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SEL 74-053

INVESTIGATION OF OUTER PLANET ATMOSPHERES USING THE PIONEER ENTRY PROBE RADIO SYSTEM

Final Report
to the
NASA/Ames Research Center

Under
NASA GRANT
NSG 2017

by
Thomas A. Croft

December 1974

RADIOSCIENCE LABORATORY
STANFORD ELECTRONICS LABORATORIES
STANFORD UNIVERSITY • STANFORD, CALIFORNIA

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ABSTRACT

Among the advanced missions being considered by the National Aeronautics and Space Administration, one candidate program is the flight of atmospheric entry probes to the outer planets and to their satellites. To make such a mission possible, it will be necessary to design a new telecommunication link which will relay information from a probe to its carrier spacecraft, the "bus", for subsequent retransmission to Earth. The purpose of the study herein described was to determine how this new radio link may be configured in order to perform scientific investigations at the same time as it also serves its primary function as an information carrier. Since the design of neither the transmitter nor the receiver was fixed at the time of this study, a wide range of possible configurations was considered.

The main purpose of this report is to forecast the radio science requirements which may eventually be placed upon the system. Specific experiments are described in varying degrees of detail, and they are rated according to the author's assessment of their relative value. The ratings were assigned in accordance with three criteria which were provided to serve as a basis for judgment. These criteria are discussed from the point of view of their impact upon the ratings; a change in criteria might lead to a different ordering of the candidate experiments. For example, the restriction of attention to the atmosphere virtually precludes radio transmission before entry, although valuable observations of ionospheres or magnetospheres might be practical if pre-entry operations were conducted. The experiment descriptions are written and organized in a manner intended to enhance their usefulness as a basis for the further development of these ideas.

In addition to the experiment ratings, two chapters are devoted to a more general discussion of radio science methods as related to telecommunications systems. First an explanation in broad perspective is devoted to the operational implications of the various approaches to scientific measurement by telemetry or tracking radios. Emphasis is placed upon a conceptual description of the physics rather than a mathematical development. Subsequently, the more restricted subject of plasma density measurement through observation of differential delay is developed in more detail with greater emphasis on the quantitative relationships relevant to the probe mission. These chapters are intended as introductory material or as a review for non-specialists who might have a need for more information than is given in the descriptions of candidate experiments.

INTRODUCTION 2

It may happen that the first atmospheric entry probes sent to explore the outer planets will be carried by a Pioneer spacecraft. If so, then presumably the bus will be spin-stabilized, as the probe is sure to be. Because the probe must withstand the high deceleration of the aerodynamic entry, its payload cannot be massive. As a result, the radio transmitter required to telemeter information back from the probe cannot be large, and it will be impractical to carry a steerable antenna. It has been concluded that the probes which enter the atmosphere of outer solar system bodies such as Jupiter, Saturn, Titan or Uranus will have to relay their information to Earth via the carrier spacecraft.

There is a considerable saving in cost, weight and complexity if the Pioneer bus antenna does not have to be despun and aimed at the probe. Engineers have analyzed this system and have concluded that the optimum probe-to-bus telecommunication would incorporate a transmitter antenna fixed to the body of the probe, communicating to a receiver via an antenna fixed to the body of the Pioneer. For best efficiency, this configuration should operate at a radio frequency in the neighborhood of 400 MHz (McDonnell Douglas MDC E0870, 1973). The information telemetered from the probe would then be conveyed to the main telemetry system for relay to Earth at S-band or X-band.

We have witnessed a gradual evolution of space exploration philosophy which has lead to the use of the telecommunications signals for tracking and telemetry simultaneously with their service as a basis for radio scientific purposes. This dual use has evolved slowly for S-band links to Earth but it is now a productive and widely-accepted approach to effective space exploration.

We have considered this combination of circumstances and concluded that there is a reasonable likelihood that NASA's future space exploration activity will require the design and manufacture of a new relay telecommunication system which involves new engineering. No data relay from one spacecraft to another has ever been accomplished at a distance such as this before. The atmospheric entry probes for Venus, presently being designed, are able to communicate directly to Earth at S-band by virture of the relative proximity of Venus to Earth.

A somewhat similar radio will operate with Viking in order to relay information from the Mars lander to the orbiter when the lander is beyond the limb of the planet. This radio operates at a frequency near 400 MHz and it is designed to transmit 30 watts in its normal mode. (The outer planet probe design is for 40 watts or more). One major difference between these systems is the bit rate; the Viking runs at 16,000 bps uncoded whereas the outer planet probe relay runs at 44 bps and is coded. This difference is primarily due to the shorter range of the Viking radio; only 6,000 km as opposed to 120,000 for the probe. (Michael et al, 1972)

Since a probe transmitter and an associated bus receiver must be designed, it is economical and effective to make an attempt to foresee the potential scientific uses of this relay signal. If both the receiver and the transmitter design are to be new, then we have an unusual opportunity to influence the design of a system at its very earliest conceptual stages. In this optimum circumstance, we can design one system which performs the telecommunications role and a radio science mission with a minimum of compromise and at a minimum of cost.

One early task in such a design coordination must be a delineation of the potential interest which will be expressed by the scientific community when the probe missions come under their intense scrutiny. That is the objective of the study reported here; a prediction, an estimate of the consensus which will eventually be expressed by the scientific community.

The early outer planet probes may be carried by a Mariner-type spacecraft. In this case the bus would be controlled in its spatial orientation, not spinning. As a result, a steerable antenna on the bus would be much more practical. This in turn leads to the conclusion that the relay telemetry should be at a higher frequency, somewhere between 800 MHz and S-band. In this study, no consideration has been given to the Mariner bus and the associated changes in the telemetry link.

CRITERIA USED IN JUDGING WORTH OF EXPERIMENTS 2.1

It is very important that the reader of this report should bear in mind the three guiding criteria which the author followed in making the value judgments which form so much of this report.

1. Is the candidate experiment capable of providing new fundamental information about the atmosphere of the planet or satellite at which the entry takes place?
2. Does the candidate experiment promise to provide information which will support or enhance the value of one of the basic scientific experiments which are flown on the probe? That is to say, can the radio scientific investigation provide backup data which may verify(or provide assistance in understanding) the scientific data returned from experimental packages?
3. Does the candidate experiment offer to provide measurements which will enable engineers to improve the radio links of future probes, both for the purpose of telecommunication and for radio science experiments?

This work was defined in scope by NASA, and this definition was obviously necessary in order that the effort could be channeled in the directions where NASA perceived its needs to lie. At the same time, we will see that the criteria are somewhat restrictive and limited, so the reader should bear this in mind in judging the validity of the result. For example, these criteria virtually eliminate the possibility that there might be any need for operating the probe radio system prior to the aerodynamic entry. In the initial stages of this study, the author took a broader view of the probe as an element in the exploration of the total environment of the outer planets, and concluded that a strong case could be made for pre-entry transmissions.

As a result, two talks were given at which this view was expressed in some detail, and written versions of the talks were produced. The possibility of pre-entry transmissions is not considered acceptable from the standpoint of this report, because of the first of the three criteria. The key element in these criteria is the stress on the atmosphere. The underlying idea is atmosphere, and that is its sole objective insofar as this study is concerned.

Within the stricture of these criteria one might bring in the ionosphere or perhaps the magnetosphere by simply defining the atmosphere so liberally as to include these regions. The prevailing trend of thought in the Outer Planet Entry Probe Science Steering Group does not support this view, however, and so for the purpose of evaluating candidate experiments the author has chosen to define the atmosphere as that region which the spacecraft enters after its extreme deceleration is completed and the radio transmitter comes on. There is one exception to this, however; the entry forces will probably be measured by accelerometers with the objective of determining the atmospheric structure in the height regime where the deceleration occurs. We will see that some pre-entry tracking of the radio signals might make this experiment more productive and thus qualify as acceptable under the second criterion (a support experiment).

SCOPE OF THIS STUDY 2.2

This study entailed one month of the author's time, distributed over a seven month period. The first month of the study was devoted to a familiarization with the extensive literature on the subject, both with respect to the previous engineering of the probe and bus systems and their telecommunication link and with respect to the characteristics of the four solar system target bodies, Jupiter, Uranus, Saturn and Titan. Two things became clear at the outset;

1. An extremely wide range of characteristics is embodied in these targets; primarily, Titan is very much different than Jupiter. Any universal probe design which must serve in all these potential missions must be very versatile. It is unlikely that the probes will be exactly the same.
2. If one accepts the ground rule that one probe design should serve for all targets, there are a number of reasons why the radio scientist would find it very productive to design the probe radio so that it can operate before the aerodynamic entry. With a single exception, these pre-entry objectives are not associated with the "atmosphere" of the various bodies. For this reason, the pre-entry transmission capability does not qualify as being acceptable under the criteria which govern this report. Furthermore, pre-entry transmission was not in the baseline design of the probes as it stood at the time of this study.

Some early views on this radio science study were presented by the author at the Outer Planet Probe Technology Workshop which was held at NASA Ames

Research Center on May 21-23, 1974. The written version of that speech is currently in the process of final revision. Unfortunately, the form of the final publication is not known to the author at this time, so a reference cannot be given here.

Because of a positive reaction to that first talk, the author was invited to summarize the arguments in favor of pre-entry radio science at the Outer Planet Entry Probe Science Steering Group meeting on October 1-2, 1974. This was also held at the Ames Research Center. At that time, the interest of the Steering Group was directed toward the atmosphere of Uranus and, from this standpoint, pre-entry radio science was not felt to be justified. Post-entry radio science was not described at that time. A written summary of that second talk was also prepared by the author at the request of NASA/ Ames Research Center. It was further condensed elsewhere, and appeared in the minutes of that October meeting. The full text will be supplied by the author upon request.

The final element of the study is this report, describing the experiments which were considered and rating them with respect to their relative scientific value according to the criteria outlined in section 2.1. There is inevitably a great deal of opinion and estimation in this report; opinion because the value judgments are necessarily subjective, and estimation because the knowledge of the outer planets and the knowledge of the probe designs is lacking.

BRIEF REVIEW OF THEORY UNDERLYING RADIO EXPERIMENTS 3

Here is presented an explanation of various possible radio science experiments using a telecommunications system. Stress is given to the operational viewpoint; for example, the objectives which can be met through the implementation of a stable local oscillator are shown to be different from, but related to, the objectives served by a second coherent frequency. As another example, it is shown why spacecraft navigators may learn all they need to know from short observations of differential Doppler, while at the same time the scientists need longer continuous observations or else they need corollary information such as differential group delay measurements.

There is a complication which confronts the student of radio science because of the simultaneous use of the same radio for scientific observation and for telecommunications. Often the engineering needs differ from scientific needs in ways which appear to be subtle but which, in fact, have far-reaching implications. An understanding of the significance of the similarities and the differences between the interests of scientists and engineers can be useful to people who fill both these roles and to those others who serve to coordinate the needs of all.

These explanations are intentionally brief and as non-mathematical as is practical. Instead of giving the governing equations, I will describe the physical phenomena in order to point out the significant consequences of the underlying mathematics. This will tie together the experimental descriptions which follow. These explanations are intended for readers who have already been exposed to the subject but who can benefit from an operationally oriented review in which the relative significance of the various facets is compared.

THE REFRACTIVE INDEX IN GASES AND PLASMAS

3.1

The refractive index is the ratio of the speed of the radio wave in free space to its speed in a medium; in this case, a gas or plasma. The index if often considered to be a property of the medium but it also depends on the frequency of the electromagnetic wave and it may depend upon the direction of propagation and the strength and direction of magnetic fields present. For our purposes, it is sufficiently exact to consider that the refractive index of a neutral gas is a scalar number slightly greater than 1.0 which does not depend upon frequency or direction. One of the most important consequences of this simplicity is the result that the group velocity and phase velocity are the same. (The phase velocity is the speed of the wave fronts while the group velocity is the speed of the information carried; that is, the speed of propagation of the modulation impressed on the signal). In a neutral gas, these velocities are slightly slower than C, the speed of light. The difference from C depends upon the identity of the gas and its density.

