3	3.3	8		0	Magnetic antenna 100 Hz-10 MHz. Two optical sensors. Requires spin.
9. Radar Altimeter Science (RAS)	0.3	5	50	500 at 10km	1000 at 1km	100	FM/CW operation, 2 GHz, 500 mW trans. power. 0.25m planar antenna. Beam width 30°. Subsurface sounding capability (500m).
10. Probe Doppler Tracking Science (DS)	0.2/0.4 1(PIH)*	5 10(PIH)*	25		10	10	Requires ultra-stable oscillator on both probe radio relay transmitters.
11. Impact/Surface Science (I/SS)	4.0	5		1	10	100-1000	Waveform transmission of accel. data during impact. Other dedicated inst. to be determined within present constraints.

*Requires extra hardware on Probe Integrated Hardward (PIH)

APPENDIX B

EXPERIENCE WITH ENTRY PROBE THERMAL RADIATION MEASUREMENTS

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A. THE PIONEER VENUS EXPERIENCE

In December 1978 Venus became the first and only planet visited by probes designed to measure thermal radiation within the atmosphere. The U.S. Pioneer Venus Mission deployed one large probe (the Sounder probe) carrying the Large probe Infrared Radiometer (LIR), and three small probes (North, Day, and Night probes), carrying the Small probe Net Flux Radiometer (SNFR). In spite of quite different design philosophies embodied in the SNFR and the LIR, they both fell prey to significant errors as they descended below the Venusian cloud deck. Although the gross characteristics of these errors are now known sufficiently to provide approximate corrections to the data (Revercomb et al. 1984, and Figure B-1), the net impact on the scientific return from these experiments has been serious enough to warrant a review of their histories so as to avoid such problems in future missions.

The SNFR instrument (Figure B-2), carried by the small probes, used an external, wide field-of-view, "flux-plate" detector similar in concept to certain net flux radiometers used for earth applications by the meteorological community (Sromovsky et al., 1980). A blackened horizontal glass plate exposed to a nearly spherical view of the ambient radiation field responded by developing a vertical temperature gradient proportional to the net flux of radiation through the plate. The temperature difference between the two sides of the plate was measured by a simple thermopile wound around the plate. To eliminate offsets and asymmetries between the two sides of the plate, the plate was flipped 180 degrees every second, and only the difference signal was retained as information. Diamond windows were provided to protect the plate surfaces from forced convective heat transfer. This instrument was inherently insensitive to the average flux, and responded directly to the net flux density spectrally integrated over the diamond passband.

The main problem encountered in obtaining the SNFR measurements was a small gas flow through the sensor head induced by the dynamic pressure gradient across the head. Because the flow reversed direction when the sensor was flipped, thermal perturbations of the flux plate acted just like those of the true net flux signal. This effect was not noticed in pre-flight laboratory testing because it had a very strong dependence on Reynolds number and was not measurable at the relatively modest Reynolds numbers reached in laboratory tests. Below the Venus cloud decks, where Reynolds numbers increased well beyond the initial range of laboratory testing, the effect became quite significant, reaching 60-100 W/m^2 at levels where the true net flux was less than 20 W/m^2. The irony of this situation is that it could easily have been avoided by sealing just one of the windows. The cure wasn't implemented because pre-launch aerodynamic testing was too limited to reveal the existence of the problem.

While the SNFR design gave priority to complete angular and spectral coverage, and direct sensing of net radiation, the design of the LIR was driven by a desire to have on-board radiometric calibration and multiple spectral channels. The LIR (fig. B-3) used an internal detector array and viewed the radiation field through a large diamond window inside the probe (Boese et al., 1980). The LIR sampled the radiation field near 45° above and below horizontal, chopping between them and returning the difference signal as a measure of the net radiation. A rotatable light-pipe was used to chop the detector view between up and down directions, and periodically also between two internal blackbody references. Six fixed detector channels measured radiation entering a fixed light pipe that was optically coupled to the rotating light pipe, which alternately flipped between a fixed up-looking light pipe and a fixed down-looking light pipe (or between the internal sources). This arrangement allowed for internal calibration but did so at a significant cost in symmetry of response.

