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GRAVITATIONAL EXPERIMENTS ON A SOLAR PROBE MISSION: SCIENTIFIC OBJECTIVES AND TECHNOLOGY CONSIDERATIONS

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1. INTRODUCTION

On June 5, 1975, Professor Giuseppe Colombo came to JPL as a consultant on a number of mission studies. One of these studies, occupying a duration of about one year, concerned the concept of a solar impact probe (Colombo, 1976). In the summer of 1976 Lou Friedman and I, working in close collaboration with Colombo, began a more detailed study of a solar probe (either solar plunger or sun grazer) with the hope that a joint Phase A study effort might be undertaken between ESA and NASA. Such a study never materialized, but we did publish the results of our own small study in the proceedings of a conference on experimental relativity in Pavia, September 17-20, 1976, sponsored by the Accademia Nazional dei Lincei (Anderson, et al., 1977). This led to the initiation of a NASA study at JPL in 1978 on the engineering and scientific feasibility of a Solar Probe Mission, named Starprobe during the study, in which a spacecraft is placed in a high eccentricity orbit with a perihelion near 4 solar radii.

The Starprobe study, headed by J. E. Randolph at JPL, showed that the concept was feasible and in fact preliminary mission and spacecraft designs were developed. During this period Colombo introduced the concept of a "solar parachute" that could reduce the final orbital period of a solar probe to the Sun (Randolph, 1978). Such a probe would go to Jupiter first and then use the giant planet's gravity field to change the spacecraft's trajectory so that it would go to the Sun. The parachute, actually a small solar sail relying on solar radiation pressure for thrust, would be deployed following the Jupiter swingby and would change the period of the spacecraft about the Sun from four years to one year, thus permitting multiple flybys of the Sun with a reasonable interval of time between encounters.

In the early stages of the Solar Probe studies the emphasis was placed on gravitational science, but by the time of a workshop at Caltech in May 1978 (Neugebauer and Davies, 1978) there was about an equal division of interest between heliospheric physics and gravitation. During that workshop several individuals and science groups presented preliminary descriptions of experiments in the areas of solar interior and general relativity, the solar surface, solar energetic particles, solar neutrons, solar wind, interplanetary dust, and gravitational waves. By 1980 sufficient interest had developed in the mission that NASA formed three ad hoc science study teams (see Table 1). The reports of these teams were published in a single document (Underwood and Randolph, 1982) along with the most recent thinking on the mission and system design concepts.

Those of us who had conceived of Solar Probe as a gravity mission viewed the influx of solar physicists with some trepidation, and indeed the prognosis for a mission of sufficient compexity to support gravitational science deteriorated rapidly in the 1983 fiscal year. It became increasingly clear to NASA that if a solar-probe mission were flown, it would be less costly if the science were restricted to the area of particles and fields. The main concern was the requirement for a drag compensation

