Status Report
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Magnetometer Instrument Team Studies
for the Definition Phase
of the Outer Planets Grand Tour

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I. TEAM ORGANIZATION AND MEMBERSHIP

The magnetic fields investigation team is organized into three groups. One is concerned with the scientific aspects of missions to the outer planets and the other two are concerned with the instrumentation required for magnetic field investigations on such missions. The activities of these three groups were coordinated by the team members at UCLA with the assistance of the staff there. The UCLA people also supported those activities of the team leader that were directly related to his participation on the Science Steering Group for the Outer Planets Grand Tour (OPGT) and Mariner Jupiter Saturn (MJS).
The members of the team are:

**Ames Research Center**
- Dr. David S. Colburn, Deputy Team Leader
- Mr. Carle Privette
- Dr. Charles P. Sonett

**Brigham Young University**
- Professor Douglas E. Jones

**California Institute of Technology**
- Professor Leverett Davis, Jr.

**Imperial College of Science and Technology**
- Professor Harry E. Elliot
- Dr. Peter Hedgecock

**Jet Propulsion Laboratory**
- Mr. A. Frandsen
- Mr. G. Reisdorf
- Dr. Edward J. Smith

**University of California, Los Angeles**
- Professor Paul J. Coleman, Jr., Team Leader
- Mr. Robert C. Snare

**University of Chicago**
- Professor Eugene Parker

**University of Newcastle upon Tyne**
- Professor S. Keith Runcorn
II. SUMMARY OF TEAM ACTIVITIES

During the period April-December, 1971, the magnetometer team defined the objectives of magnetic field investigations on missions to the outer planets, defined an instrumentation system with which to accomplish these objectives, proposed a program of studies and instrument development tasks for the mission definition phase of the Outer Planets Grand Tour (OPGT) project, and undertook the execution of this program. A report on the status of this program is given in Section III.

The team also established requirements for the spacecraft and the mission which would insure their compatibility with the magnetic field investigation proposed for the outer planets missions and developed figures of merit for encounter trajectories. Finally, the team, in collaboration with the OPGT Project Team, worked to define the spacecraft-instrumentation interface and the on board data handling system. This work is, for the most part, covered in various reports by the Project Team and in the reports by the Science Steering Group.

During the period January-April, 1972, the team participated in the defining program for exploring the outer planets within the more restrictive constraints of the Mariner Jupiter Saturn project. This task included defining a suitably limited magnetic fields investigation as well as re-examining and modifying as required the results of the OPGT tasks described in the preceding paragraph.
III. SCIENTIFIC OBJECTIVES FOR THE
MAGNETIC FIELDS INVESTIGATION
(OPGT-MJS)

A. STATEMENT OF OBJECTIVES

The objectives of the magnetic field measurements, established for OPGT, are:

To investigate the magnetic properties of the outer planets and their satellites,

To investigate the magnetic properties of the interactions of these bodies with their respective plasma environments, and

To investigate the magnetic properties of the solar wind at great distances from the sun, the interstellar medium, and the region of interaction between the two.

The objectives for MJS remain the same, although the scope of the magnetic fields investigation will necessarily be more limited.

B. DISCUSSION (OPGT)

This discussion of the significance of the magnetic fields investigation and the speculations concerning information that might result from such an investigation is related specifically to the OPGT project. However, to a significant extent, it is appropriate for MJS as well. Therefore it has been included here in its entirety.

Planetary Magnetism: Significance

The external gravitational and magnetic fields of a planetary body are the only properties of its interior that can be measured directly on a fly-by. The existence of a planetary magnetic field provides information on the internal constitution of the planet and
its internal dynamics. Information concerning these two aspects is essential to understand the origin and evolution of the body.

The radii and density of the outer planets distinguish them from the terrestrial planets (Mars and the inner planets). The terrestrial planets, because of their greater temperature and weaker gravitational fields, lost most of their hydrogen and helium during or soon after their formation. Their constitutions can be understood in terms of varying amounts of iron and ferromagnesium silicates. On the other hand, the outer or major planets almost certainly are closer in composition to their original states. Their lower densities, compared with the terrestrial planets, show that they are composed mainly of hydrogen and helium, in fact the elements probably have similar abundances to the Sun. Jupiter in particular and the other major planets to a considerable extent can be modelled simply by assuming they contain hydrogen alone. The equations of state of hydrogen can be calculated with some confidence from quantum mechanics. Of major importance is the prediction that at pressures between 700,000 atmospheres and 1,500,000 atmospheres molecular hydrogen will go into a denser metallic phase. Such pressures are attained in the interiors of Jupiter and Saturn but possibly not in Uranus and Neptune. Thus Jupiter and Saturn may have electrically conducting cores while Uranus and Neptune probably do not.

In studying the major planets we can therefore proceed with considerable confidence in the knowledge of the properties of their material at extremely high pressures, whereas in the terrestrial planets the silicates are much too complicated to allow solid
state physics theory to be of much help. It is worth recalling that the internal structure of stars was understood much earlier than planetary interiors, because in their interiors the gas laws can be assumed to hold. Thus a relatively limited body of empirical data such as mass, luminosity, spectra etc. yielded a deep understanding of the fundamental processes in star interiors. The data with which we are concerned on the major planets should similarly be of extreme importance in understanding their internal constitution and dynamics.

One of the most important ideas to be formulated about the earth is the dynamo theory of the geomagnetic field. The testing of this theory by magnetic field measurements of other planets represents an important application of the scientific method and is critical for the progress of geophysics. The only two planets known to have dynamo magnetic fields are the earth and Jupiter. The dipole moment of Jupiter's field is estimated to be $4 \cdot 40 \cdot 10^4 M_E$ (see, for example, Warwick, 1967) where $M_E$ is the dipole moment of the geomagnetic field. The dipole moment of the sun is no more than $4 \cdot 10^6 M_E$. The Mariner 4 data place an upper limit on the dipole moment of Mars at $3 \cdot 10^{-4} M_E$ (Smith et al., 1965), while the Venera 4 data set the upper limit for Venus at $1 \cdot 10^{-4} M_E$.

Little is known about the interior of Venus although its similarity to the earth suggests that it may have an iron core. The absence of a magnetic field is therefore puzzling but the low rotation rate of the planet may account for this as the asymmetry produced in core motions by the Coriolis force is an important factor in dynamo processes. The study of the precession of the orbits of Mars's satellites has enabled the difference
between its polar and equatorial moments of inertia to be measured. From this, the moment of inertia factor is found to be 0.39, cf. 0.3 for the earth. Thus Mars has a much smaller iron core than the earth. For dynamo action, the dynamo Reynolds number must not be below a value variously estimated to lie between 10 and 100.