The LIR symmetry in response to upward and downward external radiation fluxes (actually radiances) could have been upset by any of several factors which would have essentially the same effect. During the period when the NFR sampled the "upward flux," it also sampled radiation from sources inside the probe—as the light pipe moved from "downward" to "upward" orientations that it also scanned by the interior of the probe and ended by viewing the upward radiance through a different fixed light pipe. Because of angular response asymmetries in the rotating light pipe, misalignments between fixed and rotating pipes, slight differences between the two fixed pipes, and/or slight differences in the time spent in upward and downward positions, the fractions of radiation contributions from the external atmosphere and the probe varied with viewing direction. The result of this asymmetry is that the signal output was a combination of two terms: one term proportional to the net flux and a second term proportional to the difference between the fluxes from the interior of the probe and external atmosphere. Thus, as atmospheric temperatures continuously increased (while the interior probe temperature remained fairly constant), the extraneous second term eventually swamped the desired signal (see fig. B-1, Sounder Probe).

This explanation of the LIR error is confirmed by model results of Revercomb et al. (1984). The LIR error was probably not detected in pre-flight laboratory tests because most of these tests were conducted under conditions for which the asymmetry error had a relatively small effect. For example, near the surface of Venus the total thermal net flux is near zero, but the total one-way flux is more than 16,000 W/m^2 bigger than the flux from the interior of the probe, so that a 3 percent asymmetry in response produces an error of almost 500 W/m^2. On the other hand, in a typical calibration the mean external flux is almost the same as the internal flux, so that the 3 percent asymmetry produces a net flux error that is virtually zero. Laboratory testing at a mean external radiation temperature of 750K was made difficult by the fact that a 1 degree temperature measurement error leads to a net radiation error of the order of 1 percent of the mean radiation flux. At high temperatures it is difficult to obtain conventional blackbodies of sufficient accuracy to make such measurements. (Special rotating blackbodies are used in the testing of the Galileo NFR symmetry characteristics.)

The main general lesson to be learned from the NFR and LIR experience measuring thermal radiation on Venus is that instrument performance needs to be tested under conditions which simulate descent. While it may not be practical or necessary to simulate all characteristics of descent, it is certain that considerable effort should be invested in devising adequate verification tests. A more specific lesson from the LIR experience is that chopping between upward and downward views should be accomplished without varying the relative contributions of internal and external sources of radiation.

B. THE GALILEO EXPERIENCE

The Galileo Net Flux Radiometer (NFR) was originally conceived as a minor modification of the Pioneer Venus LIR. As the limitations of that design became clear, it was necessary to initiate a completely new optical design. The revised design achieved chopping of the radiation field by rotation of all optical elements as a unit, including the detector array, the single diamond window, and all elements between. An external cover was used to limit exposure of the optical head to the external atmosphere. This cover has two apertures through which the rotating optical head views the atmosphere, and two blackbody references, one servo-controlled to a high temperature and one drifting at ambient temperature. A minor flaw in this design arises from asymmetries in the transition between the up and down viewing apertures. The passage of the window by the cover wall during these transitions produces a spurious signal which is proportional to the flux difference between the wall and the average atmospheric flux, and to the time asymmetry between up and down transitions. Adequate control of the time asymmetry error requires very precise control of the stepper motor which flips the optical head. Current regulation is one factor needed to achieve stability over a wide temperature range and over the long cruise time.

Other areas of concern about the Galileo NFR which are expected to be resolved before launch are these: detector failure due to pressure and/or thermal stresses; inadequate window heater power to prevent condensation on the NFR window; detector sensitivity to spurious pressure modulations; and thermal crosstalk between detector elements.

After these problems are corrected, and with changes only in some spectral filters, the Galileo NFR could provide useful broad-band measurements in Titan's atmosphere. For example, the NFR total thermal channel (3 microns –200 microns) returns one measurement every six seconds with a noise level of about 0.04 W/m^2 for each value. This is about 1% of the total upward thermal flux at the surface of Titan, assuming a 94 K surface temperature. The noise levels in the two NFR solar channels (0.3–3.5 microns; 0.6–3.5 microns) are both near 0.01 W/m^2, which corresponds to better than 0.1% of the solar constant at Titan's mean distance from the Sun.