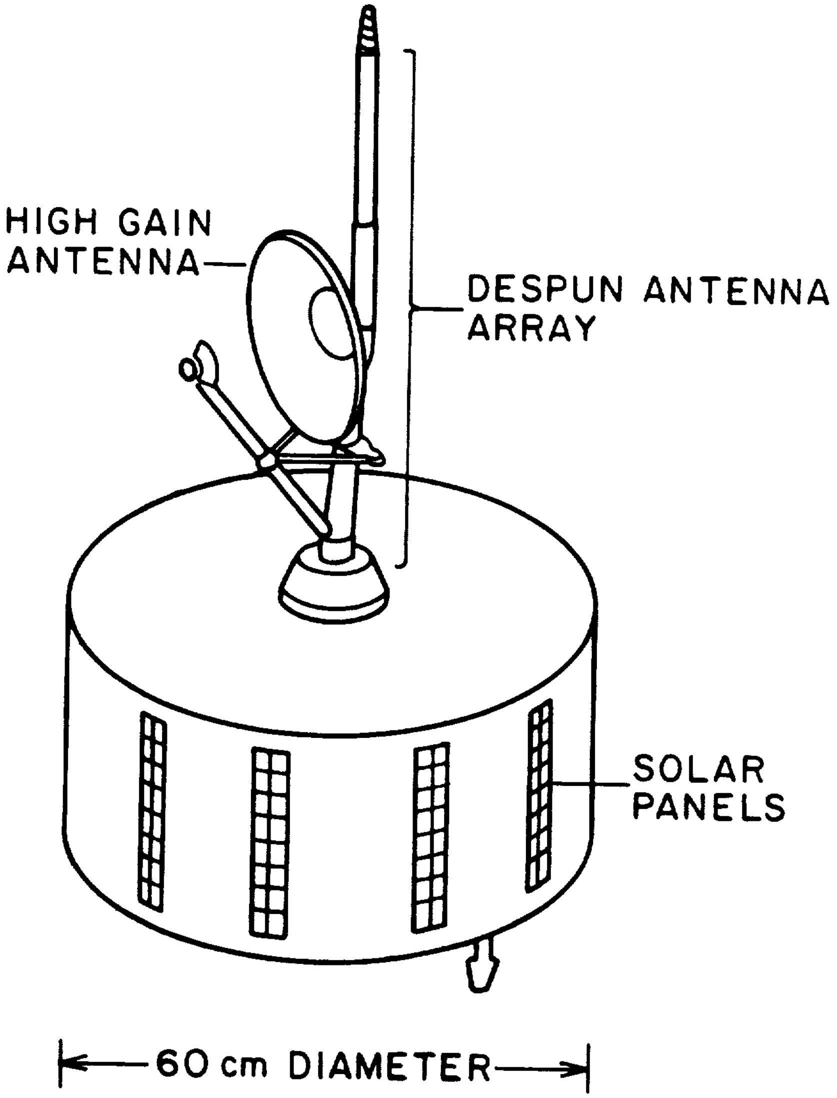

FIG. 1. -- Small Mercury Relativity Orbiter

DISCUSSION

SHAPIRO: In your respective error analyses using simulated observations, what was the smallest angular separation between the sun and the target (with the target on the far side of the sun)?

HELLINGS & BENDER: Five degrees

SONNABEND: If the initial estimate of J_{2O} were seriously worsened, would there be any significant change in the latter evolution of the covariance?

HELLINGS & BENDER: Almost no effect for either mission.

system to support gravitational science, though the Randolph study had indicated that the addition of such a system to a basic fields and particles spacecraft would increase the total cost of the mission by only 10 percent.

The last of the gravitational studies for Solar Probe was conducted at JPL in 1983 (Mease et al., 1984). Since that time, the Committee on Solar and Space Physics (CSSP) of the National Academy of Sciences has recommended the pursuit of a focused mission, featuring fields and particles instrumentation and emphasizing studies of the solar wind source region. Such a Solar probe mission is currently listed as the 1994 Major New Start candidate in the Office of Space Science and Applications Strategic Plan. More recently in October 1988 a Solar Probe Science Study Team was convened by the Space Physics Division for the purpose of studying the possible science return from the recommended focused mission.

In the remainder of this review I will reiterate the unique gravitational science that can be accomplished with a solar probe mission. In addition I will address the technology issues that were identified in 1980 by the ad hoc working group for Gravity and Relativity Science.

II. SCIENTIFIC OBJECTIVES

The primary scientific objectives of a solar probe mission from the viewpoint of gravitational science is the determination of the quadrupole coefficient J_2 in the Sun's gravity field. This objective was identified as the most important single measurement during the early studies in the 1970's, and it was reaffirmed by the ad hoc group in 1980. As shown in Figure 1, an accuracy of 2×10^{-8} is feasible. No other technique could yeild a measurement to this accuracy. Even if the other second degree harmonics are assumed nonzero, and the J_2 coefficient is assumed to vary sinusoidally with a period of 160 min, the accuracy in the mean value of J_2 is degraded to only 2.5×10^{-8} (Mease et al., 1984). A drag compensation system accurate to 10^{-10} g_e is required, but a system at 10^{-9} g_e could still produce a respectable accuracy in J_2 of 3×10^{-8}.

An accurate measurement of J_2 would yeild information on the state of rotation of the solar interior, particularly the core, and at the same time it would remove the solar oblateness as a source of error in other solar system tests of General Relativity. For example, an error of 3×10^{-8} in J_2 would result in an error of only 3.8×10^{-3} arcsec per century in the precession of Mercury's perihelion. A direct and relatively accurate determination of the PPN parameter would be possible from observations of Mercury (see for example Misner, Thorne, and Wheeler, 1973, p. 1072 for a definition of PPN parameters).

OTHER POSSIBLE SCIENTIFIC OBJECTIVES

1) A Measurement of J_4 of the Sun.

Ulrich and Hawkins (1980) have suggested that differential rotation could cause a large value of J_4, on the order of $J_2/10$. Because the effect of J_4 falls off by a factor of r^{-2} faster than J_2, it would have a negligible effect on the orbit of Mercury, but at a distance of 4 solar radii it could conceivably be detected with Solar Probe. Hill (1986) has reported the detection of a large J_4 (-2.5×10^{-6}) by means of visual oblateness observations at SCLERA in 1983. The value of J_2 from the same observations is (5.2 ± 1.7) x 10^{-6}. Such a large value of J_2 is disputed by others (Duvall et al., 1984) who derive (1.7 ± 0.4) x 10^{-7} based on solar free oscillations. Solar Probe could resolve this dispute and at the same time provide a possible detection of J_4 if it is as big as analysis of the 1983 SCLERA data indicates.

2) A Measurement of the Time Variability of J_2.