THE CONCEPT OF "CONTENT" 3.2

The slowing of the radio wave is caused by the independent action of individual particles. We cannot measure the wave speed, but we can measure the total added delay along the radio path which is proportional to the number of particles passed by. This number, in turn, is proportional to the total number of particles in a unit-area column along the path, commonly referred to as the "content". This is the fundamental reason why the various and diverse radio experiments involving delay or Doppler observations generally yield a result expressed as the content of the participating particles along the path. Since the content is proportional to the product of the path length and the average density of particles along the path, and since the path length is generally known to high accuracy, it follows that delay or Doppler observations often yield spatially-averaged density information. In the case of radio occultations of planets, the scientist may assume that particles are distributed about the planet with spherical symmetry and then the delays or Dopplers can be interpreted in terms of the radial density distribution of participating particles.

In a plasma, the free electrons are set in motion by the passing radio wave and they vibrate at the frequency of the wave. Because they have a longer time in order to execute each vibration when the radio frequency is low, they travel farther. As a result, the effect of the electrons is strongly dependent upon the radio frequency. The refractive index is

$$\mu = \sqrt{1 - \frac{80.6\ N_e}{F^2}} \approx 1 - \frac{40.3\ N_e}{F^2} \quad \text{since } N_e \ll F^2$$

where N_e is the local electron concentration and F is the radio frequency of the wave, in MKS or SI units. Notice that μ is less then unity so these waves travel faster than the speed of light. The frequency dependence of the refractive index causes this plasma medium to be classified as "dispersive". (This is because a short bundle of waves, a pulse, becomes dispersed as it travels since different Fourier components travel at different speeds.)

In such a dispersive medium, the group velocity differs from the phase velocity. For the densities of plasma and for the radio frequencies which are under consideration in this report, it happens that the group refractive index is exceedingly simple, being given by the equation:

$$\mu' \approx 1 + \frac{40.3\ N_e}{F^2}$$

Notice that the modulation wave form travels at less than the speed of light by the same small difference as that by which the wave fronts exceed the speed of light. This difference is proportional to the electron concentration and inversely proportional to the square of the radio frequency. Here, the "participating particles" are the electrons; the ions do not interact with the wave very much at these radio frequencies because of their comparatively high mass.

From the foregoing it can be seen why the radio experiments involving propagation through a plasma almost always yield the electron content or concentration or some related function. For propagation through a neutral atmosphere, as in an atmospheric occultation, the content measurements yield information regarding the density and identity of the gases.

MEASUREMENTS OF PHASE VELOCITY AND GROUP VELOCITY 3.3

It is not possible to measure phase delay; that is, the time delay for travel of a single wave front from one point to another. Any attempt to identify a wave front must involve placement of a marker upon the wave train and this, by definition, is a modulation which must travel at the group velocity. Therefore transit time measurements are inherently measures of the group delay. (Group delay is the accumulated delay for transit at the group velocity; when multiplied by C, it is called the "group path".) In a non-dispersive medium, such as a neutral gas, the distinction between radio group and phase delay has little practical significance since they are virtually the same.

While we cannot measure phase delay, we can measure the Doppler shift which is the difference between the frequency transmitted and that which is received at the far end of the path. This difference can be integrated, yielding a record of the temporal variation of the phase delay. One cannot establish the magnitude of the constant of integration and, therefore, one can determine only the variations in the phase delay with respect to some unknown starting point for each uninterrupted measurement.

This is important from an operational standpoint. Those who use Doppler tracking to navigate spacecraft need to know only the phase delay variations; they have no need for determining the magnitude of the total phase delay; that is, they do not need the constant of integration. The scientists studying the plasma itself do need to learn the magnitude of the phase delay in order to calculate the average electron density along the path. They need some means for determining the constant of integration.

It is perhaps worth digressing to explain the relationship between Doppler shift and phase delay. Consider a radio path with a transmitter at one end and a receiver at the other end and, for simplicity, let us assume that it takes one second to traverse this path at the speed C. If the transmitted frequency is 400 MHz, then a snapshot of the path would reveal 400 million wave fronts in transit between the transmitter and receiver at any given instant, provided that there is a perfect vacuum in the space at that time.

Now suppose plasma pours in along the path so that the phase velocity is increased to a value higher than the speed of light. The wave fronts will travel faster and yet they are still being emitted at 400 MHz. As a result, the distance between each pair of successive wave fronts must increase slightly because each wave travels a little farther during one period. If we now take a new snapshot of the radio path, we will find the wave fronts farther apart. Since the total path length has not changed, we will find fewer wave fronts in transit than before.

Where have the missing wave fronts gone? While the plasma was filling the path, the stretching of wave lengths along the path caused a slight increase in the rate at which the wave fronts arrived at the receiver. In other words, there was a slight increase in the radio frequency of the received signal. This slight difference is called a Doppler shift, which is somewhat of a misnomer since no velocities were involved. If the receiver had been capable of measuring the difference between the received frequency and 400 MHz, that difference would have been proportional to the rate of insertion of plasma along the path. More precisely, the difference would be proportional to the rate of change of electron content on the path.

The phase delay is the time required for one wave to travel the length of the path. So long as the transmitted frequency remains fixed, the phase delay is proportional to the number of wavelengths in transit at an instant of time. (The delay in seconds is this number divided by the transmitted frequency in Hertz.) Thus we see, based upon the simplest of reasoning, why the Doppler shift is the time derivative of phase delay or, alternatively, the phase delay is the integrated Doppler, after all velocity effects are eliminated.

MAGNITUDE OF THE DOPPLER EFFECTS 3.3.2

These Doppler effects are small in proportion to the transmitted frequency for the simple reason that $40.3\ N_e \ll F^2$ so that $\mu \approx 1$. Suppose for example that the path is filled with plasma at 7/cc, which is about the density of the solar wind near Earth. For an S-band signal, the refractive index differs from unity by only 5 parts in 10^{11} so a differential Doppler observation would have to be performed at this precision in order to yield evidence of such plasma. Even at the lower frequency used in Pioneer 6-9, 50 MHz, the refractive index at 7/cc is only about 0.1 part per million different from unity.

To permit measurements of these small percentage effects, it is necessary to fly stable oscillators or to transmit auxiliary signals which can provide a precise standard for comparison. Two main types of auxiliary signal are used in this context; for neutral gases, the signals are sent to the spacecraft and then retransmitted (with a small frequency offset) so that the experimenter depends only upon the stability of an oscillator on Earth over the round-trip signal delay, and upon the determinability of the velocity Doppler effects. For plasma observations, it has proven feasible to send 2 signals in the same direction: the test signal and also a higher frequency timing standard in coherent synchronism. This is the so-called "dual-frequency" experiment for dispersive media.

From the standpoint of electronics technology, it is a simple step to accumulate (i. e., integrate) Doppler effects if a comparison standard is available. For example, the changes may be integrated by an electronic counter which runs at the difference frequency between the test signal and the standard. One may then determine the variations of the content of participating particles added to the path, since the resulting integral is proportionally related to content changes along the path.

GROUP DELAY 3.3.3

For a scientist who wishes to determine the content from an integrated Doppler observation, the missing link is the starting value of the integral. In the 400 MHz example above, we started with free space but in an actual situation we often must start with an unknown excess delay. At times, the only way in which we can determine the starting value is through the measurement of group delay. This measurement is simple in principle and, in some cases it is simple in fact. Modulation is added to the signal and, after the wave transit is completed, the modulation delay is compared to a standard. Usually, the standard is supplied by another radio signal. The modulation must necessarily be at a much lower frequency than that of the carrier wave, and as a result the accuracy of the group delay measurements is less than that of phase delay measurements. The most important point is that group delay measurements can be obtained without integration; there is no unknown constant. While such observations are inaccurate when compared to phase delay measurements derived from Doppler, the two types of observation complement one another. When used together, they may give an accurate picture of the changes of the particle content starting from a known value.

In some cases, the phase delay alone is adequate for the radio scientific purposes. When a spacecraft is about to go behind a planet and one wishes to study the ionosphere or atmosphere by observing radio delays, it is reasonable to make the assumption that the initial radio path is well away from the planet so the ionospheric electron contribution to the total phase delay is zero. Furthermore, for rapid occultations it is safe to assume that the solar wind electron content between Earth and the spacecraft, together with the Earth's ionospheric content near the ground station, remain fixed during the progress of the occultation. In this manner, all changes in the Doppler shift integral are attributed to the ionosphere of the distant body. As a result, the accuracy of the phase delay measurement is available throughout the observation. In this case, one might say that the constant of integration is known to be zero at the beginning point.

The extent to which one can depend upon the validity of the assumptions depends upon the character of the trajectory of the spacecraft. If the occultation occurs very slowly, then changes in the electron content of the Earth's ionosphere and of the solar wind may interfere with the planetary effect in an unknown mix, destroying the validity of the result.

MEASUREMENTS OF SIGNAL STRENGTH 3.4

In the preceding sections, the measurements of signal frequency and transit time were shown to be essentially the same. These frequency and time measurements are characterized by extremely high precision, typically involving some small number of parts per million (or perhaps billion) in accuracy. To some extent, this precision is attributable to the current oscillator technology which permits the creation of very stable frequency standards and, from them, the creation of similarly accurate time standards by the expedient of electronic counting. One should also not lose sight of the fact that the precision of these experiments is also partly due to the fact that the propagation speeds are very nearly the speed of light which, itself, is an imperturbable standard.

Another type of common radio science measurement involves observations of the strength of the signal transmitted from one place to another. Various kinds of information can be obtained from a study of the signal strength and, as a general rule, this information is different in character from that derived from the time and frequency observations. Signal strength measurements are imprecise when compared to timing observations; such measurements are made with a precision typically expressed as percentage or as a portion of a decibel. (-1 dB represents a 21 percent power loss.)

It is difficult to calibrate a complete radio system with respect to strength of the signals processed from stage to stage. Furthermore there are no standard sources of signal strength with a precision comparable to that of frequency standards. As a result, environmental effects on signal strength must be fairly large if these are to be observed in practice.

LOSS MECHANISMS OF SCIENTIFIC INTEREST 3.4.1

From the time of origin through the amplification, transit, reception, and processing of a radio signal, a wide variety of devices and phenomena affect its strength, or amplitude. Out of this complexity, there nevertheless emerges a fairly simple picture if attention is centered on only those phenomena which are of interest to radio scientists. These fall into three classes:

1. Absorption of the signal due to passage through material which extracts energy from the waves.
2. Deflection of the radio wave away from the desired pathway as a result of a inhomogeneous refractive index along the path which gives rise to diffraction or refraction.
3. A modification of the polarization of the radio wave which changes the degree of match between the wave and the receiving antenna, thus causing variations in the power which reaches the electronics of the receiver.

Sometimes these effects are combined, and the combination can be used to good advantage. One outstanding example which comes to mind is the planetary occultation observation when the signal strength is diminished through the action of refractive defocusing (due to the bending of the rays) and at the same time it is partially absorbed by the gasses. In this case, an observation of the frequency of the signal produces information from which one can compute how much of the signal should be lost due to refractive defocusing alone. A measurement of the total loss can then be compared to this calculated value, and the excess attributed to absorption.

To some extent, the types of information derived from signal strength measurements depend on the length of time between pairs (or sets) of measurements. It is seldom possible to derive useful information from just one measurement, because the difficulties in calibrating a complete radio system are so severe that the resulting inaccuracies may exceed the magnitude of the parameter of scientific interest. Rather, all signal strength information is derived from a comparison between two or more measurements. The scientific information is derived from the difference between measurements and the relationships between the time interval involved and the corresponding changes in that amplitude. When the time interval between observations is short, a second or less, then the amplitude fluctuations are typically called "scintillation". Such rapid signal strength fluctuations are usually attributed to turbulence in the intervening medium which causes localized distrubances to the phase and amplitude of the passing wave fronts.

For a planetary occultation, scintillation may be caused by turbulence in the atmosphere or it may be caused by comparatively stationary atmospheric structural features which enter and leave the radio path rapidly by virtue of the high spacecraft velocity. For example, spherical layers of absorbing particles in thin sheets would cause rapid signal strength variations for an occulting spacecraft and it may be difficult to determine which of the signal strength variations were caused by absorption and which were caused by diffraction.