C. SUMMARY OF PIONEER AND GALILEO EXPERIENCE

The basic characteristics of the Pioneer Venus and Galileo thermal flux instruments are summarized in Table B-1. Lessons to be learned from work on these instruments might be summarized as follows:

1. Do not allow internal radiation sources to contribute variable inputs as the detection system is chopped between up and down viewing directions. This might require flipping optics and detectors as a unit, or chopping with an external mirror.

2. Do not assume calculated simulations of performance during descent are good substitutes for real measurements. Effects of dynamic pressure, forced convective heat transfer, particulate deposition on instrument surfaces, are just a few phenomena that might need to be backed up with hard data taken under realistic conditions.

Table B-1. Basic Characteristics of Previous Probe Instruments Designed to Measure Thermal Infrared Radiation in a Planetary Atmosphere

	Instrument		
	SNFR	LIR	GNFR
Probe	PV small	PV large	Galileo
Detector(s)	Thermopile	Pyroelectric	Pyroelectric
Location	External	Internal	Intermediate
Direct response	Net flux	Flux	Flux
Data returned	Net flux	Net flux	Net flux, up flux
Chopping	Flip optics and detector	Flip part of optics	Flip optics and detector
Field of view	Hemisphere at 0 deg and 180 deg	20 deg half-angle cone at 45 or 135 deg	20 deg half-angle cone at 45 or 135 deg
Internal calibration	No	Yes	Yes
Noise per sample	0.1-0.2 W/m^2	0.1-0.2 W/m^2	0.01-0.04 W/m^2
No. of channels	1	6	5-6
Spectral range	0.2-200 microns	3-200 microns	0.3-200 microns
Main error source	Gas leak at window seal	Asymmetry in FOV	TBD

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Tomasko, M. G.; Doose, L. R.; Smith, P. H.; and Odell, A. P.: Measurements of the Flux of Sunlight in the Atmosphere of Venus. J. Geophys. Res., vol. 85, 1980, pp. 8167-8186.