The studies by Mease et al. (1984) showed that the amplitude of a 160 min sinusoidal variation could be determined to an accuracy of about 2 x 10^{-8}. Solar oscillations with a 160 min period have been reported (Scherrer and Wilcox, 1983). Christensen-Dalsgaard and Gough (1980) have suggested that these oscillations might give rise to an oscillatory quadrupole moment.

3) Total Angular Momentum of the Sun.

This would have to be determined by using the solar probe to measure the dragging of the Sun's inertial frame by the solar rotation. The studies by Mease et al. (1984) indicated that the expected effect is too small to be detected by the dynamics of the solar flyby.

4) Redshift Experiment

By including an atomic frequency standard on board Solar Probe, it might be possible to measure post-Newtonian corrections to the gravitational redshift. Bechhoeffer et al. (1988) have shown that with a four-frequency four-link Doppler tracking system, it is potentially possible to measure the fourth-order term in the gravitational redshift. This would seem to offer an excellent opportunity to measure effects in the solar system one order beyond Einstein's predictions. Unfortunately this experiment places requirements on a 1994 Solar Probe mission that would be hard to meet, given the recommended narrow focus on solar physics, but it deserves study, particularly from the point of view of the tracking system and the amount of drag compensation needed, if any.

5) Preferred-frame Parameter a_1.

The study by Mease et al. (1984) showed that the preferred-frame PPN parameter a1 could be determined with accuracy of 0.007, assuming that the motion of the solar system in the Earth mean equator and equinox system of 1950.0 is (-353.44, 28.93, 34.08) km s^{-1}.

6) Moffat Parameter in NGT Theory.

According to the NGT theory of Moffat (1983) there is a non-PPN parameter l that can be determined from orbital dynamics. According to the studies of Mease et al. (1984) this parameter for the Sun could be measured with an accuracy of 880 km. A failure to detect this parameter would place severe restrictions on NGT as a viable alternative to General Relativity.

In addition to the specific objectives mentioned above, the NASA ad hoc working group also recognized that the radio system on Solar Probe might be advantageous to a search for gravitational radiation. Similarly, the radio system, in conjunction with a favorable Jupiter-centered flyby trajectory during the Jupiter gravity assist, might lead to new information on the gravity field of Jupiter and its ephemeris. The studies by Mease et al. (1984) suggest that no new information would become available on the PPN parameters b and g as a direct result of the solar flyby trajectory, but as pointed out by the ad hoc working group, a significant indirect determination of b in combination with other data, particularly observations of Mercury, would definitely be possible.

III. TECHNOLOGY CONSIDERATIONS

The NASA ad hoc working group identified three areas of technology which are of particular importance to gravitational physics. They recommended that all three areas should be studied in more detail before a final system design is selected for Solar Probe.

1) Tracking System

The specification and configuration of the tracking systems needs to be determined, both with respect to the required accuracy during solar encounter and with respect to Doppler and range capability.

2) Drag Compensation System

The non-gravitational accelerations on Solar Probe during the critical period of solar encounter (± 1 day) are unacceptably large for gravitational experiments. A reduction by a factor as large as 10^5 is required by means of some sort of drag compensation system. For a given proposed system it is important to evaluate its effect on the scientific objectives, particularly with regard to the environment of ionizing solar radiation and the expected noise spectrum of the drag-compensation accelerations on Solar Probe.

3) On-Board Atomic Frequency Standard

An atomic frequency standard on board Solar Probe, and operational for the period of solar encounter, would permit added flexibility in the tracking system, but more importantly, it would be required for a meaningful fourth-order redshift measurement. A study of proposed frequency standards should address the question of the reliability of the flight unit as well as its physical parameters and stability specifications.

TABLE 1. NASA Ad Hoc Science Study Teams, 1980

Gravity and Relativity Science

R. D. Reasenberg, Chairman, MIT
J. D. Anderson, JPL
D. B. DeBra, Stanford
I. I. Shapiro, MIT
R. K. Ulrich, UCLA
R. F. C. Vessot, CfA

Particles and Fields Science

F. L. Scarf, Chairman, TRW
B. E. Goldstein, JPL
A. Barnes, ARC
W. C. Feldman, Los Alamos
L. Fisk, U. of New Hampshire
G. Gloeckler, U. of Maryland
S. M. Krimigis, APL
K. N. Ogilvie, GSFC
C. T. Russell, UCLA

Imaging Sciences

A. B. C. Walker, Jr., Chairman, Stanford
A. Title, Lokheed Palo Alto
A. Kreiger, American Science and Engineering
J. Kohl, CfA
H. Zirin, Caltech
J. Underwood, JPL
E. Frazier, The Aerospace Corporation
R. Munro, High Altitude Observatory, Boulder
G. Timothy, Laboratory for Atmospheric and Space Physics, Colorado
G. Withbroe, Harvard Observatory
J. Davis, American Science and Engineering
E. Rhodes, USC