FARADAY ROTATION 3.4.2

A strong amplitude effect due to Faraday rotation is often observed when linear polarization of antennas is used. In the circumstances usually encountered in radio scientific investigations, this Faraday rotation is accurately characterized as a rotation of the plane of polarization at a spatial rate which depends directly upon the electron concentration and which is also proportional to the component of the local magnetic field which parallels the direction of radio propagation. When either of these parameters changes along the radio path, then the total amount of rotation will change. When a signal undergoes a varying amount of rotation along the radio path for this reason, it arrives at the receiver polarized in a plane which is likely to be somewhat misaligned to the plane of the receiving antenna. As a result of plane angle fluctuations, the amplitude fluctuates, sometimes in a neat repetitive fashion.

Since the total amount of rotation on any path is proportional to the integral of the product of the electron density, the magnetic field strength, and the cosine of the angle between the field and the path, the interpretation of these observations is often difficult. Usually it is necessary to depend upon the predictability of two of these three parameters, for otherwise the result could not be interpreted. For this reason, a Faraday rotation observation is only useful in a few special circumstances.

Because the signal strength fading due to the Faraday rotation is troublesome to telecommunications, linear polarization is seldom chosen by antenna designers. However this kind of observation is sometimes obtained unintentionally due to unavoidable elipticity in antennas. The data may serve a useful scientific purpose if properly interpreted in this case. A signal strength observation does not tell the direction of rotation since the observation has an inherent 180° ambiguity. Intentional rotation measurement instrumentation includes transmitting and receiving equipment which permit an unambiguous calculation of the direction of the rotation, so that one can follow the total rotation angle and observe all the changes which occur after the beginning of any particular observation.

Like the observation of phase delay through measurement of Doppler shift, polarization plane rotation observation suffers from the defect that a constant of integration is needed and cannot be obtained from the measurements themselves. In this case, the constant is the total number of turns along the radio path at the beginning of the observation. Some characteristics of the physical situation must be used to infer this value. For trans-ionospheric Faraday rotation observations, it is customary to use the nighttime observations together with the knowledge that, at night, the ion content is so low that only about one turn occurs. The operators make an assumption about total number of turns at that time, and track the variations as long as possible thereafter. For rotation observations during the occultation of a spacecraft, it is necessary to begin the measurements early while the effect is negligible. Short of this, the only thing which can be gained from such observations is the time variation of the aforementioned integral. In this strait, the scientist can only obtain information in the best of circumstances because, not only is the integral equally affected by three component parameters, but its total value is unknown. Nevertheless, there have been many circumstances where the observations have been useful. To cite one example, the great majority of the early observation of the Earth's ionospheric electron content was obtained by the simple expedient of tracking the plane of polarization of signals from the early geostationary satellites. Although imperfect, a large body of data was readily acquired and it has been exceedingly interesting to scientists for its geophysical implications and to telecommunications engineers who use the Faraday rotation results in order to determine what they should expect in the way of small time delay perturbations.(Time delay, it will be recalled, contains an additive component which is proportional to the integral of the electron content along the path; since the Earth's magnetic field magnitude and direction are fairly well known, it has been practical to calculate the electron content from the rotation measurements through the use of some fairly good approximations.)

MEASUREMENTS OF POLARIZATION 3.5

Most of the useful radio measurements which can be made are fundamentally related to the signal delay or its strength. For example, measurements of the phase of the signal at its point of reception are actually indicative of the transit delay, and therefore phase measurement is, in this sense, only another manisfestation of delay.

Despite the foregoing generalization, it nevertheless remains true that a full study of the polarization of a wave field is such a specialized analysis of the comparitive strength of the signals received by two differently polarized antennas that the subject area is usually considered to stand by itself. This distinction is also merited because the polarization of an electromagnetic wave is one of the three parameters required to fully describe it; the other two are the timing of the wave fronts and their strength, which are the two subject areas earlier segregated.

If the signal arriving at any given receiver has a well-defined polarization, then the measurement of that signal could be described in terms of the intensity, the plane of polarization and the ellipticity. In most actual situations, however, a mixture of signals arrive at the receiver and the sum of all these signals cannot be represented by a simple polarized equivalent. It is said that a state of "partial polarization" exists, and a full description of the measurement requires the inclusion of a fourth parameter which provides a description of the degree of polarization.

At the opposite extreme from a single sine wave, pure Planckian radiation is unpolarized. The simplest partially polarized field would consist of a single sinusoid in the company os such unpolarized noise, and measurements should result in numbers which provide information regarding the relative energy in the signal and in the noise field.

To meet this need for a number set giving a full description of a wave field, a set of four "Stokes parameters" have been defined and are widely used. Their definition represents a compromise between the needs of theorist and the practical considerations of measurement. In essence, the four numbers plus a little algebra yield a full description of the time average intensity of the signal, its plane of polarization, its ellipticity and degree of polarization. An unusually clear exposition to this subject is given in the book "Radiative Transfer" by M. N. Ozisik.

Earlier it was pointed out that frequency or delay observations can be made with a very high precision whereas amplitude measurements are comparitively imprecise. In the case of polarization, the actual measurement is one of comparative amplitude and therefore the accuracy with which polarization can be measured is comparable to that of amplitude measurements; typically a matter of a few percent.

PLASMA DENSITY MEASUREMENT THROUGH USE OF TWO FREQUENCIES 4

The dual-frequency method for measuring plasma content has been described in a general qualitative sense and, as we will see, the approach is unacceptable from the standpoint of the three criteria. At the same time, it is the author's judgment that the restriction of interest to the neutral atmosphere was not intended to preclude consideration of other possibilities which become apparent along the way. The dual-frequency measurement of plasma density variations appears to have much to offer and yet it is widely misunderstood. Because of this combination of circumstances, the author has chosen to devote a full chapter to the subject here. As compared to the preceding chapter, this description is more quantitative and specific to the mission under consideration.

OPPORTUNITIES DURING THE PROBE MISSION 4.1

As the Pioneer bus and its associated probe arrive in the vicinity of the target planet or satellite, they will be flying along nearly parallel courses separated by a distance of roughly 100,000 km. If one imagines a column extending along a straight line between these two arriving spacecraft, one can visualize how their joint entry into the magnetosphere will result in an increase in the electron content of the column due to its travel into regions of ever-higher concentration. The dual-frequency instrumentation would allow a continuous measurement of the content of electrons in that column. When this is interpreted in the light of reasonable assumptions concerning the distribution of electrons in space, it is seen that such a monitoring operation might give a good piece of scientific evidence concerning the magnetospheric plasma distribution. One would obtain a continuous indication of the average electron density along a 100,000 km line traveling broadside into the magnetosphere. Furthermore as the probe descends through the ionosphere where electron concentrations may be thousands of times higher than they are in the magnetosphere, the measured electron content will build up comparitively rapidly. From this content observation it should be possible to derive a fairly detailed ionospheric electron density profile down to the point at which the aerodynamic heating induces an ionization blackout of the signal.

There is some overlap between the ultimate information derived from this kind of observation and that from an observation of the radio occultation of the bus spacecraft. For most of the outer planet missions contemplated, the bus itself enters a radio occultation. This latter maneuver will yield Doppler observations which can be interpreted in terms of an ionospheric electron density profile. Because of the great distance of these target planets and satellites from the sun, such occultation profiles will be very nearly at the terminator. Therefore they will indicate the electron density profile in a sunset or sunrise ionosphere. The dual-frequency observation by the probe relay radio would give a similar electron density profile in the night-time hemisphere. A comparison between the two profiles would be informative to scientists attempting to understand the ionosphere, giving clues to the ion production and loss mechanisms.

DETERMINATION OF THE CONSTANT OF INTEGRATION 4.2

Since the bus and probe enter from outside the planetary system, there are two optional methods for determining the constant of integration. For a most simple and accurate system, we would initiate a continuous differential Doppler measurement when the craft are still well outside the magnetosphere. At this time, the constant would be known to be negligible. The difference between the Dopplers at the two frequencies could be used to run an electronic counter on the Pioneer bus and this count could be occasionally telemetered to Earth. As the magnetospheric plasma began to fill the path, the count would build up to reflect the increasing electron content. Finally as the probe entered the ionosphere, the content would increase comparitively rapidly and a higher telemetry rate for the counter output would be desired.

The probe carries no power generator, so it is probably not feasible to supply enough battery power so that it could transmit for this long time period. In this case, it is necessary to measure differential group delay to learn the constant of integration. This requires more electronic sophistication and a slightly higher transmitted power level. However it offers the advantage that it could be operated intermittently for short periods. Each such operation need only be long enough to stabilize the radio system in order to maintain the required precision during the resulting transient heating.

The main advantage of the differential group delay approach is the saving in battery power; in other respects it is inferior to the differential Doppler approach.

It is the judgment of the author that the full consideration of this matter would eventually lead to a decision against the inclusion of the differential group delay capability. The scientific value of the dual-frequency observation is primarily concerned with the ionosphere and the magnetosphere, and the continuous transmission of a differential Doppler signal from the probe to the bus for a few minutes before entry would make it feasible to telemeter a measurement from the probe to the bus throughout this final approach to the planet. Such operation would be supported by one segment of the scientific community which would like to add instruments to the probe for making in situ measurements of the plasma environment.

A THREE-FREQUENCY OPTION 4.2.1

One alternative deserves mention at this point; it may be the best approach of all. The purpose served by the group delay measurement can also be served by the observation of differential Doppler between three cw tones. If one looks at the matter in a fundamental way, it turns out that the differential group delay observation gives us a measurement of the curvature of the phase delay as a function of frequency. (i.e., the second frequency derivative of phase delay.) Thus a measurement of differential Doppler at 3 frequencies effectively yields this same curvature and serves the same purpose , (Burns and Fremouw, 1970). Because 2 tones can be obtained by simple electronic means, through phase or amplitude modulation, their relative frequency can be very precisely maintained. The probe can then be light, simple and yet have just the kind of accuracy that is needed in order to make the observation possible. In this manner, it may be possible to minimize the deleterious effects of warmup transients, permitting the probe transmitter to run only on brief occassional bursts during the long entry to the planet. After the spacecraft begins its final plunge into the ionosphere, one of the three frequencies could be shut off since a two-frequency differential Doppler observation would suffice for the remainder of the mission. The constant of integration would have been established by the preceding three-frequency operation.

THE BASIC EQUATIONS OF DIFFERENTIAL DELAY 4.3

In order to permit a specific approach to this design problem, we will give a brief derivation of some of the more important mathematical relationships. For this purpose, the following symbols will be used:

Symbol	Meaning
T	Time
S	Distance
s	Distance increment
V	Velocity
μ	Refractive index
C	Speed of light
N_e	Electron concentration
I	Electron content
F	Radio frequency
G	Subscript for "group"
P	Subscript for "phase"
H	Subscript for "the higher of two frequencies"
L	Subscript for "the lower of two frequencies"

Throughout this discussion we will use MKS units which, for our purposes, are the same as those of the SI system, the international system of units.

The frequencies under consideration here are hundreds of MHz or higher, and the electron density are typically 10^{12} per cubic meter or lower. For such high frequencies in such low density plasmas, it is an accurate approximation that

$$\mu \cong \sqrt{1 - \frac{80.6\ N_e}{F^2}} \cong 1 - \frac{40.3\ N_e}{F^2}$$

The phase delay along the entire path is the integrated value of the delay along short increments of path:

$$T_p = \int_S \frac{\mu \, ds}{C} = \frac{S}{C} - \frac{40.3}{CF^2} \int_S N_e \, ds$$

The latter integral is simply the electron content, I. This may be thought of as the total number of electrons in a unit area column extending along the entire length of path. It is equally valid to consider that it is the average electron density on the path multiplied by the path length. The Doppler shift is the time derivitive of FT_p and so it is proportional to the time derivitive of the two terms given in the above equation. Since C and F do now change with time, it follows that the Doppler shift is

$$F\dot{T}_p = \frac{F}{C} \dot{S} - \frac{40 \cdot 3}{CF} \dot{I}$$

where the dot over the symbol represents the time derivitive.

