SMALL MERCURY RELATIVITY ORBITER

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ABSTRACT

The accuracy of solar system tests of gravitational theory could be very much improved by range and Doppler measurements to a Small Mercury Relativity Orbiter. A nearly circular orbit at roughly 2400 km altitude is assumed in order to minimize problems with orbit determination and thermal radiation from the surface. The spacecraft is spin-stabilized and has a 30 cm diameter de-spun antenna. With K-band and X-band ranging systems using a 50 MHz offset sidetone at K-band, a range accuracy of 3 cm appears to be realistically achievable. The estimated spacecraft mass is 50 kg.

We have carried out a consider-covariance analysis to determine how well the Earth-Mercury distance as a function of time could be determined with such a Relativity Orbiter. The minimum data set is assumed to be 40 independent 8-hour arcs of tracking data at selected times during a two year period. The gravity field of Mercury up through degree and order 10 is solved for, along with the initial conditions for each arc and the Earth-Mercury distance at the center of each arc. The considered parameters include the gravity field parameters of degree 11 and 12 plus the tracking station coordinates, the tropospheric delay, and two parameters in a crude radiation pressure model.

The conclusion from our study is that the Earth-Mercury distance can be determined to 6 cm accuracy or better. From a modified worst-case analysis, this would lead to roughly 2 orders of magnitude improvement in our knowledge of the precession of perihelion, the relativistic time delay, and the possible change in the gravitational constant with time. For an 8 year tracking period, the accuracy for the solar quadrupole moment J_2 would be 1×10^{-9} if general relativity is assumed to be correct, or 1×10^{-8} in the general case.

1) General Discussion

To obtain a major improvement in solar system tests of gravitational theory, accurate measurements of the Earth-Mercury distance over an extended period of time are needed. Studies of the new information achievable as a function of the systematic error level in the distance measurement data have been carried out by Ashby et al. (1989), using a modified worst case analysis. The Parameterized Post-Newtonian (PPN) formulation of gravitational theory was used. The uncertainties in the PPN parameters β, γ, α_1, α_2, α_3, and ζ_w were determined for mission durations of 1, 2, and 8 years. The uncertainties in the solar quadrupole moment J_2 and in the rate of change of GM for the sun also were determined.

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The desired Earth-Mercury distance data could be obtained by ranging from the Earth to a lander on Mercury. However, a lander on Mercury in the foreseeable future probably would be small and would not have an Earth-pointed antenna. Thus, ranging to a Mercury Orbiter appears to be very attractive, provided that the orbit can be determined accurately enough so that the measured Earth-spacecraft distance can be converted into the Earth-Mercury distance with little loss in accuracy. This may not be possible for a spacecraft with high eccentricity, low periapsis, or high area-to-mass ratio. To avoid these limitations, we have studied the orbit determination problem for a Small Mercury Relativity Orbiter in a nearly circular polar orbit with roughly 2400 km altitude (Vincent and Bender, 1989). The results showed that 6 cm Earth-Mercury distance accuracy could be achieved, based on 1×10^{-14} Doppler accuracy for 10 minute observation times and 3 cm range accuracy. Since the range accuracy limitation is likely to be mainly from systematic errors, and therefore will not average out as the square root of the number of observations, only one range measurement was assumed per 8 hour arc of tracking data.

2) Conceptual Design of Spacecraft and Transponder System

The basic configuration of the spacecraft in the conceptual design is quite similar to the Pioneer Venus Orbiter, but scaled down by roughly a factor 4 in all dimensions. The spacecraft is cylindrical and is spin-stabilized about the normal to Mercury's orbit, with a de-spun antenna pointed toward the Earth. A sketch of the spacecraft is shown in Fig. 1. The dual-frequency antenna is 30 cm in diameter. The spacecraft body is 60 cm in diameter and 25 cm high, with the absorption of the sides relatively low at solar wavelengths. The sides are thermally insulated from the inside of the spacecraft to reduce the total heat input.

The dual-frequency Doppler and ranging system uses coherent transponders, with downlink frequencies of approximately 8.4 GHz (X-band) and 34.5 GHz (K-band). For each band, the modulation code bandwidth for the ranging signals is 6 MHz. An additional signal is included, which is offset by 50 MHz from the main K-band carrier. The phase of the beat frequency between these two signals is used to determine the range, subject to 2π phase ambiguities, which correspond to 3 m ambiguities in the range. The transmitted power levels when ambiguity resolution is not occurring are roughly 200 mW total at K-band and 500 mW at X-band. The expected average total spacecraft power requirement during an 8 hour tracking session is 10 W.