An important clue comes from the study of the magnetization of lunar rocks. The magnetization of the rock samples from Apollos 11 and 12 (Strangway et al., 1970; Runcorn et al., 1970) and measurements of the field of the moon's surface (Dyal et al., 1970, 1971; Coleman et al., 1972a,c) indicate that the moon's crust was once subjected to a field of about $10^{-2}$ Gauss. If this field was produced by a lunar dynamo, its dipole moment was at least $6\cdot10^{-4} M_E$ while at present any residual dynamo field must have a dipole moment less than $3\cdot10^{-6} M_E$ (Sonett et al., 1967; Ness et al., 1967; Behannon, 1968; and Coleman et al., 1972b). The moon's magnetic field of about 1,000 $\gamma$ must have disappeared some time in the last 3,200 million years, either because the small iron core in the moon, in which the field was once generated, has solidified or because the gradual diminution of radioactive heat available to drive the convection in the core has dropped below the critical value to produce velocities great enough for the magnetic Reynolds number to exceed about 10.
Planetary Magnetism: New Information

There is no evidence for planetary fields at the outer planets, other than Jupiter, or at the satellites of the outer planets. The four Grand Tour missions will make close approaches to the outer planets and possibly to a number of the satellites as well. Thus, the magnetic field measurements will determine whether these bodies have intrinsic fields and, for those with detectable fields, will obtain quantitative data.

Saturn's resemblance to Jupiter suggests that it should have trapped particle belts emitting synchrotron radiation detectable with radio telescopes. No such radiation has been detected. Magnetic field measurements near Saturn will establish if the absence of such radiation is caused by the absence of a dynamo-produced magnetic field. Other possible explanations are that the radiation belts are not populated with energetic particles because the rings absorb them; that the solar wind does not reach Saturn; or that the solar wind interacts with the planet in some other mode.

The Grand Tour will also yield important new information on Jupiter. Jupiter has a strong intrinsic magnetic field that is not symmetrical about its rotation axis (Warwick, 1967), and an extended magnetosphere that will be traversed by all the Grand Tour spacecraft as well as Pioneers F and G. Thus, for Jupiter our objectives are to use this sequence of missions to establish specific properties of the Jovian field. The vector dipole moment and the higher order multipole moments, and the extent to
which the dipole is off-center will be determined (cf. Warwick, 1967 and Roberts and Ekers, 1966).

An important characteristic of a planet is its rotation rate. It seems that the rotation rates of planets with fluid cores generating magnetic fields may fluctuate because of interchange of angular momentum between the mantle and core. If the Red Spot of Jupiter is a Taylor column generated by a surface feature, then the periods of rotation of the sources of decimetric and decametric radio noise are now shorter by about 10 sec than the solid planetary surface. It is important to determine whether the magnetic field, the inclined dipole component as well as the non-dipolar components, rotate with the same period as do the radio sources. Comparison of the rotation periods of the magnetic field sources to that of the surface will provide information on the internal dynamics of the planet.

The variations that have been seen in the Red Spot rotation rate over the last 150 years suggest that large changes in the period of the order of 10 seconds occur on a time scale of some tens or hundreds of years. It is not out of the question that measurable changes in the rate of rotation may occur on time scales shorter than this so that comparison of the rotation periods of the magnetic field between the various missions may reveal small but highly significant changes.

Hydromagnetic turbulence in the earth's core is manifested at the surface by the geomagnetic secular variation. While the predominant periods of this variation are 10-100 years, there is some evidence for more rapid changes. Similar changes in the
field of Jupiter could be detected on OPGT because the four fly-bys of Jupiter will occur over a five year period and measurements of such changes would provide additional important information on the internal dynamics of the planet.

Magnetohydrodynamic disturbances are propagated in a fluid at Alfvén velocities. In the case of planetary cores this raises the possibility that as Alfvén velocities range between 1 and 100 cm per second, depending on the field strength, it is possible that field changes at the surface of the core will take a time equal to this velocity divided into a typical eddy size ($10^7$ to $10^9$ cms).

The sources of the bursts of decametric radio noise are in three longitudes, the noise is assumed to be beamed in a fan shaped distribution to explain the apparent variation in the radio period over one Jovian year. It is apparent that these phenomena must originate in sizeable magnetic anomalies at heights where this noise is generated. Thus, mapping the Jovian magnetic field is an important aspect of the study of the sources and the cause of the beaming.

Recently radio astronomers have found some evidence for a non dipole component from the study of the rocking of the plane of polarization of the decimetre noise. The time variation of the angle of the plane is not exactly sinusoidal and this can only be explained in terms of a non dipole field. Radio studies alone do not allow this field to be completely determined, thus actual measurements near Jupiter of the magnetic field are of great significance.
Very little is known about Pluto but it appears to be a "terrestrial" type planet. The possibility that it possesses an iron core in which dynamo action is possible must be considered.
Interaction of the Planets with Ambient Plasmas: Significance

The interaction between a planetary body and its plasma environment depends upon the properties of both the plasma and the body. For a given set of plasma properties, the interaction depends upon whether the plasma interacts with the magnetic field at the planet or with the matter that constitutes the planet and its atmosphere.

There are at least three known types of solar wind interactions with planets and satellites. At a body with an internally generated magnetic field of sufficient strength, the solar wind momentum flux density is balanced by the magnetic pressure of the planetary field and the bow shock and magnetopause are formed. A weak planetary magnetic field may produce more complex interactions not yet observed in the solar system.

At a planet that has both an atmosphere and an ionosphere, but no strong magnetic field, as in the case of Venus (Bridge et al., 1967) and possibly Mars (Smith et al., 1965), the interaction produces currents in the ionosphere and a bow shock in the solar wind. The interaction with the moon is different from either of these two. At the moon, the solar wind is intersected by the body (Colburn et al., 1967; Ness et al., 1967; Lyon et al., 1967; Siscoe et al., 1969, and Sonett et al., 1972) and is for the most part absorbed or converted into neutral particles. The first two modes of interaction are characterized by the presence and position of a bow shock and magnetopause. All three have characteristic tails or wakes. Each of these features is easily identifiable.
from the magnetometer data.

For bodies such as the moon and Mercury, and thus perhaps for the satellites of the outer planets as well, the steady state interaction has been shown theoretically to depend upon the conductivity of the body and the steady state electric field impressed on the body by the magnetized solar wind plasma in relative motion (Sonett and Colburn, 1967, 1968; Johnson and Midgley, 1968; and Colburn et al., 1972). Interactions, characterized roughly as strong, intermediate, and weak, are found to occur depending upon the overall electrical resistance of the planet. This resistance is determined, in turn, by the interior conductivity and the surface or contact resistance of the body. The interior conductivity is, of course, an important property which is related to the interior constitution. The interaction of the solar wind with the highly conducting plasma of a planetary ionosphere is theoretically similar in many respects to the interaction with the body of a highly conducting planet and therefore may also be classified as strong interaction.

