APPLICATION OF THE DEEP SPACE NETWORK (DSN) TO THE TESTING OF GENERAL RELATIVITY*

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ABSTRACT. Over the past two decades, radar and radio observations of planets and spacecraft have been made by stations of the Deep Space Network (DSN), which by the unprecedented nature of their accuracy have produced the most accurate tests of general relativity available. We review the history of the instrumentation and data analysis of the first spacecraft test, the three percent determination of the effect of solar gravity on radio signals between DSN stations and the two spacecraft, Mariner 6 and Mariner 7 (Anderson et al., 1975), as well as later more accurate tests using the Mariner 9 spacecraft anchored to Mars (Reasenberg and Shapiro, 1977; Anderson et al., 1978) and the Viking orbiters and landers (Shapiro et al., 1977; Hellings, 1985). We also review tests of the metric nature of gravity using radar, optical observations, and radio astrometry of the planets (Anderson et al., 1978; Reasenberg, 1985; Hellings, 1985) and the limits placed on the variability of the gravitational constant G (Hellings et al., 1983). Finally, we discuss the prospects for improved accuracy through ongoing upgrades of DSN instrumentation and show the results of covariance analyses for a possible future NASA mission to the Sun (Solar Probe) in the mid 1990's (Mease et al., 1984) and the next NASA mission to Mars, the Mars Observer mission planned for launch in late 1990.

1. INSTRUMENTATION

The NASA Deep Space Network (DSN) is a precision telecommunications and radio navigation facility designed to support space science and exploration of the solar system by communicating with unmanned, automated spacecraft. The primary purpose of the DSN is to place reliable scientific data in the hands of scientists - provide new knowledge about our solar system and the universe beyond (Renzetti, 1971).

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*The research described in this paper was performed by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

J. Kovalevsky and V. A. Brumberg (eds.), Relativity in Celestial Mechanics and Astrometry, 329–344.
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https://doi.org/10.1017/S0074180900148363 Published online by Cambridge University Press

The DSN utilizes large antennas, low-noise, phase-lock receiving systems, high-power transmitters,and atomic frequency standards to perform its basic functions: telemetry reception, command transmission and the generation of radio metric data (position and velocity). These functions also enable the DSN to perform flight radio science, radio astronomy, and radar astronomy.

The DSN is physically located on 3 continents, with communication complexes in California, U.S.A.; near Canberra, Australia; and near Madrid, Spain. Each complex consists of one 64-meter diameter antenna, one 26-meter antenna, and either one or two 34-meter diameter antennas. A ground communications facility connects the 3 complexes to the DSN control center at the Jet Propulsion Laboratory in Pasadena, California.

Beginning with its first 26-meter antenna in 1958, the DSN has been managed as an evolving telecommunications and data acquisition capability. The DSN technologies can be effectively applied, either directly or indirectly, to the field of experimental gravitation (Anderson and Estabrook, 1979, and references therein).

The DSN tracking system (Figure 1) measures Doppler and range. The frequency and timing system supplies stable references produced by a hydrogen maser. The planetary ranging assembly (PRA) generates a square wave ranging code, which is used to modulate the uplink carrier in the exciter assembly. The 13 cm signal is amplified as high as 400 kW by a klystron amplifier and transmitted through a diplexer and microwave antenna to a spacecraft (Renzetti, et al., 1982).

The spacecraft receives the transmitted uplink signal and demodulates the ranging waveform. The uplink carrier is multiplied by a rational fraction (240/221 for 13 cm and 880/221 for 3.6 cm) to produce