If $\dot{S}$ could be determined with adaquate precision, then one could measure the Doppler shift and subtract the first term to obtain the second term yielding $\dot{I}$, the parameter of interest. Technology has not advanced to this state and therefore we transmit a second signal at a different frequency and measure the differential Doppler.

$$\dot{T}_{PL} - \dot{T}_{PH} = \frac{d}{dt} \left[\left(\frac{S}{C} - \frac{40.3}{CF^2} I \right) - \left(\frac{S}{C} - \frac{40.3}{CF_H^2} I \right) \right]$$

$$= \frac{40.3}{C} \left(\frac{1}{F_L^2} - \frac{1}{F_H^2} \right) \dot{I}$$

In this expression, all the velocity effects on the Doppler have been cancelled and that which remains is known to a high degree of accuracy.

The implementation of this idea is exceedingly straightforward. The high frequency signal is generated as a harmonic of the lower frequency signal. At the receiver, the higher frequency is divided by the appropriate factor (using electronic counting circuitry) so that it would equal the lower frequency if there were no plasma effects. The difference between the low frequency signal and the divided high frequency signal is then the differential Doppler. This small difference-frequency is used to drive an electronic counter which inherently performs the necessary integration. The accumulated count is proportional to the electron content along the path, provided only that the constant of integration can be obtained somehow.

CHOICE OF FREQUENCIES 4.3.1

An examination of the differential Doppler equation above will show that the value of the higher-frequency signal is not of critical importance so long as it is well separated from the lower-frequency signal. For example, consider two cases: (1) the high frequency signal is twice the low frequency and (2) it is so high that $1/F_H^2$ is truly negligible. In the first case, the expression

$$\frac{1}{F_L^2} - \frac{1}{F_H^2}$$

is fully three quarters as large as it is in the second case. Therefore little is gained by going to a higher frequency if the F_H/F_L ratio is already 2:1. Once F_L is selected, the value of F_H is comparatively inconsequential insofar as it affects the proportionality between the measured Doppler and the electron content, provided only that the F_H/F_L

ratio is 2 or more. For the systems which have flown, this ratio has been 8.5 and 3.67. Since the present study is predicated on a 400 MHz carrier, it will be assumed hereafter that F_H = 800 MHz.

MAGNITUDE OF SOME DIFFERENTIAL DOPPLER EFFECTS

It is instructive to have some specific numbers in hand so that the practicality of these ideas can be assessed. For this purpose, let us consider a differential Doppler measurement using 400 and 800 MHz, and we shall calculate the differences of the various physical quantities for the case when the electron content is 10^{16} per square meter. To put this in perspective, we note that the electron content of Earth's ionosphere is 3 to 5 times this much at night, and 25 to 40 times as much in the daytime. Then the time delay difference would be

$$\Delta T = \frac{(40.3)(10^{16})}{2.997925 \times 10^8} \left(\frac{1}{(400 \times 10^6)^2} - \frac{1}{(800 \times 10^6)^2} \right) = 6.3 \text{ nsec}$$

This very short time delay is equivalent to a light distance of 1.89 meters which is 2.52 wavelengths at the lower of the two frequencies. Therefore, the injection of this much plasma into the path would cause differential Doppler shifts which total 2.52 cycles when integrated with respect to time, provided that the cycle counting is done at the lower frequency by the expedient of counting down the 800 MHz signal to 400 before the difference is formed. (This has been the practice in the past missions.)

INSTRUMENTATION APPROACHES TO DOPPLER MEASUREMENT 4.4

A question naturally arises concerning the engineering of Doppler difference measurement: How shall it be done, and with what precision? For the earliest missions, (those flown on Pioneers 6 through 9 by Stanford University) the frequency was so low that simple cycle counting served to provide more electron content resolution that was useful. For the implementation of this dual-frequency approach on Mariner 5, half-cycles were counted through the electronic detection of zero crossings of the difference frequency signal. This doubled the resolution and, for the 400-800 MHz example, this detection method would provide a content resolving power of $(1/2)(1/2.52) = 0.198 \times 10^{16}$ electrons/meter^2. For the current dual-frequency at S-band and X-band, the resolution is being carried out to parts of a cycle through the incorporation of a means for detecting the phase difference between the lower frequency signal and the divided higher-frequency. With such electronics, the resolving power depends not only upon the number of cycles per unit of content, but also on the strength and stability of the signals received because this is the major determinant of the accuracy with which phase comparisons can be made. (Actually, both S and X Dopplers are independently measured relative to a local frequency standard, and the difference is formed by subtracting the resulting numbers.)

In order to carry forward a quantitative example, the assumption will be made that zero-crossings are counted because this is electronically much simpler than the phase comparisons. With the resulting resolution of 0.198 $\times 10^{16}$ m^{-2}, we see that an entry into the Earth's daytime ionosphere would produce a differential Doppler count totaling 126 to 202 zero crossings, (i.e., 25 to 40 $\times 10^{16}$). The timing of each crossing would represent an increase of 0.198×10^{16} in content versus height of the descending probe.

The experimenter would learn the total number of electrons from the top down to the height of radio blackout, and would also learn their distribution in space with a resolution of 1 part in 126 to 202; about 1/2 percent. With phase measurement, this would improve further.

For the giant planets, the peak electron density in the ionosphere is somewhat lower than Earth's but the vertical extent is greater. These factors compensate somewhat, so the electron contents are comparable to Earth's. Uranus and Titan are largely unknown. The existence of official models of their atmospheres and ionospheres is less an indication of knowledge and more an indication of a need for all workers to have a unified goal. The formulation of a system requirement is therefore subjective, and with this in mind, the author concludes that the 400-800 MHz system operating with zero-crossings will represent a close similarity in capability to any such system which may be eventually flown on a Pioneer probe mission.

CALCULATION OF DIFFERENTIAL DOPPLER DURING A JUPITER ENTRY 4.4.1

At the time of this writing, there has just become available a preprint (Fjeldbo, 1974) describing the results of the Pioneer 10 radio occultation measurements of the ionosphere of Jupiter. Dr. Fjeldbo has kindly consented to permit me to use these preliminary conclusions as a basis for a calculation of the expected electron content that would be observed during the entry of a Jupiter probe. This is useful as a means for establishing the need for accuracy in the instrument and the need for telemetry allocations.

Dr. Fjeldbo has cautioned that the electron density profiles are still undergoing improvement and so I have not taken great pains to assure accuracy when I have integrated the profiles to obtain electron content. Using approximate methods, I first derived content as a function of distance downward from the highest altitude of measurement; approximately 4200 km. This is the electron content which would be measured along a vertical column above the probe, since there is comparatively little plasma above. Because the bus will not be directly over the probe at the time of the observation, the measured content will lie along a column which is somewhat longer than the vertical column; assuming that the bus is 40° away from the zenith of the probe, it follows that we must multiply the vertical content by sec (40°) = 1.3.

The probe will penetrate this region traveling at about 60 km/s at a shallow angle, only 7° from horizontal. Its vertical descent velocity is then 60 sin (7°) or 7.3 km/s. From these values, applied to Fjeldbo's profiles, we readily calculate the electron content as a function of time which would be observed by the probe using differential Doppler. With the instrumentation arrangements suggested in section 4.4, it follows that one measurement quantum is 0.198×10^{16} electrons/meter^2.

Assembling all the foregoing information, the author has constructed figure 1 which has duplicate labels on ordinate and abscissa. One set of axis labels identifies the vertical electron content as a function of height within the Jupiter ionosphere, measured downward from 4200 km. The second set identifies the count accumulated by a differential Doppler, half-cycle counter for a probe entering at 7° and a bus 40° from its zenith.

The curve of figure 1 is an excellent data base with which to address the question of a bit rate requirement for the experiment. The counter will reach slightly less than 157 counts before the expiration of the probe, and <u>all</u> of the available information could be compressed into a list of numbers giving the time when each of those counts occurred. A grand total of 157 numbers would preserve the results of the entire experiment. (In an earlier treatment of the occultation results using a different assumption concerning the spacecraft oscillator behavior, Fjeldbo derived a profile from which I calculated that there would be 284 counts) the point is that these count estimates are only approximate guides to instrument design). The only way in which more information could be derived would be through the use of a lower radio frequency or a more fine-scale technique than half-cycle counting.

It is useful to provide an indication of the maximum count rate expected of a differential Doppler half-cycle counter. This does not depend on the electron density profile but only upon the local density at the position of the probe. For purposes of explanation, let us consider that the electron concentration is negligible above some reference level which is a few thousand kilometers above the visible surface. Then let L denote the length of the radio path below this altitude; it is this length along which the electron content is to be measured. For the probe and bus geometry and speed assumed above, the integration path length will increase at the rate

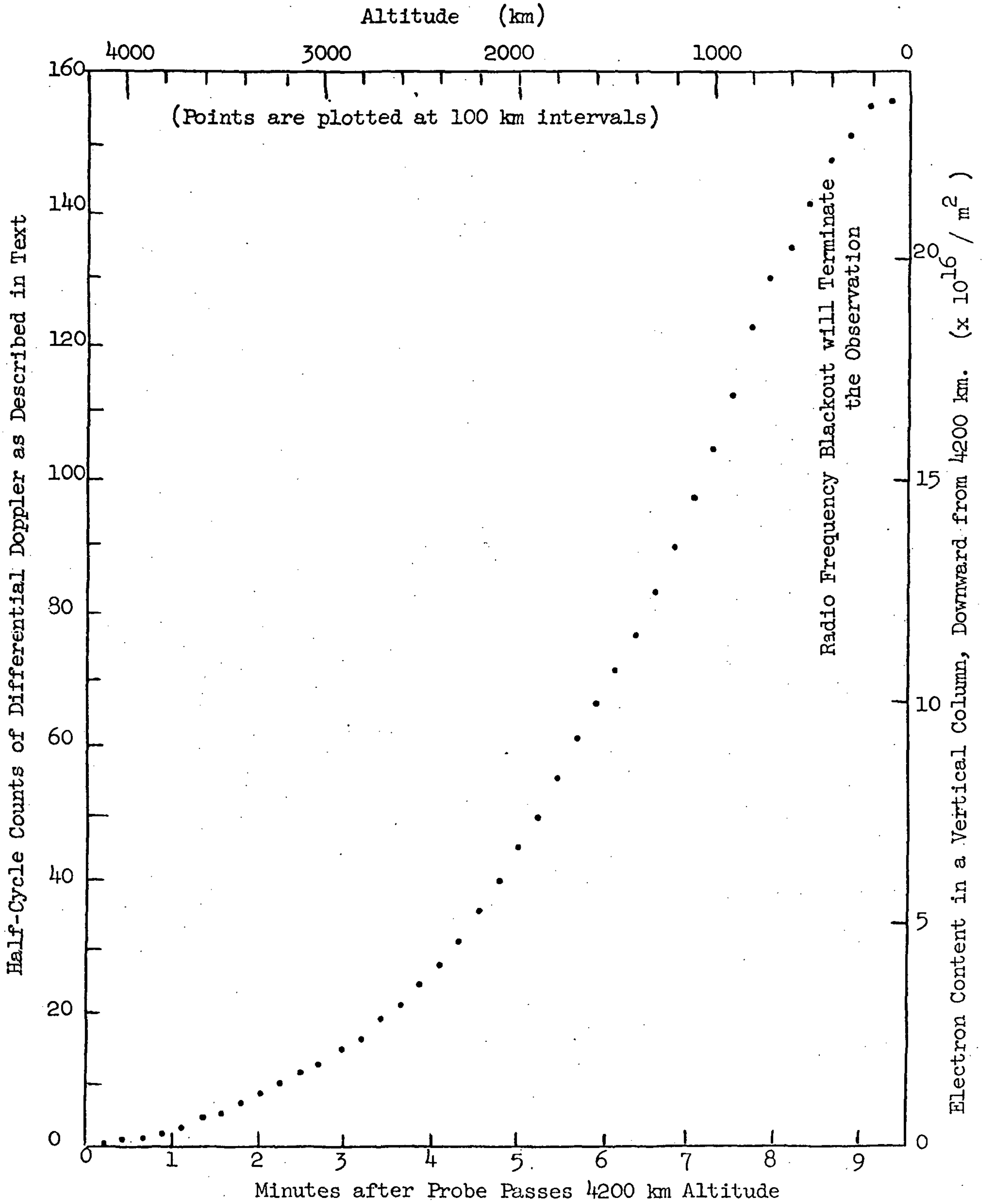

Figure 1. Electron content at Jupiter as it would be measured by a dual-frequency observation with the probe radio. The count rate is proportional to the electron concentration near the probe. (Computed from the Pioneer 10 results of Fjeldbo)

$$\frac{dL}{dt} = (60 \text{ km/s}) \left(\frac{\sin 7°}{\cos 40°}\right) = 9.5 \text{ km/s}$$

Here the slight effects of planetocentric curvature and relative bus motion are neglected.