Thus, if no planetary (dynamo) magnetic field is measured directly at a particular planet or satellite, the detection and quantitative investigation of any of these modes will provide a good estimate of the dipole moment of the body or its upper limit. If the planetary field is weak enough, they will provide important information on the physical properties, especially the electrical conductivity, of the interacting planetary material.
As mentioned previously, the four missions may provide close approaches to a number of satellites. Some of these may be in the solar wind, others may be immersed in magnetospheric plasma, as is Io. The interactions of these bodies with their surrounding plasma may well resemble that of the moon with the plasma in the geomagnetic tail. On the other hand, in some cases the interactions may be much stronger. A strong interaction between Io and its surroundings, and the resulting disturbances in Jupiter's magnetosphere, has been suggested as a likely cause of some of the puzzling features of Jupiter's decametric radio emission (Marshall and Libby, 1967; Goldreich and Lynden-Bell, 1969). Thus, if trajectories permit, the study of satellite-plasma interactions will be a significant part of the magnetic field investigation on OPGT.

Some of the satellites of Saturn and Jupiter are comparable in size with the moon. In view of the growing evidence that the moon once had a magnetic field, the possibility that some of these smaller objects also have magnetic fields must be taken into account.
Interaction of the Planets with Ambient Plasma: New Information

Measurements of the magnetic effects of these interactions will yield information on the electrical conductivity of the planetary bodies on their atmospheres. They will also provide data on planetary fields that are too weak to produce a magnetosphere extending beyond the spacecraft trajectories but strong enough to disturb the surrounding plasma.

At planets that interact with the solar wind, the effects of greatly reduced solar wind fluxes upon the properties of the interaction will be determined. This information is essential to understand how magnetospheric particles are trapped and how the solar wind interacts with planetary atmospheres. At satellites, such as Io, that are immersed in local magnetospheric plasma, information on the properties of the body will also be obtained.

An exciting possibility is that a new mode of interaction will be found. The spin axis of Uranus, and presumably its magnetic axis, if one exists, will be directed roughly toward the sun at the time of the Grand Tour. Thus, Uranus' interaction with the solar wind may be quite different from those of the earth and Jupiter, where the dipolar axes are nearly perpendicular to the wind (Siscoe, 1970).
Solar-Interplanetary Magnetic Field: Significance

The magnetic and plasma properties of the solar wind between the orbits of Venus and Mars have been studied extensively. The characteristics of outwardly propagating Alfvén waves (Belcher et al., 1969) and discontinuities have been determined. Changes in the field and its fluctuations and in the plasma density with distance from the sun have been detected (Coleman et al., 1969). Theory predicts that the average properties of the magnetized solar wind change with increasing heliocentric distance (cf. Parker, 1958; 1963) but gives very little indication of likely behavior of other important phenomena. In particular, it is not known how the waves observed in the solar wind are excited and damped, or what is the fate of the discontinuities. Cosmic ray observations and their interpretation in terms of diffusion theory suggest a substantial change in the magnetic characteristics of the interplanetary region in the vicinity of 3 to 5 AU not predicted by present solar wind models.

Thus, an important objective of the proposed experiment is to obtain field measurements over the range from 3 to 30 AU which are essential to solar wind studies and are indispensable in establishing how cosmic rays near earth are related to those in the galaxy. Since cosmic rays are the only material that reaches us from outside the solar system, important astronomical conclusions hinge on the correct interpretation of cosmic ray data.
Solar-Interplanetary Magnetic Field: New Information

Measurements of the solar wind field on this mission will provide data on the growth and damping of waves as functions of heliocentric distance, and thus on the effects of instabilities and dissipative processes in tenuous astrophysical plasmas. In particular, the results will establish whether merging is an important process in the termination of the field. The mapping of the field structure will lead to improved models for cosmic ray propagation.
Solar Wind Termination and Interstellar Fields: Significance

A study of astrophysical significance is that concerned with the termination of the solar wind (Axford et al., 1963; Dessler, 1967) and the region of transition from the solar plasma to the interstellar or galactic plasma, i.e., the structure of the outer boundary of the region occupied by solar plasma, the heliosphere. The simplest model of the transition includes a terminal shock, similar to the earth's bow shock, outside which highly heated and moderately compressed solar plasma flow subsonically in a region called the heliosheath.

The location of the heliopause, and other of these inner layers, is highly uncertain. Arguments based on the balance between the momentum flux of the solar wind and the pressures in the galactic medium suggest a general scale of the order of 100 AU for a spherical structure (Axford et al., 1963).

If neutral hydrogen from the galaxy flows well into the solar plasma before being ionized by charge exchange or photoionization, the properties of the solar wind could be modified throughout a substantial layer, which could extend inside the shock (Blum and Fahr, 1970; Semar, 1970). Thus, as a consequence of the interstellar hydrogen the shock may be shifted inward.

Since the sun is probably moving with respect to the surrounding gas, the heliosphere is not spherical; its outer boundary will be closest in the direction of the relative motion of the sun and there may be a tail out of which all the solar wind flows. A number of observations, including Lyman-alpha measurements (Thomas and Barth, 1971), provide some support for the closer
distance in the direction within roughly 60° of the direction of the sun's motion. Fortunately, this is approximately the direction of the Grand Tour trajectories.
Solar Wind Termination and the Interstellar Field: New Information

If the Grand Tour traverses the interaction region, or reaches even its innermost layer, the magnetic field observations would provide data essential to our understanding of the propagation of galactic cosmic rays and the physics of the solar wind plasma. The differences in the trajectories of the several missions, which vary by 60° to 70° in ecliptic longitude, should provide significant information on the shapes of these heliosphere boundaries.

If the Grand Tour trajectories permit measurements at the outer limits of the heliosphere and beyond, the data will provide the empirical basis for a model of the interaction of the solar wind and the interstellar gas. If the spacecraft go beyond this boundary, the measurements will provide the first data on the interstellar magnetic fields.

Another question concerns the fate of the angular momentum lost from the sun. The sun's rotation is slowed in part by the braking action of the electromagnetic field. Theoretical calculations suggests that the angular momentum carried away from the sun by its electromagnetic field may ultimately be deposited in the interstellar gas that enters the heliosphere as neutral atoms and becomes ionized as it approaches the sun (Coleman and Winter, 1971). If this occurs, the large-scale spiralling found to characterize the average interplanetary field between the orbits of Venus and Mars will unwind beyond the orbit of Mars. Thus,
measurements of the interplanetary magnetic field on the Grand Tour missions will permit a test for this process.

If the Grand Tour missions reach the interstellar medium, direct measurements of the interstellar magnetic field, which is probably weaker than 1 gamma (Verschuur, 1968), and its fluctuations will be obtained. Thus, the experiment may provide essential astrophysical data.
References


IV. TECHNICAL STUDIES AND INSTRUMENT DEVELOPMENT

A. TECHNICAL STUDIES

1. Introduction

The purposes of these studies are to establish performance specifications and requirements for the instrumentation, spacecraft, and mission procedures and to determine the relative merits of the achievable trajectories for the magnetic field investigations on missions to the outer planets. Thus, a portion of our work is directed toward modeling the magnetic environments of the outer planets and their satellites and the outer heliosphere.