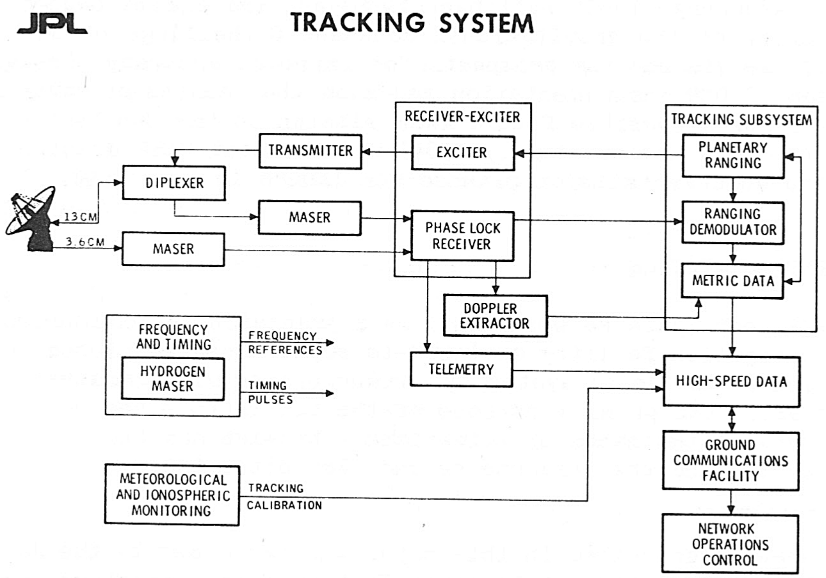

Figure 1. The DSN Tracking System

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coherent downlink carriers which are phase modulated with telemetry and the ranging waveform. The spacecraft radiates the downlink through a diplexer and antenna to the ground station.

The ground station receives the signal, amplifies it in a maser amplifier, and sends it to a triple conversion superheterodyne phase-locked loop receiver. The receiver reference frequency is supplied to the doppler extractor and is also used to rate-aid the planetary ranging assembly. The received ranging signal is cross-correlated with the current uplink range code and in a separate channel, with the ranging code offset by ninety degrees. The time delay is determined by comparing the relative cross-correlated power in the two channels. The highest frequency range code used is a one hertz square wave. During signal acquisition, lower frequency codes are serially employed to remove ambiguities.

As shown in Figure 2, the evolution of the DSN from crystal oscillators to hydrogen masers and from 30 cm to 13 and 3.6 cm, has improved the Doppler system fractional stability from 10^{-9} to several times 10^{-14}.

The first DSN ranging capability, the Mark 1 Apollo ranging system, was first used to support the Lunar Orbiter missions to the Moon. The nominal resolution of the Mark 1 system was approximately 1 meter (Lindley, 1965); the delay instability was under 5 meters in an 8-hour period. An analysis of the ephemerides produced residuals of less than 100 meters (Mullholland and Sjogren, 1967). This system was designed for operation at lunar distances, used analog technology, and a pseudo-noise modulation technique. The actual Mark 1 distance limits were an order of magnitude greater than required. This was demonstrated in the early portion of the Mariner 5 mission to Venus when the Mark 1 was used to range out to distances greater than 200,000 kilometers.

The Mark I system was replaced by the Tau ranging system (named for its principal engineer, R. C. Tausworthe) for the Mariner 5 mission to Venus and the Mariner 6 and 7 missions to Mars. The Tau system also used pseudo-noise range code; a computer replaced much of the analog circuitry, making it possible to obtain a much narrower loop bandwidth with a correspondingly improved signal-to-noise ratio. This made ranging at interplanetary distances possible. The improved internal stability of the Tau system made it possible to obtain Differenced Range Versus Integrated Doppler (DRVID), which is essentially a measurement of the difference between the phase and group velocities, thereby giving an indication of the rate of change in columnar electron content (Tausworthe, 1967). An analysis of the Mariner 6 and Mariner 7 orbital data showed that Tau ranging produced absolute accuracies of about 30 meters and a random component of about 9 meters (Anderson et al., 1971).

2. THE FIRST SPACECRAFT RELATIVITY TEST WITH MARINER 6 AND MARINER 7 AT SOLAR CONJUNCTION

The first spacecraft test of general relativity was conceived in the Spring of 1966 by D. O. Muhleman, then at Cornell University, and