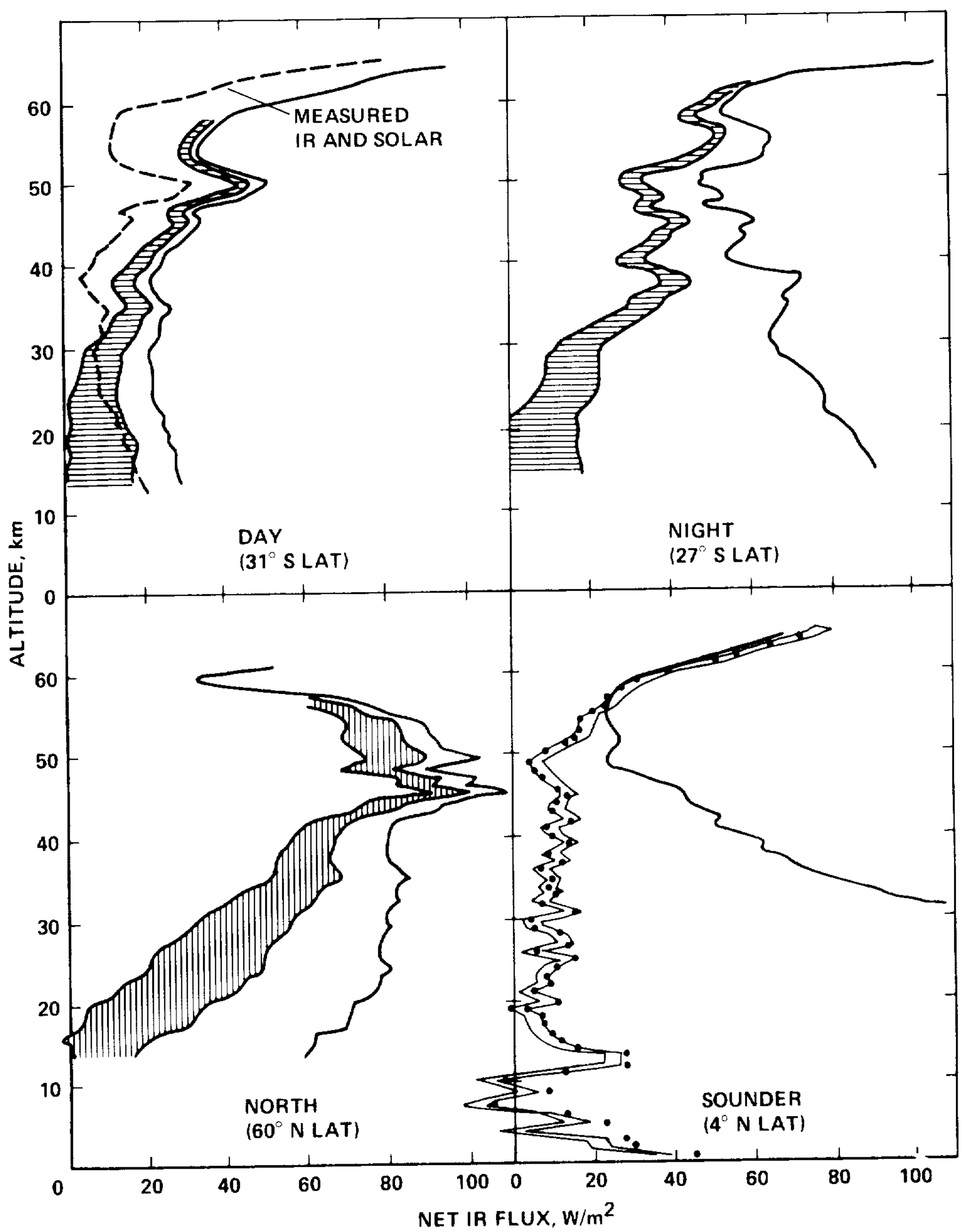

Figure B-1.– Raw and corrected thermal net flux measurements taken by instruments on the Pioneer Venus entry probes. In the first three quadrants, solid single curves show the raw thermal net flux profile determined from SNFR measurements on the three small probes, while the parallel curves connected by shading show the range of estimates for the corrected flux profiles. The lower right quadrant shows the raw LIR measurement of the thermal net flux as a single isolated solid curve, with corrected flux estimates indicated by the closely spaced pair of curves and also by isolated dots (for a modified correction procedure). The figure and corrections are described in detail by Revercomb et al. (1985).