The electron content will build up a rate which is equal of the product of dL/dt and the local electron number density at the position of the probe. Therefore the maximum rate of increase of electron content will occur when the probe is in the region having the highest electron concentration. The early results of Fjeldbo indicate that the ionosphere of Jupiter contains several thin layers, among which the maximum density is always less then 3.5×10^5 electrons/cc. From this we deduce that the content will build up at a rate which never exceeds 0.33×10^{16} electrons/m^2 per second. This seemingly illogical use of centimeters in one case and meters in the other has become a well-established convention. It can get worse; in pulsar work, the unit of content is parsec-cm^{-3} and we note that 1 pc-cm^{-3} $= 3.0856 \times 10^{22}$ electrons/m^2. Since one quantum of electron content is smaller than this number by a factor of about 1.7, it follows that the maximum count rate will be 1.7 per second. An examination of Fjeldbo's curves shows that during the final minute or so of the pre-entry transmission, the counter will run at an average rate of about 1/2 count per second; higher-rate bursts will be brief as the probe travels through the layers of more concentrated ionization.

From these calculations we may draw some useful conclusions; one might choose to build a simple system which merely reads the status of the counter at intervals of time which are shorter than a second. A readout at a slower rate, in this simple mode of operation, would not preserve the information relating to the structure of the dense layers of Jupiter's ionosphere because several counts would occur between readings. Since the timing of these counts establishes the layer profile, it will be information of very great interest. It would be wasteful to implement a simple counter readout system with intervals much longer than 1/2 second between readings.

A less garrulous system could be built if the bus had a small special-purpose processor capable of forming and storing the 200 or so numbers which give the time of the various counts. This would preserve all of the information, provided that the electron content does not exceed the capacity of the digital storage provided. Nevertheless, a thousand-word memory probably suffice for any planet in the solar system and so this requirement is modest in the light of current technology.

It is a common defect in research that the capability of the equipment may dictate the character of the experiment. A research worker with a new kind of machine will ask, "What new kind of measurement can I make ?" If an answer can be found, then the measurement will be recorded. Subsequently, it is necessary to address the question of how best to gain worthwhile scientific knowledge from the body of new measurements. In a sense, this represents a placement of the cart before the horse. One should ask, "What new kind of scientific information do I need ?" Then the measuring system should be designed to provide that answer. This ideal is not often realized, for practical reasons. Here, for example, we are faced with a situation where we know (or, at least, we have strong reason to believe) far in advance that there will be a new radio system designed to provide the telemetry relay from a spinning probe to a spinning spacecraft.

If we let this process of radio design go on unaffected by scientific needs, then the system will be built in such a way as to perform the telemetry function, and none other. At a later time, when scientists realize that a slight modification of the radio system would permit scientific measurements to be obtained at the same time as the telemetry is conveyed, it may then be too late to make the modification. Even if changes are agreed upon, their implementation will entail a great deal of expense. We can foresee many of these needs early. By this effort, it is intended that scientifically desirable features will be anticipated and included in the radio system from the beginning. Such a process is inherently the most economical.

As a result, we are indeed asking the cart-first question, "What kind of measurement should we make with this new device ?" The author has considered the possible applications of the telemetry link to radio scientific investigations directed at determining characteristics of the atmosphere of Jupiter, Uranus, Saturn or Titan. Colleagues have been consulted and literature has been searched but, obviously, not all the potential scientific experiments can be identified in this manner at this early stage. In order to identify the area of investigation which was undertaken here, we provide a listing of the specific experimental approaches which were considered during the progress of this study.

As a matter of convenience, I have arranged these experiments in four catagories:

1. Measurements of environmental effects on the direct signal as it successfully propagates from the probe to the bus.
2. Observations involving major changes from the direct propagation.
3. Tasks for the probe only
4. Tasks for the bus only

MEASUREMENTS OF ENVIRONMENTAL EFFECTS ON THE DIRECT SIGNAL AS IT SUCCESSFULLY PROPAGATES FROM THE PROBE TO THE BUS 5.1

As the signal travels from the probe to the bus, its strength, timing and polarization will vary in a multitude of ways. Some of these can be measured to provide useful information, and some should be measured in order to provide supporting data to designers of future probes a decade or more from now.

MEASUREMENT OF TELEMETRY CARRIER AMPLITUDE AND PHASE

The strength of the signal from the probe which reaches the bus can be measured at the bus. This might provide information about absorption and perhaps refraction losses as the probe penetrates the atmosphere. Such changes in signal strength would occur slowly over a matter of many minutes or tens of minutes. These changes would probably be monotonic; that is, the signal level would continuously decrease. In addition, there might be comparatively rapid fluctuations of signal strength, with both decreases and increases intermingled, which are commonly termed scintillation. These fluctuations would be attributable to turbulence in the atmosphere. The phase of the telemetry carrier signal might also be monitored in order to provide indications of scintillation.

TELEMETRY SOFT-DECISION FEATURE IMPLEMENTATION

A somewhat parallel requirement is placed by both the telecommunications engineers and the radio scientists, in the sense that both groups want a measure of the moment-by-moment signal strength fluctuations. The telecommunicators plan to obtain this information by means of a so-called "soft-decision" feature of the circuitry. The present course of development will lead radio scientists to obtain scintillation data independently. A joint approach might permit one system to fill these two needs.

DOPPLER SHIFT MEASUREMENT

A radio communication link is inherently a valuable means for determining the relative velocities of the transmitter and receiver to a high degree of precision. This requires either a stable oscillator on the probe or else it requires that the bus must be able to transmit to the probe. In the latter case, the probe must be able to respond with a coherent signal. The main benefit of such an instrumentation lies in the more precise determination of the motion of the probe relative to the bus. If pre-entry transmissions are utilized for this purpose, then the place where the probe strikes the planet might be found to a higher degree of accuracy. Post-entry transmissions might aid in determining the dynamics of the falling probe and its reaction to winds.

DUAL-FREQUENCY DIFFERENTIAL DOPPLER OBSERVATIONS

If the probe could transmit two coherent frequencies, the bus could be instrumented to obtain a measurement of differential Doppler and this would provide information concerning the dispersive characteristics of the propagation medium along the path. This might be useful primarily as a means for determining the ionospheric and magnetospheric electron density distributions.

DUAL-FREQUENCY DIFFERENTIAL GROUP DELAY OBSERVATIONS

The dual-frequency method would permit the observation of solar wind electron concentration in the final days of free fall toward the target body. This observation depends upon a determination of the constant of integration and since continuous transmission from the probes is impractical, the system would have to measure group delay or three-frequency differential Doppler.

OBSERVATIONS OF FARADAY ROTATION

The signal from the probe will undergo Faraday rotation of the plane of polarization, even if the antenna is not plane-polarized. Imperfections in equipment intended to produce circular polarization inevitably lead to the generation of a signal which can be considered as the sum of a circular plus a plane polarization. The plane portion will rotate as it travels, in proportion to the electron concentration, N_e and also in proportion to the strength of that part of the magnetic field which is parallel to the radio path, H_L. A measurement of the total angle of Faraday rotation then provides the value of the integral of (N_e) (H_L) along the path.

OBSERVATIONS INVOLVING MAJOR CHANGES FROM THE DIRECT PROPAGATION 5.2

In addition to the perturbations to the successfully propagating signal which were the subject of the preceding section, there are several other observations which one might make which involve indirect propagation paths or major disruptions of the direct path.

TRANSMISSIONS VIA THE RING OF SATURN

The probe and bus could be targeted in such a manner that the pre-entry signal would pass through the ring of Saturn on its way from the probe to the bus. A study of the scintillation of this signal would provide valuable information about the ring material and structure. This measurement will have been obtained at S-band and X-band by the MJS spacecraft, according to current plans.

RADIO OCCULTATION OF A SATELLITE

Since the probe will be released from the bus about a month before it arrives at the planet, it is possible that one of the satellites of the major planets might lie along the path between the probe and the bus as this pair of spacecraft approach the target planet. This is only possible in a case of Jupiter and Saturn; at Uranus, the satellites rotate in a plane which is nearly perpendicular to the line of approach. Nevertheless it is possible, for Jupiter and Saturn, to perform satellite occultations at 400 MHz if pre-entry transmissions are provided.

SURFACE REFLECTION OBSERVATION

At least in the case of Titan, it is possible that the probe will descend to a solid surface. In this case, the signal from the probe may reflect off the surface and be detectable at the passing bus. A study of this reflective signal would provide information about the character of the surface, even though the probe might not survive the impact.

RADIO BLACKOUT CAUSED BY AERODYNAMIC HEATING

If the pre-entry transmission continues during the onset of the aerodynamic entry, then the atmospheric ionization caused by the entry heating will lead to a cessation of the signal. Some information regarding the character of the upper atmosphere would be provided by an observation of this effect. The implementation of a dual-frequency capability (for other purposes) would permit this blackout to be measured at two frequencies, a step which would probably more than double the value of the observation.

TASKS FOR THE PROBE ONLY 5.3

Some worthwhile objectives can be performed by the probe acting alone. The bus would be involved in these only in the sense that it relays the telemetered information back to Earth.

MULTI-FREQUENCY NOISE SURVEY AT THE PROBE

By means of a special receiver, the probe might be instrumented to perform a survey of the noise at several different frequencies as it falls within the atmosphere of the planet. This might yield good atmospheric information. It would certainly provide future engineers with a very valuable base of data for use in designing future telemetry systems which might incorporate transmission from the bus to the probe. If such an investigation is performed, then the probe's radio transmitter will need careful design to avoid generation of noise which masks the natural background under study.

SPECIAL SENSOR ANTENNAS ON THE PROBE

The telecommunication requirement for a steady strength of signal brings about a requirement that the antenna pattern on the probe should not vary with respect to longitudinal angle so that there will be no spin rate modulation. Furthermore, quite a wide range of illumination angles is anticipated during the operation of the relay link with the result that the probe antenna has to be nearly isotropic. It follows that any noise surveys obtained with this antenna are necessarily indicative of the sum of all the noise signals coming from a wide range of angles. Since diverse sources of radio noise are anticipated, such a measurement will be ambiguous and may not be very informative. It would be better if the antenna were decidedly directive and, since such an antenna cannot serve the telecommunication purpose at the same time, we consider the possibility that a special antenna might be carried on the probe for the purpose of measuring noise.

OBSERVATIONS OF VOLTAGE STANDING WAVE RATIO, VSWR

The radio transmitter aboard the probe must send energy into the probe antenna. The probe will have endured very high accelleration forces during the entry process, and it will be falling in an atmosphere which is extremely inhospitable. A number of unforeseen disasters might occur; ice might form over the aft shield on the space probe, or elements of the antenna might break under the G forces. The telemetry designers will surely want to monitor the performance of the antenna, probably through a measurement of the VSWR since this is fairly well understood and easily instrumented. Such a measurement might also provide an indication of the presence or absence of ionized plasma in the vicinity of the probe during the transmission, since this affects the VSWR.

TASKS FOR THE BUS ONLY 5.4

The availability of the 400 MHz receiver on the bus might serve as the basis for observations which are not associated with the probe's signal. Since the probe's active life is such a small proportion of the mission duration, these experiments provide an unusually effective utilization of the resources available.

TELEMETRY CHANNEL NOISE SURVEY

Since the bus spacecraft will need a receiver tuned to the telmetry frequency, it should be a relatively easy matter to measure the noise level at that frequency. Such information would be useful in the design of future telemetry systems and as a means of evaluating the performance of the system itself. It might also serve as a basis for study of the environment of the planet.