2. Status

In one of the studies, at CIT, it is assumed that the magnetic field observed in the vicinity of a planet such as Jupiter is due in part to an essentially constant current system in a core that rotates at a constant but unknown angular velocity and in part to a current system in the magnetopause and magnetosheath. This latter system is assumed to be constant; the fluctuations actually present are treated as superposed noise. The fields can be defined in terms of the coefficients in the spherical harmonic expansion for the magnetic scalar potential in the spherical shell between the two source regions. These coefficients, including the angular velocity of the core, should be determinable from observational data by least squares.

The aim of this study is to develop a computer program the input to which is the data recorded along a flyby trajectory and the output from which is the desired parameters. In order to determine how many coefficients can usefully be computed, and to what accuracy, the program is to be tested with artificial data for
typical fly-by trajectories.

The basic mathematical analysis has been completed. This includes the development of the formulas that:

1. give the coordinates as functions of time along a hyperbolic trajectory, the parameters of which are easily specified;

2. give the three components of magnetic field at a series of points along this trajectory for any specified values of the dipole, quadrapole, and octapole moments, the corresponding coefficients for the external source, and the rotation rate of the core; and

3. determine all of these parameters by least squares from either artificial or real data.

Computer programming has now been completed for items 1) and 2). As soon as it is complete for item 3), noise will be superposed on the artificial data and the accuracy with which we can recover the coefficients used to generate the artificial data will be determined. We will then investigate how many multipole coefficients can be determined with reasonable accuracy and how the accuracy depends upon the flyby trajectory.

At ARC, models of the planetary fields alone are being used in studying the identification and measurement of planetary dipole and higher order fields during practical flyby trajectories anticipated for the outer planets missions. For this effort a computer simulation combines planetary field models with trajectory models in which the spacecraft motion is approximated as a hyperbola in the planetary frame.
During the period covered by this report only certain cases were investigated, in particular the case of Uranus, the spin axis of which lies nearly in the ecliptic plane. From typical encounter trajectories computed by JPL, the spacecraft is assumed to approach the planet in a direction along the planetary spin axis, coming to a point of closest approach at an altitude of 0.16 planetary radius near the planetary equator and leaving in a direction asymptotically 40 degrees deflected from the original approach vector.

Figure IV-A-2-1 shows the magnetic field signature expected from a centered planetary dipole aligned along the spin axis. Under these conditions the observed field reaches a maximum of 0.79 the equatorial surface field to which the plot is normalized, and the period of time in which the field is above 10% of its maximum value is approximately 90 minutes, allowing considerable time for study of higher order modes and possible ring current systems along with time varying effects.

In the future, the program will be applied to the study of Jupiter and Saturn encounters and the results compared to the CIT program which includes effects of external currents, e.g., magnetopause currents and noise.

At Newcastle, a theoretical study is being carried out to determine the information about the magnetic field and its harmonics that can be obtained on a flyby. It can be demonstrated by Gaussian analysis that a field known over the surface of a sphere can be separated into internal and external parts and the amount of current flowing across the sphere measured. In the case
Figure IV-A-2-1

MAGNETIC FIELD, normalized

TIME, min

Figure IV-A-2-1
of a planetary flyby, the three vector components of the magnetic field are measured over a wide range of distance and relatively limited ranges of latitude or longitude, or both. The objective of this study is to develop theorems giving the amount of information about the field and its harmonics which can be obtained on such trajectories.

B. INSTRUMENT DEVELOPMENT

1. Introduction

In order to insure the availability of instrumentation suitable for the proposed magnetic fields investigations on missions to the outer planets, several instrument development tasks were undertaken by the team. The objectives are to analyze and test modified state-of-the-art magnetometers in order to identify any modifications and improvements that would be desirable for such missions. Two types of magnetometers were examined in this study, the vector fluxgate magnetometer and the vector helium magnetometer. The test-model fluxgate is one designed at the Ames Research Center and incorporating ring core sensors designed at the Naval Ordnance Laboratory. The test-model helium magnetometer is a modification of one developed at the Jet Propulsion Laboratory for Pioneer/Jupiter.

2. Sensor Radiation Environment and Its Simulation

An important question in these studies concerns the long-term reliability of instrumentation subjected to radiation. Nuclear and space radiation produce changes in organic materials primarily because of ionization caused by gamma rays, high energy neutrons and charged particles. The effect of high energy radiation on
on the molecules of polymeric insulators is the breaking of bonds. The ions formed at the site of a broken bond may either recombine, leaving the structure unchanged, or may diffuse away and form bonds at other sites. When the site of a broken bond is in a side chain of a long chain polymer, two such long chain molecules may cross-link. When the broken bond occurs in the main chain, and results in splitting the molecule, the mechanism is called scission. Both crosslinking and scission are often accompanied by the evolution of gas. Crosslinking and scission have opposing effects on the mechanical properties of a polymer. Crosslinking hardens the polymer and increases its strength. Scission softens and weakens the polymer. When a polymer receives high energy ionizing radiation, the effects of crosslinking predominate at low and moderate radiation doses, but the affects of simultaneous chain scissions predominate at high doses. Thus, an initially flexible polymer will go through successive stages of hardening, embrittlement, and powdering under continuous ionizing radiation.

In order to predict whether the organic insulators in the magnetometers would survive the ten year TOPS mission, the ionization dose deposited in organics by each component of nuclear and space radiation specified in TOPS Document 3-300 (January 1970) was calculated. The individual doses were summed, so that the total dose could be compared with published radiation damage. The dose calculations were repeated for two later estimates of the Jupiter particle spectra. Due to changes in the spectra, the estimated dose increased from $10^5$ to $10^7$ rads (carbon), and the proton
component became increasingly important, providing at first 61% of the total dose, then 97%, and finally 99.5%.

The contributions to dose from the different components of the TOPS spectra are shown in the following table. The spectra of electrons and protons used was that from the 1971 Jupiter Workshop, and supplied by the Jet Propulsion Laboratory in September 1971.

The total calculated ionization dose of about $10^7$ rad (carbon) (see Table IV-B-2-1) was then compared with published damage levels for the individual insulators used in the magnetometers. Definite conclusions were difficult because little information could be found on insulation strength. The best indication was given from radiation tests done on transformers, wherein no significant degradation of electrical characteristics occurred up to $5 \times 10^{17}$ neutron/cm$^2$ and $2 \times 10^9$ rad (carbon).

An overall radiation test of the magnetometers was considered desirable since the magnetometers should remain operable at radiation levels much higher than can be predicted by considering the individual organic insulators that are used in the device. This is because gas evolution causes little or no damage if a vent hole is provided and a weakened and cracked insulator will serve satisfactorily if it has mechanical support and is not penetrated by water vapor.