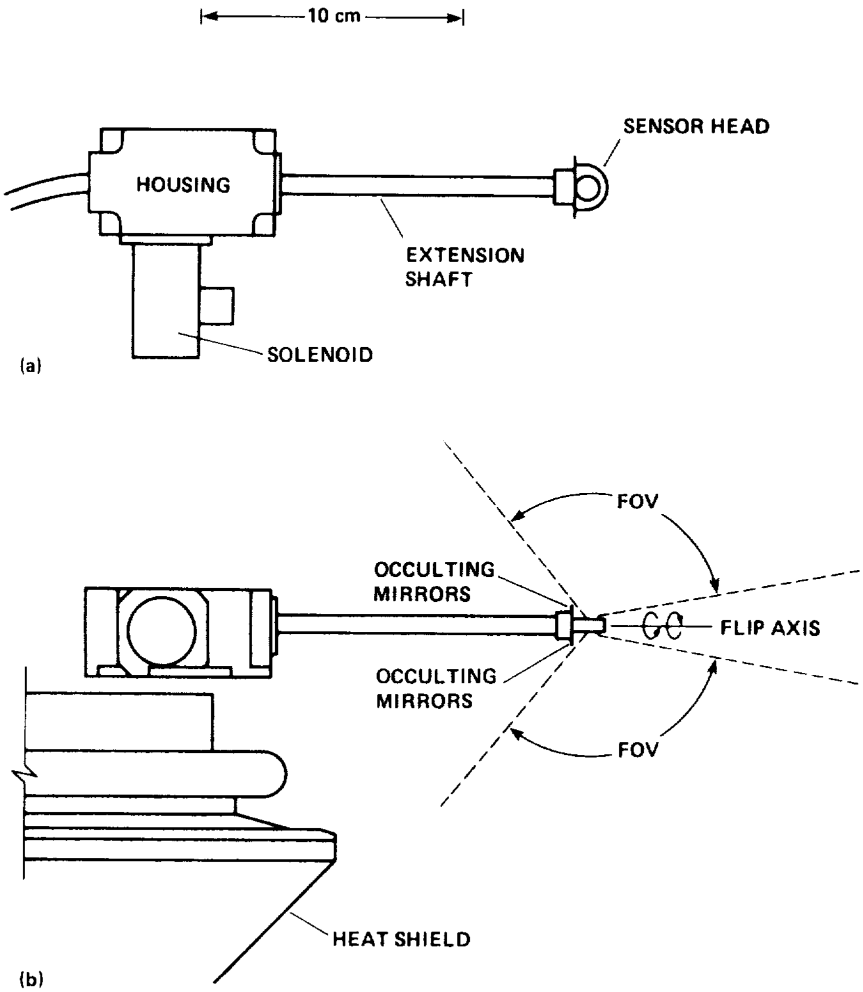

Figure B-2.– Pioneer Venus SNFR Sensor Assembly. The flux plate detector was simultaneously exposed to upward and downward fluxes through two opposite diamond windows. The plate responded to the net flux and was insensitive to the one-way flux. Occulting mirrors prevented radiation reflected or emitted by the probe from reaching the detector. Lack of a tight seal on both windows allowed a small gas flow through the sensor head, which caused substantial errors in the deep atmosphere. (a) Top view. (b) Side view in the deployed position. [Figure from Sromovsky et al. (1980)]

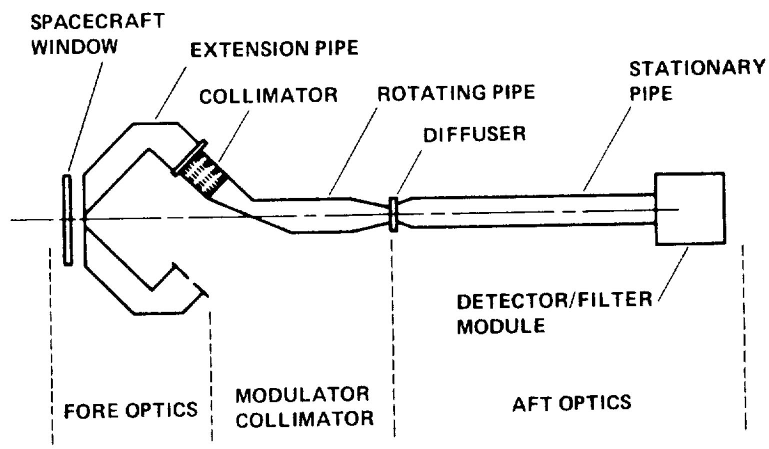

Figure B-3.– Pioneer Venus LIR optical design. A rotating light pipe chopped between upward- and downward-looking fixed light pipes to measure atmospheric fluxes, and between two reference blackbodies to perform on-board calibrations. Large flux errors were produced deep in the atmosphere because of asymmetries in response to up and down flux streams. The asymmetry could have arisen from light pipe misalignments, asymmetries in light-pipe construction, or in timing asymmetries in light-pipe rotation. [Figure from Boese et al. (1980)]