USE OF A DIRECTED ANTENNA ON THE BUS

If a steerable high-gain antenna were available on the bus, then certain special observations would become feasible. For example, one could search for reflections from the particles of the ring of Saturn, even though the probe might not be directly behind the rings at the time of the search. Some of the probe's radio signal must reflect off the rings toward the bus, but the strength of this signal would be very low and undoubtedly its detection would require the use of gain to obtain adaquate signal levels. Supressed sidelobes and backlobes would assist by their discrimination against noise.

RECEPTION OF 400 MHZ SIGNALS FROM EARTH

The probe will transmit for only about an hour, and so for many years before and afterward the 400 MHz receiving equipment will have no scientific function except, perhaps, as a noise monitor. If the receiver were to be connected to the main antenna, which will probably be a 9-foot dish, then it could lock onto signals from existing Earth transmitters out to distances beyond Jupiter. This would permit performance of some useful scientific observations.

EXPERIMENT RATINGS AND DESCRIPTIONS

Putting together the group of experiments and rating them into a single order of preference, the author was reminded of the reports published by a popular consumer magazine which attempts the same categorization of common household products. Often the reader sharply disagrees with the rating sequence thus established, and an examination may show that the difference of opinion is founded in the criteria used for rating. The reader must bear in mind these criteria (section 2.1) since the author is attempting to predict the eventual consensus that the scientific community would reach if all involved were agreed upon these criteria. For one example, the author would favor an outlook upon the probe-bus pair as a travelling system, and would exploit the inherent capability of such a system to make observations that are not feasible by means of a single spacecraft. In this light, pre-entry transmission would rate much higher in the ratings.

For reference, the experiments are listed in order of rating:

--- Measurement of telemetry carrier amplitude

--- Telemetry channel noise survey by the bus

--- Observation of the VSWR

--- Doppler shift measurement

--- Determine radio blackout caused by aerodynamic heating

--- Coordination with telemetry soft-decision feature implementation

--- Use of a directed antenna on the bus

--- Multi-frequency noise survey at the probe

--- Install special sensor antennas on the probe

--- Measure transmission via the ring of saturn

--- Make dual-frequency differential Doppler observations

--- Reception of 400 MHz signals from Earth

--- Surface reflection observation (at Titan)

--- Dual-Frequency differential group delay observations

--- Observe the radio occultation of a satellite

--- Observations of Faraday rotation

MEASUREMENT OF THE STRENGTH AND SCINTILLATION OF THE SIGNAL 6.1

The measurement of signal amplitude would serve both scientific and engineering needs in a direct fashion. Furthermore it can be performed by the bus where instrumentation is easier to install than in the probe. Becasue the derived information has value to many different communities of workers, and becasue the instrumentation is comparatively inexpensive, it seems clear that the probe's telemetry carrier amplitude should be measured and this information sent back to Earth.

The long term variations will be interpreted in terms of the absorption of the signal by the atmosphere as the probe falls. It may also be possible to account for some of this loss through the action of scattering or refraction. The total amount of loss is of direct use in the design of later probes which may be sent to the same astronomical body.

In order to make the long-term changes meaningful, it is necessary to have information concerning the strength of the signal transmitted toward the bus. As a result it is important that the probe should send a signal whose strength can be determined at a later time, based upon the sum of all information which becomes available. It is not necessary that the signal strength should be constant or even that it should follow a pre-programmed schedule. It is only necessary that we should later be able to reconstruct what happened. Therefore, the probe should be instrumented to measure its own environment for telemetry to Earth. It should also provide the values of some key radio parameters which the designers may then use to make their final determinations.

Since the probe antenna pattern is variable with respect to zenith angle, it is necessary to know the zenith angle of the bus as seen from the probe. In the author's estimation, this requirement is not a constraint because the same information is required by the atmospheric structure experiment to a considerably higher degree of accuracy.

While the zenith angle of the bus may be known, because of this other motivation, it is also possible that the probe might not maintain a vertical orientation throughout its fall because of the action of aerodynamic forces. Either a constant list or a wobble about the vertical axis would lead to an amplitude variation. If this source of variation were not correctly reconstructed, then the amplitude changes might incorrectly be ascribed to absorption, scintillation, etc. Therefore it is important that the probe attitude be determinable. The degree of accuracy of this requirement is directly associated with the details of the transmitting antenna pattern, which is not known at the time of this study. For attitude fluctuations with a time scale of roughly one second, and which do not vary in synchronism with the spin rate of the probe, it is important that the relative transmitted signal strength should be known to ± 0.1 dB or less. For slow variations in attitude, those lasting on the order of one minute or more, the antenna pattern effect should be reconstructable to ± 0.2 dB.

Perhaps the most cost-effective approach to the reconstruction of the probe signal strength might be an actual physical simulation of the probe environment in a laboratory on Earth after the entry is completed. A duplicate of the radio transmitter could be subjected to the closest possible simulation of the environment of the actual probe, as determined from telemetered data. It would then be possible to measure the power output of the transmitter and use this as a basis for a reconstruction of the performance.

At the bus, the receiver should provide indications of the strength of the signal coming in from its own antenna. Since the bus attitude will be known comparatively accurately, there will probably be little problem in reconstructing the receiving antenna gain variations throughout the descent of the probe.

From the standpoint of absorption and scattering interests it will be important to filter out the short term jitter in the received signal indications for occasional telemetry to Earth. The scintillation information should be observed with the widest practical bandwidth because of the unusual degree of uncertainity in our ability to predict of this parameter. At the time of this writing, the only data in existence is that derived from S-band occultations of Pioneer 10 at Jupiter, but the scintillation of that signal has not yet been analyzed. By the time the probe is launched, there will probably be some information available concerning measurements of scintillation in the atmospheres of Jupiter and Saturn at S-band and perhaps at X-band. When that information becomes available, we will be better equipped to specify the expected range of scintillation of the probe signal.

During the probe's fall through the atmosphere, it will be fairly close to the layer in which the turbulence lies, perhaps within the Fresnel region. As a result it would be desirable to record phase scintillations in addition to amplitude scintillations since the information would be complementary. Nevertheless, it is comparatively difficult to provide the instrumentation required to measure the phase scintillations, and a stable probe oscillator is needed if this is to be done. These observations will be obtained at the most crucial part of the mission when the bus telemetry system is under its peak demand. Therefore, it is unlikely that raw scintillation data can be sent back to Earth.

It is the author's estimate that the value of the amplitude and phase scintillation data is not high enough to justify the utilization of a significant fraction of the telemetry or data storage capability of the bus. Instead, it should be feasible to provide a small special-purpose computer which derives the basic scintillation statistics. These processed data can be placed in the telemetry chain for transmission to Earth at a much lower data rate than would be required if the statistical calculations were performed from the full set of data on Earth. The advent of powerful digital calculators in integrated circuit form should make this approach tractable, and comparatively inexpensive.

NOISE SURVEY BY THE BUS RECEIVER IN THE TELEMETRY CHANNEL 6.2

The telecommunications designer is always faced with the requirement for matching the signal's strength to the expected noise in each new operational environment. For each mission to the planets, the designers must evaluate previous measurements of noise levels and any other clues contained in other types of measurements or in the theoretical developments which are available. Since the weight of a transmitter and its associated power sources is roughly proportional to the transmitted power, and since this in turn is necessarily proportional to the expected noise, it follows that an accurate forecast of the noise has a great practical value. For this reason, there is little doubt that the bus will be configured in such a way that it can measure the noise both before and after the probe's operation, in order to aid in the designs of future years.

It is not clear to this author that there is a strong requirement for continuing the noise measurement through the operation of the probe. Such an objective could be met through the inclusion of special features in the receiver to enable it to sample the noise at a frequency which is near the carrier but clearly separated from it. Becasue the bus receiver antenna is so broad in its polar angle pattern, and because it is uniform over 360° in its azimuthal angle, each measurement of noise will represent a spatial average over a solid angle which is roughly a hemisphere. As a result, the strength of the noise received by this antenna will not change rapidly during the approach of the bus to the planet or during its later departure. If the receiver can measure the noise prior to the initiation of the probe transmission, and if it can continue the noise measurement after the probe goes off the air, then the bus will obtain a good noise vs. time profile before and after the prime mission. Special radio receiver features allowing continuation of this measurement during the prime mission would only serve to provide the interpolation between the "before" and "after" curves. The information available from other sources, coupled with the measurements before and after the prime mission, should permit this interpolation to be carried out with adequate accuracy. For this reason, it is surmised that the engineering and scientific purposes will be adequately served if the bus monitors noise in the 400 MHz channel only when the probe transmitter is off.

In the case of Jupiter, it appears certain that the predominant noise source is the synchrotron radiation which will be at a level equivalent to a noise temperature roughly of 3000 to 8000°K. A recent analysis of the Pioneer 10 measurements has been provided by Northrop in Birmingham, (1974). For Uranus and Titan, the noise survey should be sufficiently sensitive to permit detection of the surface temperature. This will be difficult because the receiver itself is expected to have a noise temperature of roughly 300°K.

MONITORING CHANGES IN THE PROBE ANTENNA VSWR 6.3

The voltage standing-wave ratio is a sensitive indicator of the match between the signal sent to the antenna and the antenna's ability to accept that signal. Anything which disturbs the electrical characteristics of the antenna generally affects the VSWR. Furthermore the VSWR is comparatively easy to measure and, as a result of this combination of circumstances, it is the conventional parameter which is watched by radio engineers when they monitor a system in operation. A body of experience has been built up and a theory has been developed to relate the VSWR to the condition of the antenna and to the character of its surrounding environment.

It seems likely that the VSWR will be monitored for purely pragmatic reasons associated with the engineering of the probe. The antenna structure must endure the many hundreds of G's during the atmospheric entry. During the fall into the planet's atmosphere, the imagination is hard-pressed to foresee all the combinations of untoward events which may befall the space probe in such unearthly conditions. For example, it may fall through thick swirling clouds of snow composed of a chemical. The residual heat in a heat shield might melt this snow, which might then flow around the edges of the heat shield only to freeze on the back cover over the antenna. In this manner, there might accumulate a thick layer of frozen material clinging to the cover a short distance from the antenna. This would interfere with the near-field electromagnetic radiation pattern of the antenna and impair its ability to accept the signal from the transmitter. The output power would fall, and the VSWR would rise. The behavior of the VSWR, plus other environmental indications telemetered up from the probe, would assist us in an understanding of the problem and permit its avoidance during future missions. The reconstruction of this scenario would be of great assistance to scientists attempting to understand the character of the atmosphere. The author offers this hypothetical story only as an extreme example as the kind of purpose which might be served by VSWR monitoring.

If the probe transmitter were operated prior to the aerodynamic entry, then it is expected that the VSWR would provide an indication of the plasma density in the vicinity of the probe. From this, one might reconstruct the ionospheric electron density profile above the point at which the spacecraft induces ionization. In this brief study, the author has been unable to assess the validity of this idea in a quantitative manner because the current design calls for a cover to be placed over the antenna at some distance from the antenna and the details of the design are not fixed. Yet, the details determine the degree of sensitivity of the VSWR to the plasma environment. Furthermore, this objective itself is outside the range of the three guiding criteria which govern this study and, even if we could show that it would work, pre-entry VSWR monitoring would be unacceptable in the present context. This artificial constraint should not preclude an evaluation of the ionospheric effect, however. It seems clear that the VSWR will be monitored and, furthermore, it may be desirable to warm up the transmitter. If, in addition, it is determined that the ionospheric electron density could be determined with useful accuracy by this means, then a strong case could be made for a brief pre-entry transmission. Thus, while the measurement is not an approved objective, its continued study is warranted. The VSWR measurement after entry is definitely needed for the engineering of future probes and for the understanding of data from this probe.

DOPPLER SHIFT MEASUREMENT TO DETERMINE THE PROBE VELOCITY RELATIVE TO THE BUS 6.4

The existence of a radio link inherently offers the possibility of making a very precise measurement of the range rate between the probe and the bus. To permit this measurement, it would be necessary to place a fairly stable local oscillator on the probe or, alternatively, to provide for a signal from the bus to the probe which could be coherently transponded.

From the standpoint of atmospheric science, the primary benefit of this measurement lies in its value as a means for determining exactly where the probe encountered the planet or satellite. This information, in turn, serves to provide a more accurate knowledge of the angle between the probe velocity vector and the local vertical at the point of entry. This angle is required by the atmospheric structure experiment, if the deceleration observations are to be properly used to deduce atmospheric characteristics. Thus by this direct chain of reasoning, the Doppler measurement tends to permit more accurate atmospheric measurement. Therefore the measurement qualifies as acceptable under the second criterion (a support experiment).