In our search for a test that would produce radiation damage equivalent to the proton and electron radiation encountered in passing through the trapped particle belts near Jupiter, the spectra of secondary electrons and recoil protons produced by the gamma
### Table IV-B-2-1

**Ionization energy deposition in organic insulators from TOPS spectra**

<table>
<thead>
<tr>
<th>Radiation type</th>
<th>Absorbed dose (rad-carbon)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gamma</td>
<td>10,000</td>
</tr>
<tr>
<td>Neutron</td>
<td>6,000</td>
</tr>
<tr>
<td>Electron, collision</td>
<td>26,000</td>
</tr>
<tr>
<td>Electron, radiation</td>
<td>2,000</td>
</tr>
<tr>
<td>Proton</td>
<td>9,500,000*</td>
</tr>
<tr>
<td>Alpha and heavy particle</td>
<td>Negligible</td>
</tr>
<tr>
<td></td>
<td>9,544,000</td>
</tr>
</tbody>
</table>

*Spectrum of September 1971 was used for worst case orbit.
and neutron fluxes of a TRIGA reactor were studied. It is, of course, impossible to arrange for isotropic irradiation by energetic protons (1 to 300 MEV) and electrons (0.1 to 100 MEV) in the laboratory. However, it was felt that a reactor test would produce a reasonably good simulation. The reactor gammas produce internal bombardment of the insulator by electrons of average energy 0.5 to 1.0 MeV. These electrons have the same energy loss, dE/dx, in the insulator as do the electrons over the entire spectrum at Jupiter and have also the same dE/dx as the high energy part of the proton spectrum (E_p > 100 Mev) at Jupiter. The reactor neutrons produce internal bombardment of the organics by recoil protons of average energy 1 to 2 MeV, and thus should represent very well the low energy part of the Jupiter proton spectrum. There is no component of reactor radiation capable of generating ionization tracks exactly like those due to the middle part of the Jupiter proton spectrum (10 to 100 Mev). However, the most damage is done near the ends of the proton tracks, where the ionization becomes very dense as the particles slow down. Therefore, the neutron generated proton recoils would simulate the ends of the space proton tracks. Thus, it is probable that equivalent radiation damage could be produced per equivalent ionization dose.

Calculations are being performed to provide scale factors between the various components of reactor and space radiation, with respect to radiation damage to organic insulators, so as to put dose equivalence on a quantitative basis. Assistance in this
complex problem is being provided by the Naval Research Laboratory, where the inverse problem is being attempted: that of developing a code to predict neutron damage from irradiation damage by heavy ions.

In the course of these studies, sensor components have been exposed to energetic protons as well as gamma rays and neutrons. The results of these tests are discussed in the following section.

3. Vector Fluxgate Magnetometer (ARC)

Studies of the VFM suggest the use of transformers in the narrow band tuned amplifier channels and the drive sub-assembly. With transformers wherever possible, the instrument has greater radiation resistance and higher reliability since the performance requirements on the active devices are reduced. Table IV-B-3-1 shows the parts usage and assignment for the baseline instrument. A measure of redundancy is incorporated into this baseline system through the use of three sensors, one for each vector direction and three amplifier/demodulator channels. All three channels must fail for the instrument to become completely inoperative.

This baseline configuration should be capable of withstanding most types of radiation without significant damage. The possible exception involves the protons, with a predicted fluence of $7 \times 10^{12}$ part/cm$^2$. Our studies indicate that in order to minimize the deleterious effect these protons have on semiconductor devices, one should

- use bipolar rather than MOS devices
- avoid using SCR's and unijunction transistors
- avoid using germanium devices
<table>
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<th>SUB-ASSEMBLY</th>
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<th>XEMR</th>
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d. minimize the rating of power type devices
e. require evacuation of device packages

The reliability of the VFM can be considerably increased by redundancy. Redundant circuitry can be incorporated for all functions in the main signal channels or where the function cannot be modified by spacecraft command. As in the baseline system, transformers are used for their increased radiation resistance and higher reliability. The comparative simplicity of the fluxgate type magnetometer allows this redundant system to have a parts count (see Table IV-B-3-2) of approximately 560 which is comparable to nonredundant instruments of more complex design. Because of the type of circuitry (low level signal) which makes up the majority of the electronics in the VFM the power required for the redundant system is less than the power required by an instrument of more complex design.

The most desirable VFM system incorporates electronic redundancy and sensor redundancy, hence offering complete signal redundancy from input to output. The nature of the fluxgate sensor is such that the dual sensors can be added with a parts count increase of less than 10% over the redundant electronic system. A power increase of approximately 120 milliwatts is required to drive the extra sensors raising the total sensor power to 240 milliwatts.

The weight and power required for each of the units described in this section is as follows.
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Power

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<td>1.5w</td>
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<td>--encounter</td>
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<tr>
<td>--encounter</td>
<td>1.8w</td>
<td>2.2w</td>
</tr>
</tbody>
</table>

Weight

Baseline 2.27 lbs; elec red. 3.28 lbs; comp. red. 3.54 lbs.

During the reporting period reactor tests were performed on four VFM sensors. Each received a different ionization dose, the four doses being $2 \times 10^6$, $7 \times 10^6$, $2 \times 10^7$, and $7 \times 10^7$ rads (carbon). The irradiation produced no effect whatsoever on electrical performance.

It is believed that the magnetometer will perform perfectly to at least $2 \times 10^9$ rads (carbon), which is a safety factor of 100 above the estimated dose for the worst case or orbit of closest approach. However, because of uncertainty in the specification of the proton spectrum, which may yet not indicate the actual dose, a conservative safety factor of 10 is confidently stated.

4. Vector Fluxgate Magnetometer (Imperial College)

In order to establish the radiation tolerance of a commercially produced fluxgate sensor, a three-axis sensor manufactured by the Schonstadt Instrument Company was irradiated by A. Balogh at Imperial College at the request of the team members there. The instrument was a prototype of the magnetometer carried on board HEOs 1 and 2.
The exposure was performed at the synchrotron facility at Harwell, Atomic Energy Research Establishment. A proton fluence of $10^{13}$ cm$^{-2}$ at an energy of 160 Mev was applied. No measurable degradation occurred in the instrument performance.

5. **Vector Helium Magnetometer (JPL and BYU)**

The vector helium magnetometer sensor development consists of three phases. They are: (1) component study and evaluation, (2) fabrication of a science evaluation sensor, and (3) science evaluation and tests.

The tasks performed and results obtained under the component study and evaluation phase consisted of the following:

a. A cell was radiated at the expected TOPS radiation level and there was no change in the transmission of the cell.

b. A polarizer was radiated at the TOPS expected radiation level and there was no degradation in its transmission or polarization characteristics.

c. A Pioneer type $\text{As}_2\text{S}_3$ lens was radiated at the expected TOPS radiation level and no degradation was observed.

d. Radiation tests were run with two different types of infrared detectors. The first detector was a lead sulfide type used in Pioneer. The second detector was a silicon detector used in a magnetometer by Texas Instruments. The tests were run on both detectors to measure the effects on the noise from each detector and to determine whether effects would degrade the performance of the magnetometer. There was no measurable degradation in the performance of the closed loop VHM.
The radiation tests on components unique to the VHM were performed at three facilities. The neutron tests were conducted at Northrup Aircraft Co., El Segundo, California. Neutron fluences were $10^{12}$ cm$^{-2}$ with neutron energies in excess of 10 kev. Energetic proton tests were conducted at the Space Radiations Environment Laboratory of NASA, Langley, Va., at fluences of $9 \cdot 10^{12}$ cm$^{-2}$ and energies of 140 Mev. Additional energetic proton tests were conducted on the cyclotron of the UCLA Physics Department at fluences of $2 \cdot 10^{11}$ cm$^{-2}$ and energies in the range 33-38 Mev.