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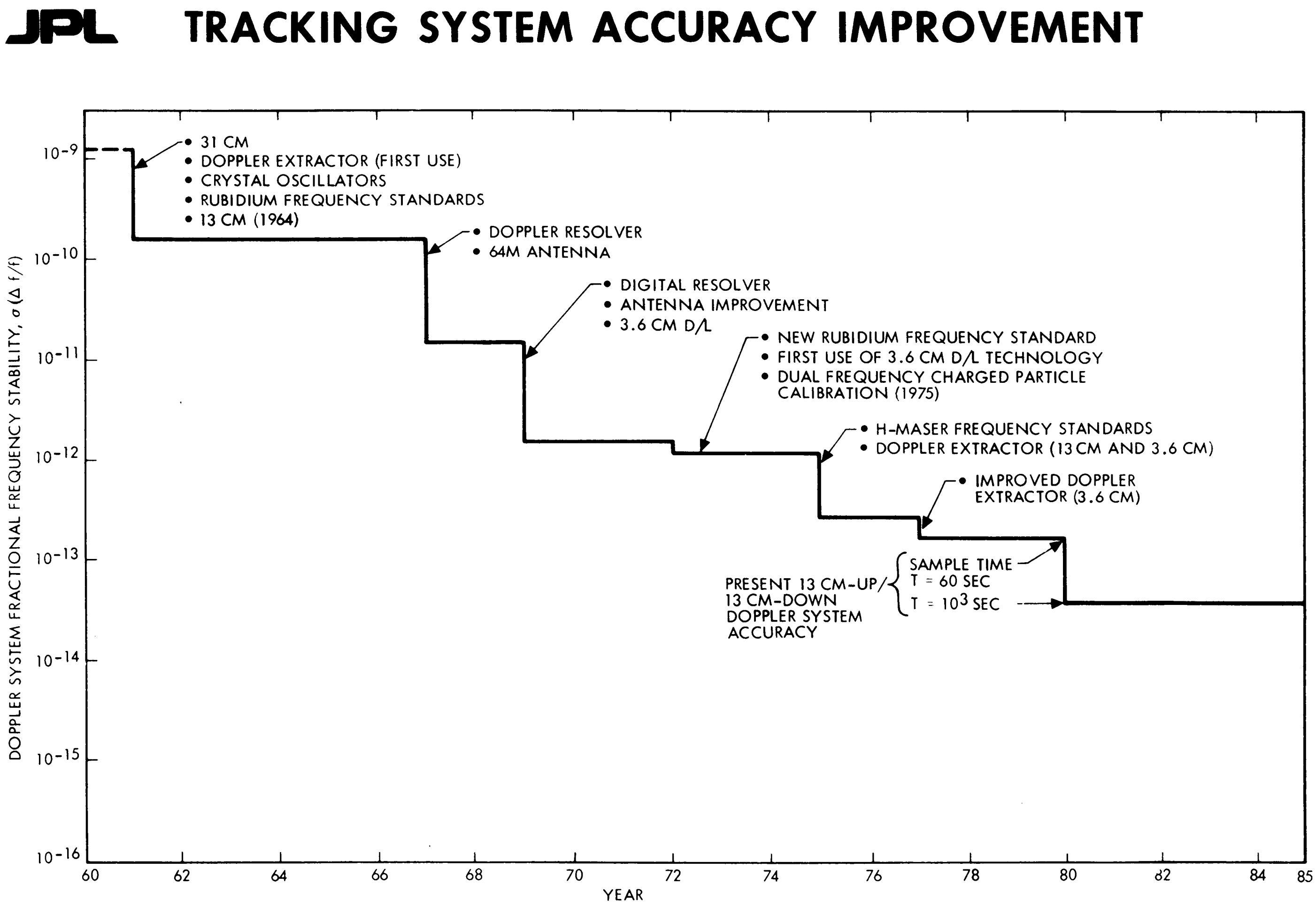

Figure 2. DSN Tracking System Accuracy Improvement

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R. M. Goldstein of JPL, who proposed to use post-encounter 13 cm range measurements to the Mariner 6 and Mariner 7 spacecraft that would encounter Mars in 1969. Their scientific goal was to demonstrate the presence or absence of a propagation time delay caused by the gravitational field of the Sun. The idea behind a relativistic excess ranging delay caused by solar gravity had been published earlier (Shapiro, 1964). Muhleman and Goldstein estimated that they could achieve ranging accuracies of 100 meters or better at 2 AU. A new 64-meter antenna at Goldstone, California, and a 400 kW transmitting capability would be required for the uplink of the roundtrip ranging signal. The large antenna aperture was also needed to receive the weak spacecraft downlink.

The DSN developed a technical plan and a resource plan for supporting the test. It was determined that the spacecraft would have to be oriented by attitude control so that its high-gain parabolic antenna would point at the Earth during each data acquisition. This not only made the orbit determination more difficult but would require new ground-based ranging equipment and a low-noise feed cone for the DSN 64-meter antenna. The proposed 400 kW 13 cm transmitter, associated high-power feed cone, low-noise receive cone, and ranging equipment were accomodated in the plan as research and development (R&D) equipment supported by NASA's Office of Tracking and Data Acquisition (T&DA Office).