The Doppler tracking accuracy requirement must be based upon a study of the error budgets in the trajectory reconstructions for both the probe and the bus. Such error budgets must be computed both with and without the Doppler measurement in order to establish the levels of Doppler accuracy which are required to produce varying degrees of improvement. It is necessary to determine the quantitative relationship between Doppler improvement and entry angle determinability. Armed with this knowledge, the atmospheric structure scientists may then provide an assessment of the effectiveness of such improvement. Only in this manner can a rational assessment be made of the relative value of Doppler tracking accuracy as opposed to its cost and weight. It is the author's understanding that performance of this task has already begun, although in association with the Mariner Jupiter/Uranus mission which is presently under consideration.

The Doppler shift measurement might provide information concerning the rate of fall of the probe within the atmosphere of the target planet. To see how this might work, consider what might happen if the probe falls through a region of vertical turbulence. (The Earth analogy of this circumstance would be a region of cumulus clouds, or a thunderstorm region). While the probe might fall at a predictable rate relative to the atmosphere, nevertheless its speed of fall relative to the surface of the planet would vary because of the addition or subtraction of vertical winds as the probe moves from one region into another. This effect might be monitored by means of the Doppler measurement. The present Venus probe oscillator specification calls for a stability of one part in 10^9 during a period of about 90 minutes which includes the descent of the probe. If we assume as a worst case that this total error is incurred throughout 90 minutes, then the error in total phase path accumulation (1620 meters) is equivalent to a velocity error of 30 cm/sec.

A sizeable vertical wind would mislead scientists if they were unaware of its presence, since they might otherwise conclude that the probe fell faster or slower because of aerodynamic effects. In this sense, the measurement of speed of fall would not only reveal vertical winds, but it would also increase the accuracy of aerodynamic results.

There is a serious weakness in the foregoing discussion of vertical winds. Because the bus is usually not directly above the probe, the range rate from the bus to the probe is also affected by horizontal winds to the extent that the horizontal wind velocity has a component along the line of sight. For most of a mission this is a sizeable component. Unless some way could be found to compensate for this horizontal wind effect or to determine its value by some other means, the author judges that it would mask the vertical winds effect or at least the suspicion of horizontal wind Doppler would lower confidence in the vertical-wind interpretations. Toward the end of the fall, there is an interval when the bus is nearly at the zenith of the probe. During this period, the Doppler will be unaffected by horizontal winds and the observations may be interpreted as falling speed with confidence.

Despite the difficulty which is inherent to a system which must measure velocity along a non-vertical direction, it is of potential value to make this measurement. At the earliest times, the carrier bus will be about 40° away from the zenith of the probe and so it will be possible to measure horizontal winds using the method pioneered by the Soviet probes. In this application, one must calculate the vertical fall speed and subtract its effect; if horizontal winds are larger than the residual error in this observation, then the calculation yields the component of the horizontal wind speed in the great circle plane containing the bus and probe.

In the foregoing paragraphs I have mentioned three areas of study which might be based upon Doppler observations of the free-falling probe after its entry; (1) aerodynamic data, or how fast does it fall relative to the local atmosphere (2) vertical wind measurement and (3) horizontal wind measurement. It is not possible to learn about all three at once, since we will measure only the sum of their effects. Nevertheless the changing zenith angle of the bus will facilitate this analysis by providing a varying mix of the effects of vertical and horizontal motions; this mixing ratio will be accurately known. Furthermore, the aerodynamic data may be extricated from the mix by taking advantage of the known character of the height variations within the atmosphere.

In summary, the pre-entry Doppler observation would probably back up the atmospheric structure experiment and is therefore desirable. If this measurement capability is incorporated, then Doppler measurement after entry is virtually free. These latter observations may reveal some features of the character of local winds and vertical convection, and possible aerodynamic information can also be gleaned from the data.

OBSERVATION OF THE RADIO BLACKOUT CAUSED BY AERODYNAMIC HEATING 6.5

When an entry body encounters an atmosphere at very high speed, it ionizes the surrounding gases. As the ionization rate increases, the density of the released electrons in the surrounding gas may reach such a level that $80.6\ N_e > F^2$. As may be seen by reference to section 3.1, the refractive index then goes through zero and becomes imaginary. In this circumstance the radio wave can no longer propagate. The cessation of the signal is called a "radio blackout". The onset of ionization depends both upon the Mach number and upon the kinds of gases in the atmosphere. The time of the radio blackout depends not only upon the rate of buildup of electron concentration but also upon the radio frequency. Therefore an observation of the blackout would provide information about the atmospheric constituents.

If a dual-frequency capability is incorporated for other purposes, then it would be a natural consequence that two different radio blackouts could be observed by this method. It would thus be possible to establish two different levels of electron concentration during the onset of the aerodynamic heating.

Since signal strength is likely to be measured for other purposes, as described in the preceding sections, no added instrumentation is required for the observation of blackout. However the accuracy of the timing measurement would depend upon the nature of the instrumentation, both with respect to the timing within the telemetry system and to the quantization levels of the amplitude determinations. From an instrumentation standpoint, then, the blackout observation entails a need for attention to the details of telemetry and of design of the amplitude detection circutry. To achieve fine resolution in the timing of this event without requiring a high data rate, it would be feasible to incorporate special circuitry in the bus which records the time of signal strength decrease through one or more preset thresholds. These few data could be sent to Earth during the blackout. I have not enough information to provide a reliable estimate of the accuracy of timing that would be required, although I have benefited greatly from a discussion of this matter with Dr. Alvin Seiff of NASA/Ames. The timing should be known to some portion of a scale height, probably about 0.1 H_ρ. At the planets, the probe descends through a scale height in about 3 seconds and so I would tentatively recommend a timing accuracy of less than a second. For Titan, the need is probably not so severe.

From an operational standpoint, the blackout detection can only be performed if a pre-entry transmission is made. This is presently not included in the baseline design, but the radio system may be undergoing warm-up at the time when this measurement is desired and so a short pre-entry transmission to serve this purpose might be easy to perform.

CO-ORDINATION OF REQUIREMENTS WITH THE TELEMETRY SOFT-DECISION FEATURE 6.6

There is an alternative approach to the measurement of amplitude scintillation which deserves mention here. This is an entirely new concept, to the author's knowledge.

Basically, the idea stems from the fact that the telemetry community and the scientific community both have an interest in the details of the signal strength fluctuations. For telemetry, the periods of low signal strength are periods when the confidence in the telemetered information is low. By looking at the radio system with this thought in mind, the engineers have determined that their needs are most effectively met through the incorporation of a multi-level bit code rather than a single binary bit. In other words, the decoded telemetry string is not converted into ones and zeros, it is rather converted into a sequence of numbers chosen from a range of numbers. The lower the number, the greater the likelihood that the original datum was a zero. The higher the number, the more likely that the original number was one. This approach is called a "soft-decision" feature and, for the Pioneer probe, an eight level code has been considered (3 binary bits per original bit).

If operated in this manner, the telemetry system would process three times more information then that which was encoded from the original data. It is clear that the original data plus a synchronized observation of the signal strength fluctuation would provide the same confidence indications. As a result we can see that the scientists and engineers might both benefit if these two problems were jointly considered; then it might be possible to provide only one history of the signal strength fluctuations which would serve both purposes. At the very least, radio scientists and telemetry designers should be aware that their parallel requirements are being met by independent plans.

INSTALLATION OF A SPECIAL DIRECTIVE ANTENNA ON THE BUS 6.7

The present plans call for the bus to contain a high-gain antenna permanently directed at the Earth. It will also contain a 400 MHz antenna which is wide in polar angle and invariant with respect to azimuthal angle. As a result, the capability for performing 400 MHz observations is limited by the lack of directivity. Because the bus antenna lacks directivity, the signal which it receives at any instant is the sum of all the signals from a wide range of angles. It has no ability to discriminate among the regions which it views.

Many purposes would be served if the bus had a directive antenna in addition to the broad one which is required for telecommunications. It would then be possible to map a noise field and establish the distribution of the sources of noise in space. In this way the noise generated from the vicinity of the atmosphere could be isolated from that generated in the magnetospheric regions, for example. As it will be seen in the discussion of the Saturn ring experiment described later, the directive antenna could be very useful as a means for performing other kinds of measurements not associated with the atmosphere of the target planet.

The main disadvantage of this idea is the considerable cost and weight of the added equipment if the antenna is to be fixed in inertial space while the spacecraft rotates. The objectives to be served by this antenna probably do not warrant such added complexity and weight. Therefore a directive 400 MHz antenna would probably be constrained to rotate with the spacecraft. The rotation would have the advantage of providing an automatic scanning action, but it has the disadvantage of limiting the length of time during which integration can be performed in any one region.

The most practical implementation of this idea would be a possible modification of the feed structure of the telecommunications antenna which might convert it into a directive antenna. This modification could be performed after the probe signal ceases to be detected, for after that time there is no longer any need for the broad antenna pattern. Alternatively, the conversion from a broad pattern to a directive pattern could be an indefinitely reversible condition effected on command from the ground. In this case, the 400 MHz receiver could be used throughout the life of the spacecraft in association with the antenna in its directive mode. If the receiving antenna can be configured so that it serves both purposes, then this concept may be deemed acceptable both from the standpoint of cruise science and from the standpoint of the capability it provides for monitoring the noise from the atmosphere during the prime experiment. For the latter purpose, the antenna beam should subtend an angle no larger than the disk of the planet. Beams of 35° to 45° would suffice for Jupiter and Saturn. For Uranus a finer beam would be desired, while for Titan the beamwidth would be so small as to make the concept seem impractical at the outset.

MULTI-FREQUENCY NOISE SURVEY BY THE PROBE 6.8

It is possible that a special receiver may be incorporated in the probe for the purpose of surveying the noise levels at a number of different radio frequencies as the probe descends into the atmosphere. This would be of interest to radio astronomers; it would also be important data if, in the future, mankind wishes to send a probe into the same atmosphere which receives signals from its bus. In the latter case, it will be important to know how the noise varies with height and frequency in order to select the best frequency and optimize the system with respect to power level, bandwidth, etc.

While a convincing case can be made in support of this idea, nevertheless it is the author's estimate that such an experiment would not be flown because the idea would not survive the competition with other concepts. The noise survey information would require telemetry from the probe and this capability will be extremely scarce and valuable. The competition for probe telemetry will be fierce. Furthermore the alternative of noise observation from the bus with a moderately directive antenna should provide the key information,(although to a lesser degree of accuracy) at potential communication frequencies. It is not expected that there will be a great deal of absorption down to the level where the probe ceases to function (probably 10 atmospheres). As a result the noise temperature,when viewed from the bus, will be almost the same as that which the probe would measure. The amount of absorption may be deduced with fair accuracy, and it should be possible to infer what the probe would have measured, based upon measurements obtained with the bus. In the bus, equipment constraints are much less severe and there is a more generous telemetry capability.

Despite these negative prognostications, the designers of the probe telemetry transmitter should bear in mind that a multi-frequency noise survey may be performed, since the author's forcast of a future concensus might be wrong. If this survey is undertaken, then it will be necessary for the probe transmitter signal to be "clean"; that is, the probe should not transmit signals at monitored frequencies at a level which would interfere with the noise survey. For Uranus and Titan, it is expected that this noise level to be monitored might be very low, and therefore the transmitter should be spectrally pure.

INSTALLATION OF A SPECIAL SENSOR ANTENNA ON THE PROBE 6.9

For the purpose of conducting a sensitive noise survey, the probe might be equipped with a special antenna providing directivity and gain, probably aimed in the downward direction. Through the control of the back lobes on the antenna, it might then be possible to detect the atmospheric noise even in the presence of stronger synchrotron noise from above. It might even be decided to perform a noise survey at a frequency so high that the absorption above the probe is considerable; in this case, the variation in the noise level during the descent of the probe would provide information concerning the height distribution of the noise generating mechanisms, and of the loss rate.