During the second phase a complete prototype sensor was fabricated. Under the third phase, this sensor was irradiated without measurable degradation in its performance.
V. BASELINE INVESTIGATION DESCRIPTION

For the magnetic fields investigation on the outer planets missions, the magnetometer system will measure the *vector* magnetic field. Desired general system specifications are as follows:

**Frequency Ranges:**
- 0 to 3.0 Hz maximum
- 0 to 0.1 Hz minimum and intermediate ranges

**Dynamic Ranges:**
- 0 to $\pm 8 \, \gamma$ minimum
- 0 to $\pm 10 \, \Gamma$ maximum and intermediate ranges

**Digital Resolution:** 1 part in $2^{13}$

**Instrument Noise:** 0.005 $\gamma$ rms, 0-3.0 Hz

The specified sensitivity is based on the estimates of the strength of the interstellar magnetic field. The dynamic range is based on estimates of the Jovian field. The upper limit of the frequency range is based upon estimates of the Doppler shifted gyro frequency in the solar wind.
VI. INSTRUMENTATION

A. INTRODUCTION

In the course of the mission definition work for the exploration of the outer planets, the spacecraft and payload became more and more limited. With each iteration, the scientific instruments were more tightly constrained. Following are descriptions of three versions of the magnetometer that were defined during the study. The first is that originally proposed for OPGT, the second is the so called minimum experiment for OPGT, and the third is the minimum experiment for MJS.

B. PROPOSED OPGT SYSTEM

The proposed magnetometer system includes a JPL vector helium magnetometer (VHM) and an ARC vector fluxgate magnetometer (VFM). This combination of flight proven designs provides a highly reliable experiment with the measurement capabilities required for the Grand Tour.

We recognize the severity of the requirements for reliability and long instrument life for this mission and we propose to meet with these requirements by employing two different magnetometers, each of which has an ideal history of reliable, long-lived operation in space. The two magnetometers are functionally redundant but dissimilar in design and operating principles. If an unanticipated environmental factor or aging process causes an inflight failure in one instrument, it is not likely to be fatal to the experiment objectives since it is unlikely that the same phenomenon will have catastrophic effects on two basically different instruments.
Other promising types of magnetometers were considered, e.g., Josephson junction sensors for low fields and Hall effect sensors for high fields. However, the exceptional performance capabilities of the flight proven VHM and VFM magnetometers and the primacy of reliability in the Grand Tour requirements, which ruled out the use of instruments with no flight history, dictated the choice of the system proposed here.

Only one instrument, the vector helium magnetometer, will normally be operated in interplanetary space. During special events, such as programmed spacecraft rolls, interplanetary data will be acquired simultaneously from both magnetometers. Also, simultaneous data will be acquired from both during planetary encounters. This plan has the advantage that it requires the reduction and analysis of only one set of interplanetary data. Furthermore, it provides the option of powering or not powering the
fluxgate in the standby mode depending upon which state provides longer life.

Functional block diagrams of the magnetometer systems are shown in Figures VI-B-1 and VI-B-2. The specifications for the magnetometer system are listed in Table VI-B-1.

The instrument bandwidths should be sufficient to cover the frequency range up to the Doppler shifted proton gyrofrequency, $f_G$. Presently, the TOPS baseline payload includes a plasma wave experiment which covers the frequency range from $f_G$ to much higher frequencies. If this coverage is not provided, then we would propose to increase the bandwidth of the magnetometers.

The telemetry data rate requirements are dictated primarily by the instrument bandwidth. The number of bits necessary to make each vector measurement is 44, i.e., $3 \times 13 + 3$ polarity bits + 2 bits for range. In addition, subcommutated data, roughly eight 8-bit words, will be needed to monitor the instrument status. With both magnetometers acquiring data over the specified instrument bandwidth, 0-3 Hz, approximately 1000 b/s are required. As the spacecraft travels outward and the data rate decreases, the instrument bandwidth will be reduced. A reasonable data rate at 30 AU could be as low as 100 b/s corresponding to a bandwidth of 0.3 Hz.

No provision for on-board data processing or compression is included in the magnetometer system proposed here. During the mission definition phase, the on-board data handling system will be defined so that possibilities for on-board processing, particularly data compression, by the spacecraft computer and by the magnetometer system can be properly compared.
Table VI-B-1

MAGNETOMETER SYSTEM SPECIFICATIONS

**Dynamic range:** Four full scale ranges for each. VHM: ±8γ, 256γ, 8000γ and 2.5T. VFM: ±32γ, 1000γ, 32,000γ and 10 T.

**Instrument noise:** VHM: 0.005γ, 0 to 3 Hz (10⁻⁵γ²/Hz, white). VFM: 0.015γ, 10⁻⁷ to 3 Hz (10⁻⁴γ²/Hz, at 0.1 Hz, pink).

**Digital resolution:** VHM and VFM: 1/8192 or 2⁻¹³ × full scale.

**Absolute accuracy:** better than 1% of the measured field + 0.01γ (VHM) and ±0.1γ (VFM).

**Frequency response:** VHM and VFM: 0 to 3 Hz maximum; 0 to 0.6 Hz and 0 to 0.1 Hz programmable.

**Mass:** Sensor: VHM: <0.7 kg (<1.5 lbs); VFM: <0.5 kg (<1.0 lbs).

Main electronics ass'y: VHM: 2.6 kg (5.75 lbs); VFM: 1.4 kg (3.0 lbs).

**Power:** Low field (<8000γ): VHM, 5.75 watts; VFM, 2.50 watts.

High field (planetary encounter): VHM, 7.25 watts, VFM, 4.00 watts.

**Dimensions:** VHM Sensor: 10⁻³ m³ (4" × 4" × 8"); VFM Sensor: 1.25 × 10⁻⁴ m³ (2" × 2" × 2"). Main electronics ass'y: VHM, 5 × 10⁻³ m³ (14.5" × 7" × 3"); VFM, 1.7 × 10⁻³ m³ (14" × 7" × 1").

**Temperature operating range:** Sensor: -50°C to +60°C both VHM and VFM; Main electronics assembly: -55°C to +85°C.

**Command requirements:** (a) Initiate in-flight-calibration sequence. (b) Override automatic range selector. (c) Override automatic bandwidth selector. (d) Power commands for both the VHM and VFM.