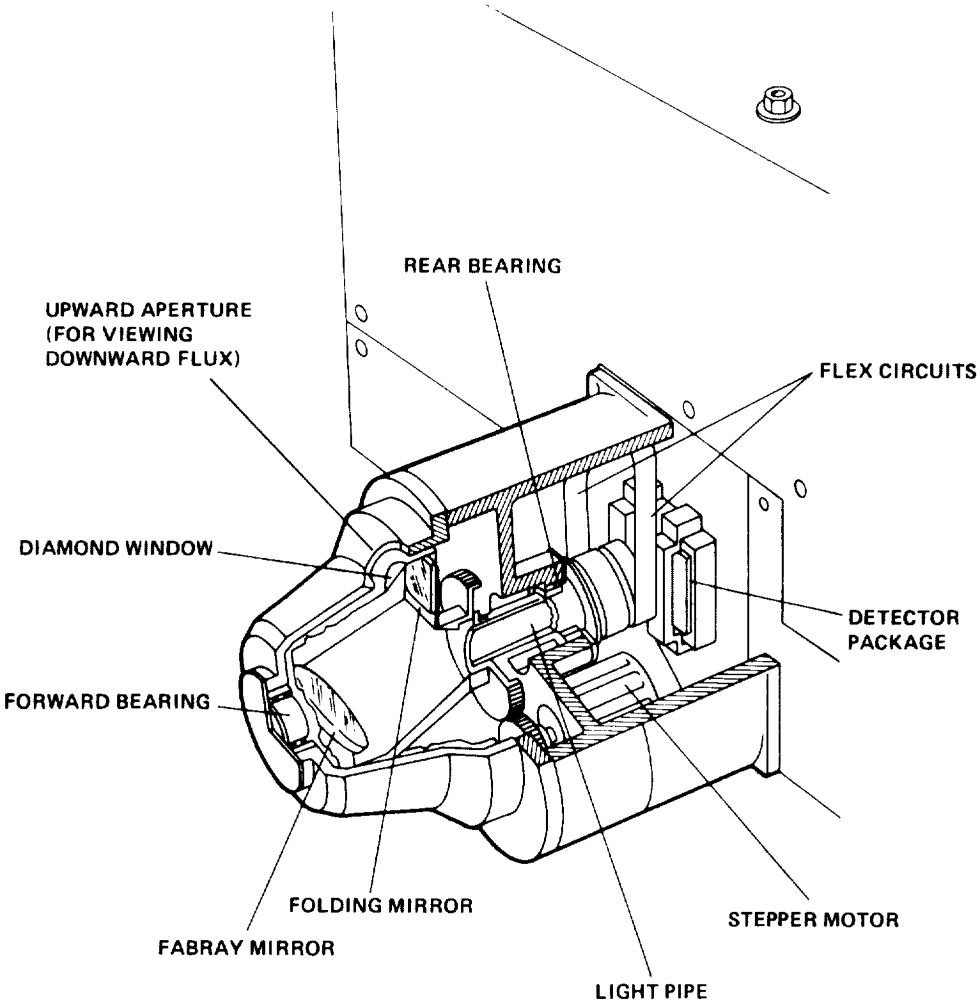

Figure B-4.– Galileo NFR optical design. Optics and detector array rotate between upward and downward apertures for net flux measurement, between ambient and heated blackbodies for calibration, and between the downward aperture and reference blackbodies for measuring upward flux. The ambient and heated blackbodies are located at horizontal positions on the wall containing the upward and downward apertures. Here "upward" and "downward" refer to optical head positions relative to the rotation axis, at which points the optic axis will be 45 degrees above or below the horizontal plane.

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15. Supplementary Notes

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16. Abstract The planned 1995 joint ESA-NASA Cassini mission to the Saturnian system will include an atmospheric probe to be dropped into the atmosphere of Titan for in situ measurements during descent. Because of the unique properties of the Titan atmosphere it is necessary to consider the peculiar requirements for such measurements and applicable techniques. The proceedings of two workshops dealing with the measurement of particles and radiation in the atmosphere of Titan are presented in two parts. The first, part I, held in August 1986, dealt with the measurement of particulate matter in the atmosphere of Titan. The second, part II, held in December 1986, dealt with the measurement of radiation in the atmosphere of Titan. The proceedings were first published and distributed informally, and are presented here with only minor editorial changes. In the report of the particulate matter workshop, discussions of the mission background, the importance of the measurements, and descriptions of the desired information are followed by a description of appropriate measurement techniques and conclusions and recommendations. The proceeding for the workshop on radiation measurement and imaging contains a discussion of the importance of radiation measurements and imaging, and presents a summary of participants' experience with such measurements made from entry probes. This is followed by a description of appropriate measurement techniques and conclusions and recommendations.

17. Key Words (Suggested by Author(s)) Planetary exploration, Cassini mission, Titan's atmosphere, Entry probes, Particle measurements, Radiation measurements	18. Distribution Statement Unclassified-Unlimited Subject Category - 91

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