TRANSMISSION VIA THE RING OF SATURN

This and all the following experiments are not relevant to the atmospheres of the planets, nor do they qualify as acceptable under the second and third criteria. As a result, this and the following experiments would be rated comparatively low. At this early date, one cannot view the criteria as rigid rules, and so these experiments must be regarded as competitive in a broader sense.

A measurement of the spectrum of the 400 MHz signal while it travels through the ring of Saturn would provide key data to those scientists which specialize in the study of the ring. The author's colleague, Dr. G. L. Tyler, supports this view; he is participating in the current program to obtain similar data at S-band and X-band using signals from the MJS spacecraft. The 400 MHz ring occultation would therefore provide a third frequency and, according to Tyler, this information would be valuable as an indication of the frequency dependence of the scattering characteristics of the ring particles.

The ring occultation would be informative only if spectra could be computed. Pre-entry transmissions are required, of course. Since the current concept is that one bus-probe design will serve for Jupiter, Saturn, Uranus and Titan, the observational capability must be incorporated in the basic concept even if it is only to be used useful at one target body. As with the scintillation instrumentation, the author believes that the spectral analysis required for processing this ring data might best be carried out aboard the bus through the incorporation of a modern microcomputer. If such a computation capability is incorporated for the scintillation observation, it could also serve as a basis for the ring observation provided that the bandwidth and depth of fading are within the range of operation of the equipment. In this sense, the ring occultation does not require extra equipment, but it may require extra capability in the existing equipment. The primary cost of the observation is probably that of the battery power needed to run the transmitter of the probe during the passage behind the rings.

There is a practical consideration which may preclude this observation; it is feared that the rings of Saturn may contain destructively large particles out to a distance far greater than the outer perimeter of the visible rings. Until this suspicion is proven or disproven, it is unlikely that the probe or the bus will be flown through the plane of the rings in the region deemed to be dangerous. As a result of this concern for safety, the trajectories which allow the ring to pass between the probe and the bus may be impossible to achieve except at those times when the plane of the rings is nearly parallel to the direction of flight of the bus and probe.

DUAL-FREQUENCY DIFFERENTIAL DOPPLER OBSERVATIONS 6.11

As discussed at length in chapter 4, the transmission of two frequencies from the probe would permit measurements of changes in the plasma distribution between the probe and the bus. Closely related data will be obtained by the radio occultation of the bus itself. In comparison with the latter, the two main advantages of the dual-frequency approach are (1) it can provide ionospheric profiles well away from the terminator whereas the occultation must occur at the limb and (2) the dual-frequency data can be interpreted without invoking a requirement for spherical symmetry such as is conventional in the analysis of occultation observations. In its simplest form, the dual-frequency experiment would be performed using only the Doppler, since that requires only the generation of a second cw tone at the probe which could be accomplished with a simple modulation.

For the second frequency, a second antenna may be required since it is difficult to devise a single antenna which works at both frequencies. However there is one promising approach which is mentioned in association with a candidate probe antenna; it appears that microstrip antennas can be fabricated with two feeds working different sides of a rectangle, and the result is a two-frequency antenna in the form of a single thin, sturdy plate, (Kuhlman, 1974).

This experiment is not compatable with the three criteria, but if the mission of the probe was expanded to include study of the ionosphere, then this experiment would deserve serious consideration.

PROVISION FOR THE RECEPTION OF A 400 MHZ SIGNAL FROM EARTH 6.12

It has been suggested by Professor V. R. Eshleman that the radio occultation of the bus might profitably be observed at 400 MHz in addition to operation at S-band or X-band. The use of a lower frequency would allow the observation of lower plasma densities than would otherwise be detectable.

All of the equipment needed to do this work is already available on the bus; the 400 MHz receiver will have finished its primary work and can be connected to the main antenna which is directed toward Earth. Assuming that a nine foot dish is used, the author's calculations indicate that the 400 MHz signal from existing Earth-based transmitters (Stanford's,for example) should be detectable as far away as Jupiter and perhaps Saturn. The calculated signal-to-noise ratio is based upon an assumed bandwidth of only about 15 Hz in the phase lock loop. The detectability of the signal is intimately dependent on the level of noise generated by synchrotron emission, but it appears that this is not so high as to preclude reception. However the sidebands of the S-band telemetry transmitter may be troublesome. At the time of this writing, this idea has not been analysed with sufficient care to firmly determine its feasibility. It does not qualify under the three criteria but nevertheless it appears to be an efficient use of resources.

With respect to this particular experiment, it is doubtful that one should comply with the restriction of the first criterion to atmospheres only; that restriction was undoubtedly a reflection of the philosophy that the mission of the probe is the in situ study of the atmosphere. This suggested experiment does not involve the probe at all; instead it is a bus mission, and the work of the bus includes study of the plasma environment and other more broadly-based interests.

SURFACE REFLECTION OBSERVATION 6.13

At the target planets, it is expected that the signal which the probe unintentionally transmits in the downward direction will vanish from view, being absorbed until an undetectable remnant remains. However at Titan it is possible that the downward signal might be reflected from the surface and then reach the bus at a detectable level. The fact that this is "possible" is primarily due to our ignorance of the atmosphere and surface of Titan; it is not based upon a dependable forecast that the signal would be detectable. Conservative calculations of the expected strength of the reflected signal indicate that it would be too weak, but there is a great deal of uncertainity in this calculation. There is particularly severe uncertainty concerning the reflectivity of the surface and the backlobe suppression of the probe antenna. Fortunately, the bus-probe separation distance would probably be less than 10^5 km.

If indeed the probe reaches the surface of Titan, it would probably not survive the impact. Then the only information about the character of the surface would be that derived from the atmospheric experiments by the probe and from bus observations. In this case, those scientists who are interested in the surface of Titan could derive valuable information from the strength and spectral spread of the reflected signal. A measurement of the spectrum might permit determination of whether or not probe reached the surface, since the Fresnel zone would shrink dramatically in the final minute.

The equipment required to make this observation would include a receiver which could measure the spectrum of the reflected signal which will have a Doppler shift about 50 to 100 Hz different than that of the descending probe.

Scintillation-measurement circuitry could probably be designed to perform this task as an adjunct process, since the basic requirements are similar.

A description of differential Doppler and differential group delay was given in comparatively great detail in chapter 4. If differential group delay (or else three-frequency Doppler observation) is implemented, it will be possible to measure the plasma content along the radio path without any requirement for integration and the attendant need for a constant of integration. Since the probe will have been released from the bus roughly a month before the encounter, it will be well-seperated from the bus throughout the final days of the approach to the target body. Solar wind electron concentrations near Jupiter are so low that the expected electron content of this radio path will be only about 4×10^{13} electrons/m^2. At the more distant planets this content will be even less, since the concentration varies as the inverse square of the distance from the sun. As a result it is unlikely that solar wind electrons could be monitored by a dual-frequency system operating at 400 and 800 MHz. In order to make observations at densities this low, a much lower frequency would have to be used.

To place this in perspective, we note that the 50 MHz system which was operated on Pioneer spacecraft and on Mariner 5 (by the author's organization) was configured to make a differential group delay observation having a resolution of about 10^{16} electrons/m^2. The measurement of solar wind electron concentration by this means would require a frequency of only a few MHz, in turn requiring specialized equipment on both the probe and the bus. It is unlikely that such a system would be incorporated.

As the probe and bus enter the system of Jupiter or Saturn, plasmasphere electrons should begin to fill the path and these might have a detectable density. Such detection of the plasmasphere might be an objective worth approaching by the differential group delay method. As described in chapter 4, the ionospheric electrons could probably be measured by differential Doppler without the requirement for group delay observation.

This group delay measurement does not meet any of the three criteria, and furthermore it is the author's conclusion that the method is not competitive when compared to other alternative methods.

RADIO OCCULTATION OF A SATELLITE OF JUPITER OR SATURN 6.15

As the probe and bus enter the system of satellites surrounding Jupiter or Saturn, it is possible that they might pass on either side of one of the satellites. Operation of the probe transmitter would then permit the measurement of a radio occultation. The 400 MHz frequency would provide a more sensitive indication of plasma than could be obtained by S-band or X-band.

The choice of a trajectory which would produce such an occultation would be so confining that it would probably not be possible to meet other trajectory objectives on the same mission. It seems likely, then, that the strong competition offered by other requirements for other trajectories would outweigh the need for this 400 MHz occultation. In particular, it would probably be easier and less constraining if the navigators chose instead to perform a radio occultation using the main S or X-band signal from the sun to Earth. This navigation would not require an accurate knowledge of the probe location, and furthermore final trajectory corrections could be made in the last month, well after the probe had been released from the bus. Even though the 400 MHz frequency offers the increased plasma sensitivity, it is the author's conclusion that the radio occultation idea would not be found acceptable. Furthermore, of course, it does not meet any of the three main criteria unless one chooses to argue that the occultation might lead to a detection of an atmosphere on the satellite. In this respect, it is likely that the atmospheric restriction of criterion 1 is intended to refer to the atmosphere of the probed body only.

FARADAY ROTATION OBSERVATIONS

I have placed this experimental method last on the list because it is unlikely that the antennas will be designed in such a manner to accentuate Faraday rotation. Nevertheless it is possible that unintended Faraday rotation observations will be obtained because it is difficult to make a real antenna which does not have some component of linear polarization in addition to its circular polarization. (Eliptical polarization may be regarded as circular plus linear, mixed).

Aside from the fact that it is difficult to implement an unambiguous Faraday rotation experiment between two spinning spacecraft, neither of which has a despun antenna, it is also difficult in the best of circumstances to interpret the resulting data. After considering various hypothetical observations of this type which could be made with the 400 MHz system, the author has concluded that the main information that might be derived would be the presence or absence of a magnetic field. The threshold of detectability of the field would depend partly on the radio system and partly upon the distribution of electrons along the radio path. It would be an uncertain experiment, at the very best.

The determination of the presence or absence of a magnetic field should be fairly easy by means of an on-board experiment, at least in comparison to the Faraday rotation instrumentation. Because of these considerations, the author does not believe that the observation of this effect will be a design objective; furthermore, it does not meet any of the three criteria.

CONCLUSION

A brief look has been given at the concept that radio science might be included early as a design objective associated with the Pioneer Venus probes to Jupiter, Saturn, Titan and Uranus. In this examination, three criteria were specified in advance; (1) the experiments must provide new information about the atmosphere or (2) they must backup scientific data return from experimental packages or (3) they must aid engineers in the design of future probe radio links.

Applying these criteria, the author considered the relative merits of the various experimental approaches which seemed at all worthy of attention. Value judgments were made, comprising estimates of the eventual consensus which would be reached by the scientific community with the assumption that the three criteria were unanimously accepted. The candidate experiments were then rated in order of their desirability according to these ground rules.

The value of this line of reasoning lies in its potential use as a means for a more cost-effective design of the 400 MHz relay radio. Experience has shown that the consensus of the radio scientists is often not known to the radio designers until much of the design is complete, with the result that duplication of effort occurs when early designs are found wanting.

The defined criteria and ground rules serve a valuable purpose; these value judgments must serve as a basis for further evolution of these ideas and ratings. The clear statement of ground rules facilitates the reconsideration of the rating sequence if the underlying ideas are changed. With this thought in mind, the author has provided much descriptive material in this report which would not be required if the ground rules were guaranteed to hold fast to the end. In particular, descriptions have been devoted to experimental approaches which require radio transmissions from the probe prior to the aerodynamic entry and also to some measurements unrelated to the study of the atmosphere. A consideration of these ideas, which are exterior to the main theme of the report, may serve to provide a common starting point for future reconsideration of these experiments and of the criteria which were used in their rating.

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9 ACKNOWLEDGMENT

I received helpful assistance from many people in the preparation of this report. The technical monitor of the sponsoring agency, Mr. Terry Grant of NASA Ames Research Center, was generous with his time in providing explanations, documents and critique. My colleagues at Stanford provided advice on several points and I would like to thank G. L. Tyler, E. Marouf, and V. R. Eshleman for such aid. I was pleased that Dr. Gunnar Fjeldbo allowed me to process his early data and present a derived form here, in figure 1. I would also like to thank Drs. Alvin Seiff and James Warwick for providing me with the benefit of their judgment on some of the matters discussed here.