**Mounting requirements:** The sensors should be located at the end of a long boom to reduce the contributions of spacecraft magnetic fields to 0.01γ or less at the VHM sensor and 0.04γ or less at the VFM sensor. In addition, the VHM and VFM sensors should be well separated.

**Remarks:** (a) Both the vector helium magnetometer (VHM) and the vector fluxgate magnetometer (VFM) will incorporate automatic ranging to accommodate both very weak and very strong fields. (b) The resolution of 2⁻¹³ does not require 13 bit analog to digital conversion. This resolution is usually obtained by using a combination of field apertures and state of the art precision converters. (c) The instrument power requirements will be 6 to 9 watts in interplanetary space. In fields with vector component strengths greater than or equal to 10 gauss, a maximum power of 11.25 watts will be required.
Figure VI-B-1. Functional block diagrams of the basic magnetometers
Figure VI-B-2. Functional block diagram of auxiliary circuitry.
The helium magnetometer sensor is a quantum mechanical device containing a source of circularly polarized IR radiation, a helium absorption cell which is optically pumped by the incident IR at 1.08 microns, and a 4 inch diameter triaxial Helmholtz coil system which encloses the helium cell. The coil system alternately produces a 360° rotation of a constant amplitude sweep vector in one plane, then in an orthogonal plane. Both planes contain the optical axis of the sensor. In the absence of any external magnetic field, the rotation sweep vector destroys the optically pumped condition twice during each rotation. As a result, the IR detector senses a purely sinusoidal variation in the transparency of the cell at twice the sweep frequency. When an external field is present, the instantaneous angle between the rotating sweep vector and the optical axis is altered by the perturbing influence of the ambient field vector. This causes an asymmetrical variation in optical transparency, giving rise to odd harmonics, the strongest of which, the fundamental, is extracted by a filter, then synchronously demodulated to obtain "error" signals proportional to the two field components which lie in the plane of the sweep vector. The error signals are used to generate precision currents which are fed back to the Helmholtz coil system so as to null out the ambient field components.

In this closed loop mode of operation, the field components are proportional to these feedback currents which are the magnetometer outputs. Detailed discussions of the principle of operation of this instrument are given in Connor (1968) and Slocum and Reilly.
The ARC fluxgate magnetometer consists of a triaxial sensor and electronics assembly interconnected by a long boom cable. The sensor consists of three saturable core probes arranged in a mutually orthogonal array to provide measurements of three orthogonal vector components of the magnetic field.

Each sensor is wound with three windings, the primary, secondary, and feedback windings. A common drive circuit, consisting of an oscillator, frequency divider, filter and amplifier, provides a periodic driving signal at approximately 5 kHz to the three primary windings. At the output of each secondary winding is a detector circuit that consists of a filter, preamplifier, demodulator, and integrating amplifier. This circuit selects the component at the second harmonic of the driver frequency that appears in the signal from the secondary winding, amplifies it, demodulates it, and provides to the integrating amplifier a voltage that is proportional to the vector component of the magnetic field in the direction determined by the orientation of the sensor. The voltage output from the demodulator controls a current source which applies a nulling current to the feedback winding on each axis of the sensor. The measurement of ambient field components is achieved by sensing and reading out these nulling currents. A detailed discussion of the ARC magnetometer has been published by Dyal, et al., 1970.

Other important features in the magnetometer system are the aperture/range control unit, which adjusts the sensitivity of each component magnetometer according to the intensity of the electromagnetic environment.
ambient field; the programmable data filter, which adjusts the output filters in accordance with the sampling rate available for the magnetometer; and a calibration sequence control, which periodically applies known fields to the sensor in order to check the magnetometer sensitivity.
C. OPGT MINIMUM SYSTEM

As before, in order to ensure that the experiment objectives can be accomplished over long periods of time, in unusually adverse environments, the magnetometer system will include two triaxial magnetometers which have similar performance but different principles of operation. The similarity in measurement capabilities makes the two magnetometers functionally redundant for a wide range of measurements while the dissimilarity in operating principles makes it unlikely that both will exhibit the same failure modes.

The two instruments are a vector helium and a vector fluxgate magnetometer (VHM and VFM). They are designed to operate in the fractional hertz portion of the spectrum so as to detect both steady state planetary fields and hydromagnetic disturbances. The operating ranges of the VFM and VHM will be identical except that the dynamic ranges of VFM will extend to 6 \( \mu \mathrm{T} \) full scale component while that of the VHM will extend to 1-1/2 \( \mu \mathrm{T} \).

Meaningful magnetic field measurements in the distant solar wind and interstellar medium require that the total spacecraft
Remanent magnetization contribute no more than $0.01 \gamma (10^{-7} \text{T})$ to the reading of the sensors. This suggests the use of a 50 foot boom. With the VHM mounted at the end of this boom, the fluxgate sensors would be mounted a meter or so inboard to eliminate mutual interference. The recommended mounting configuration is then as follows: the 1.5 pound VHM sensor mounted at the end of a 50 foot astromast and the $\sim 0.75$ pound triaxial array of fluxgate sensors mounted $\sim 30$ feet out on the same boom.

With regard to data interfaces, the present minimum magnetometer experiment will include two 11 bit analog to digital converters, one for the VHM system and one for the VFM. Should the dollar, power, or weight constraints turn out to be too restrictive, the spacecraft measurement processor would be used to perform the necessary axial commutation and analog to digital conversions of output signals from the magnetometer system.

The minimum experiment will have four automatically selected operating ranges for both the VHM and VFM. When the operating range of the VHM or VFM sensor changes, it will change simultaneously to some new value on all three axes of that sensor. Thus, three data bits are sufficient to indicate which of the six ranges is being used. The three range bits plus eleven bit data words, one from each axis, give 36 bits per vector measurement. Assuming a 240 bps average encounter data rate at 5 AU, the experiment will make continuous vector measurements of magnetic field fluctuations up to 2 Hz with the VHM sensor and make vector fluxgate measurements, also up to 2 Hz, but less than 10% of the time.
As the spacecraft travels farther from earth, and the average data rates go down, a spacecraft generated bit rate signal will be required for switching in the pre-sampling, low pass filters. That is, besides the basic 2 Hz bandwidth of the VHM and VFM systems, there will be two lower bandwidth, selectable filters. The requirements of the minimum instrument are contained in Table VI-C-1. The interface with the spacecraft will include power input lines, command input lines, housekeeping data output lines, and magnetic field data output lines.

The most confining technical constraint is power, followed by weight, with bit rate being the least confining. For an extra watt, the experiment could be made to achieve perhaps a 10 \( \mu \) full scale operating range while some of the additional power could be devoted to restoring redundant control functions. As an alternative to using most of the extra watt to restore the originally proposed 10 \( \mu \) full scale fluxgate range, the one extra watt plus an 8 \( \mu \) fluxgate range should leave enough power to restore at least one of the originally proposed 14 bit range and aperture schemes.