With the above spacecraft Doppler and ranging system and one of the 38 m diameter Deep Space Network (DSN) antennas, the signal-to-noise ratio for the Doppler signals should be high. The expected DSN accuracy for the dual frequency Doppler tracking data during the Galileo gravitational wave observing periods (S-band and X-band downlink) is 5×10^{-15} for 100 to 1000 s averaging times. The availability of K-band capability is not currently scheduled for the DSN, but there is considerable interest in adding this capability for use in other missions. The dual-frequency sidetone ranging system would give sufficient signal-to-noise ratio for 3 cm accuracy in 10 min observing times, after correction for the interplanetary and ionospheric electron density along the path.

Since the 8 hour measurement intervals are assumed to occur only about every other day, the average power required is about 2 watts. This power would be supplied by solar cells and a battery charging system. The mass of the required long-lifetime batteries and charging system for about 100 watt hours storage capacity is estimated

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to be 10 kg. This mass plus the required structural mass of the spacecraft are the main items in the mass budget. It is believed that a total spacecraft mass of 50 kg is achievable, although no studies of the spacecraft structure have been carried out. This mass plus the spacecraft dimensions given earlier yield an area-to-mass ratio of 0.005 m^2/kg, which was the value used in the orbit determination studies.

ACKNOWLEDGMENTS

REFERENCES

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Vincent, M. A. and P. L. Bender, "Orbit determination and gravitational field accuracy for a Mercury transponder satellite, "*J Geophys. Res.*, submitted (1989).
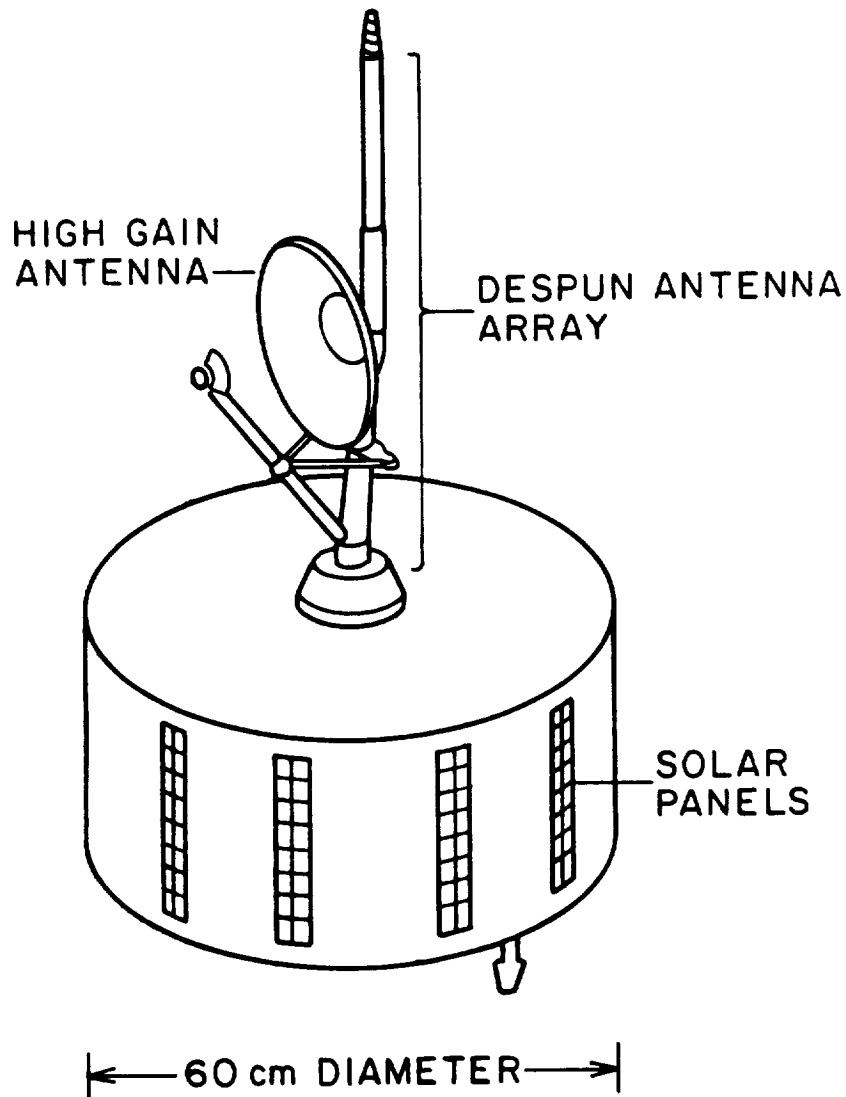
HIGH GAIN ANTENNA—

DESPUN ANTENNA ARRAY

SOLAR PANELS

|←——60 cm DIAMETER——→|

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.