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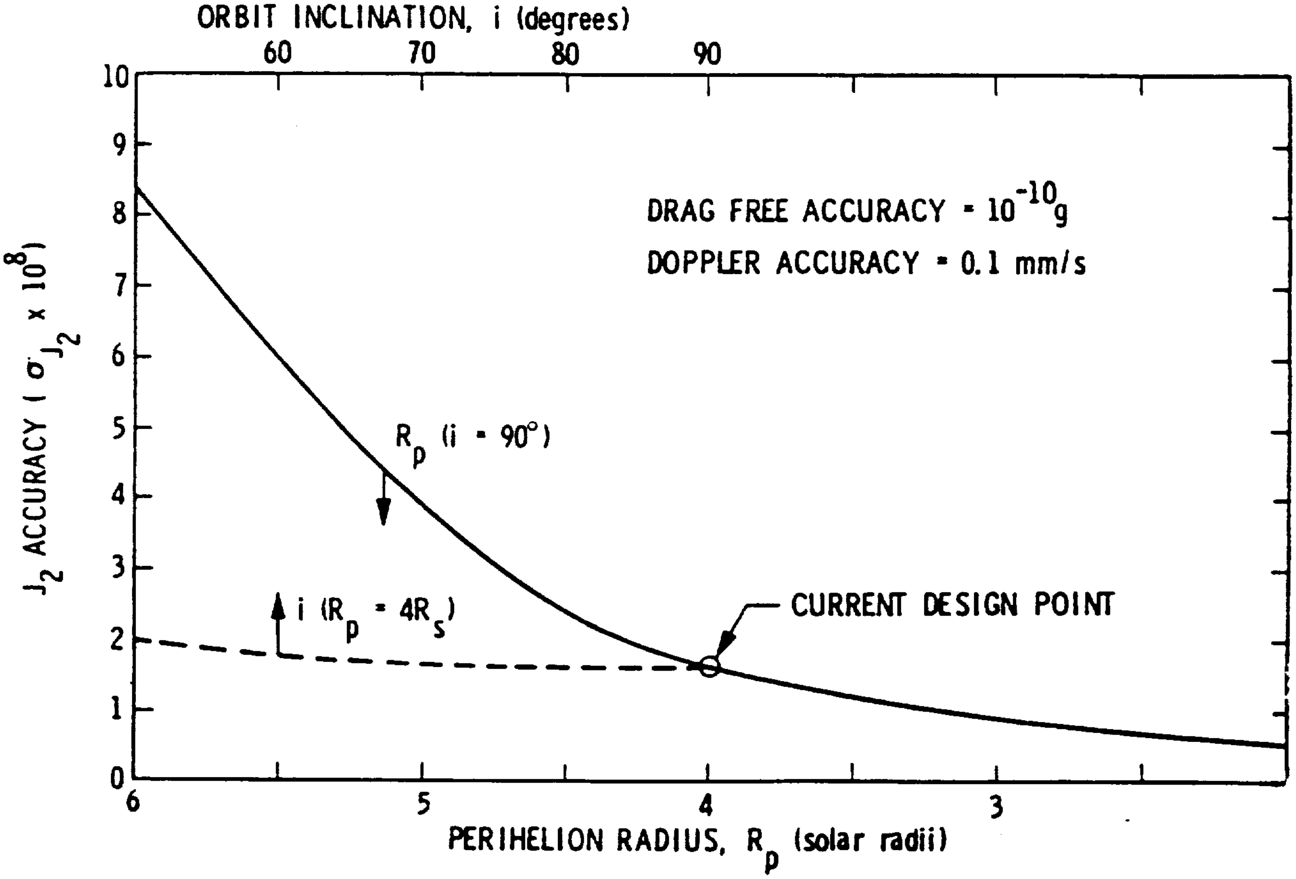

Fig. 1 - Estimated accuracy of a determination of the quadrupole moment in the Sun's gravity field from the Doppler tracking of Solar Probe. The solid curve shows the degradation in accuracy as the perihelion distance is increased from the design point of 4 solar radii. The dashed curve shows a small sensitivity to the orbital inclination to the ecliptic, but this is only realistic under the assumption that all gravity harmonics except the quadrupole moment are negligible. Under the assumption of white noise during the solar encounter, the Doppler accuracy of 0.1 mm/s represents an estimate of the one-sigma accuracy of reduced range-rate measurements at a sample interval of 60 s. Under the assumption that the error in the drag-free system is dominated by the DC component, the solid and dashed curves represent realistic estimates of the error for a drag-free accuracy of 10^{-10} g_e, but they are too optimistic if the drag-free system contains significant noise components with periods on the order of 10,000s (10^{-4} Hz).