The most serious constraint is weight because it limits our ability to rely upon redundancy as a means of assuring planned system performance.

While the data rate constraint is considered least confining, it should be pointed out that any increase in the available data rate, up to 1000 bps, could be effectively utilized with no change in the magnetometer system.
Table VI-C-1
OPGT MINIMUM INSTRUMENT DESCRIPTION

I. Location
   A. Sensor: VHM: \{ At end of 50' astromast
            VFM: \{ 20' from end of 50' astromast
   B. Electronics: Science bay.

II. Weight
   A. Remote: 2-1/4 lbs.
   B. Bus: 5-3/4 lbs.

III. Size
   A. Remote: \{ VHM sensor: 4"x4"x8"
            VFM sensor: 3"x3"x3"
   B. Bus: 14"x7"x4"

IV. Orientation
   A. Field of View: N/A
   B. Preferred Viewing Direction(s): N/A
   C. Scanning Rates: N/A
   D. A/C Stability - knowledge of the orientation of the sensor axes to within ±1/2° with respect to an inertial reference.

V. Power
   A. Remote: cruise: \{ VHM 1.3W†
            VFM 0.6W*
            encounter: \{ VHM 2.0W†
            VFM 1.3W

†RF losses in VHM boom cable assumed to be <1db.
*Planned VFM operation is <10% of cruise duration.
Table VI-C-1 Continued

B. **Electronics:** cruise: \{VHM 3.0W, VFM 1.1W*\}
   encounter: \{VHM 3.3W, VFM 1.4W\}

VI. **Thermal**

A. **Sensor:** -40°C to +60°C
B. **Electronics:** -10°C to +60°C

VII. **Data**

A. **Profile:** continuous.
B. **Bits/sec:** 240 bps average at 5 AU
   36 bits per vector measurement

VIII. **Mission Sequence:** Continuous operation.

IX. **Other Constraints**

1) Magnetic constraints imposed on the design of all spacecraft subsystems.
2) A long boom on which to mount the magnetometer sensors.
3) Five ground commands.
4) A spacecraft generated bit rate signal used to control the bandwidth of presampling filters.
5) Possible use of analog to digital conversion by the spacecraft Measurement Processor.
6) Possible use of the spacecraft Measurement Processor to do onboard averaging and other forms of data compression, if those features are available.

*Planned VFM operation is <10% of cruise duration.*
A magnetometer system suitable for the MJS mission will make accurate measurements of magnetic field components in the range $10^{-1}$ to $10^5 \gamma$ (1 gauss). The necessity for measuring fields as small as $10^{-1} \gamma$ is likely to come about in the distant solar wind or interstellar medium where an exceptionally low noise, low drift dc vector magnetometer will be needed. A magnetometer instrument with a combined noise and drift of less than $10^{-2} \gamma$ is considered adequate for this objective. In addition, the sensor must be remotely located such that unknown changes in the spacecraft remanent magnetization will be unlikely to cause field changes exceeding $10^{-2} \gamma$ at the sensor location during the time interval between successive spacecraft calibration roll maneuvers ($\sim$ once per AU and after planetary encounters). It is expected that this requirement can be met by constraining the spacecraft's prelaunch remanent magnetization to a steady state value of approximately $3 \times 10^{-2} \gamma$ at the sensor location.

At the other measurement extreme, the requirement to measure fields as large as 1 gauss comes about during planetary encounter. At Jupiter, where, because of considerations for radiation damage on the one hand and flight time to Saturn on the other, periapsis is restricted to lie between 4.5 $r_J$ and 11 $r_J$, a 1 gauss full scale range permits the direct measurement of field strengths corresponding to surface fields in the range 100-1000 gauss, well in excess of most current estimates. At Saturn, however, little is known about the orientation and strength of the dipole moment. Nevertheless, a 1 gauss surface field is often assumed.
The mass and power allotments considered reasonable for an MJS magnetometer experiment are \( \approx 3 \) kilograms and \( \approx 6 \) watts. A volume of \( \approx 3 \times 10^{-3} \) cubic meters has been reserved in bay 2 to accommodate the magnetometer electronics assembly. The electrical interface with the spacecraft includes: power input lines, command input lines, housekeeping data output lines, and magnetic field data output lines. There is provision in the Flight Data System to accept each magnetic vector measurement in the form of 33 serial bits which give the instantaneous operating range as well as the magnitude and sign of each field component. These vector measurements will be taken at equally spaced intervals for long periods of time. However, as the spacecraft travels farther from earth and the average data rate diminishes, a spacecraft generated bit rate signal will be provided to the experiment for the purpose of switching in pre-sampling, low pass filters. The planned sampling rates are 200, 5, and 0.5 bps, corresponding to operating bandwidths of dc to 2 Hz, 0.5 Hz, and 0.05 Hz, respectively.
References


VII. RECOMMEND MISSION AND SPACECRAFT CONSTRAINTS

A. Trajectory Preference

Planets and Satellites

1. Distance of closest approach:
   a. Planets: Smallest distance consistent with mission objectives
   b. Satellites: Same

2. Solar occultation preferred at both planets and satellites

3. Earth occultation undesirable at either planets or satellites

4. Phase angle:
   a. Planets: cover as much as possible of 0-180° range and come as close as possible to solar occultation.
   b. Satellites: as close to occultation as possible, especially for satellites in the solar wind.

5. Planet-centered latitude:
   a. Planets: widest range consistent with mission objectives.
   b. Satellites: same

6. Time of arrival: arrival times at planets should be such as to provide best coverage of satellites.

Interplanetary

1. Move radially outward as fast as possible after last encounter.

B. Mounting Requirements

Magnetometer sensor to be stably mounted with sensor axes parallel to spacecraft reference axes and in a location such that the requirements D.6 and D.7 are satisfied.

C. Special Spacecraft Orientations or Maneuvers

1. Description: Roll maneuvers about two axes (one at a time preferred)

2. Rate: Greater than 1 revolution per hour.

3. Duration: at least 30 revolutions about each axis.
4. Frequency of occurrence: at least once every 0.5 AU along trajectory and as soon as possible after each encounter.

D. Others

1. Operations Requirements
   a. On board commands: change magnetometer output filters with changes in data rate.
   b. Ground commands: two on-off commands, in flight calibration, range increment and decrement, automatic ranging. Filter bypass. (calibration once per week.)

2. Locations: sensor on boom (see B) electronics in spacecraft body

3. Temperature operating range: Electronics -10°C to +60°C Sensor -40°C to +60°C

4. Commands: six ground and one spacecraft (see la,b).

5. Elimination of sources of interference (e.g., electric and magnetic fields, boom vibrations, devices that affect local plasma, pickup in circuits.)

6. Magnetic fields due to remanent spacecraft magnetization should be less than 0.03 gamma (1 gamma = 10⁻⁵ gauss) at the sensors.

7. Field variations in the frequency range 0-10 Hz should be less than 0.0003 gamma rms at the sensors (roughly 10⁻⁵ gamma²/Hz).