A prototype Mu ranging machine (named for its designer, W. L. Martin) was used for the Mariner 1969 and 1971 missions to Mars. The Mu system was sequential binary coded machine that yielded a factor of 40 improvement in acquisition time compared to the Tau machine. The Mu machine also employed an RF doppler rate-aiding for range decoding. This type of rate-aiding automatically produces DRVID information. Because of the very stable high-speed digital logic used in the Mu system, the ranging instrumentation itself approached a negligible drift level. The 1.5 meters of drift measured over 8 hours was the result of other station equipment (Renzetti, 1971).

The first successful ranging acquisition to Mariner 6 with the Mu machine was obtained on October 8, 1969 over an integration time of 1337 seconds and with 20 kW of transmitted power at the 64-meter station. The distance between Earth and Mariner 6 was about 242 x 10^6 km. By April, 1970, the spacecraft would be rapidly receding to its maximum distance of about 404 x 10^6 km. This prompted concern that 20 kW of transmitted power would not be sufficient for the test; not because of the distance to the spacecraft, but because the uplink signal carrying the ranging code would be passing through the solar corona. The DSN was working hard to get a higher power transmit capability on line in time. Meanwhile, the Mu machine was obtaining successful acquisitions over periods of approximately 35 minutes. By the end of December, with the spacecraft operating in low-power mode into its zero db gain omnidirectional antenna, the worst possible condition, the available received power had fallen to 200 db below a milliwatt (-200 dBm). The fact that we continued to obtain good range acquisitions in this low-power mode prompted us not to maneuver the spacecraft to point the

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high-gain antenna toward Earth, thereby minimizing the non-gravitational forces on the spacecraft. The conditions for Mariner 7 were similar. The decision not to maneuver and remain in the low-power mode was later justified when the Mu machine provided good ranging acquisitions throughout the two conjunctions, even at a received power level of -203 dBm.

With completion of the 400 kW transmitter, tracking at power levels greater than 20 kW was attempted for the first time on April 22, 1970. The 400 kW capability of the new transmitter was never used, however, after a test on Mariner 7 at 300 kW convinced us it would be unwise to transmit at full power. Tracking both spacecraft after April 22 was accomplished at a power level of 200 kW, which provided a clear ranging code to the spacecraft even when the signal ray-path passed within one degree of arc from the center of the Sun. An analysis of range data acquired in late April when the two spacecraft were tracked at 20 kW convinced us that the relativity experiment would have been impossible at the 20 kW power level.

By the end of May, 1979, the first paper on the experiment was delivered at the XIII-th Plenary Meeting of COSPAR, Leningrad, and later appeared in the proceedings of the meeting (Anderson, et al., 1971). The data acquisition and analysis were still in progress, but nevertheless we could claim a 10% test of Einstein's theory at this meeting, just from the near-conjunction data. We predicted that the final accuracy of the experiment would be 4% or less, not a bad estimate of our real final accuracy of 3% (Anderson et al., 1975). We also demonstrated that the error contribution from propagation of the 13 cm signal through the corona was about 1%, a fair indication of the accuracy of the upcoming time-delay test with the Mariner Mars 1971 Orbiter. The analysis of the Mariner 6 and 7 data eventually required four years to complete. The data accumulated by the Mu ranging machine had an RMS error outside of conjunction between 0.1 and 0.2 microseconds (15 to 30 meters) which far exceeded the estimate of the ranging error in the original proposal by Muhleman and Goldstein. Even at one degree from the Sun's center, the solar corona introduced an error of only about 4 microseconds in the ranging measurement at 13 cm. With an excess delay of 200 microseconds caused by general relativity, the data were certainly accurate enough for a test in the neighborhood of 2%. The actual 3% uncertainty in the measurement reflected problems in using free-flying spacecraft subject to non-gravitational forces.

3. THE MARINER 9 MARS ORBITER AND SUBSEQUENT RANGING DEVELOPMENTS

The relativity tests performed with the Mariner 9 spacecraft in orbit about Mars were part of a celestial mechanics experiment organized as a team effort by NASA for the Mariner Mars 1971 Project (Lorell, Anderson, and Shapiro, 1970). The team consisted of two groups, one at JPL with J. Lorell as Team Leader and principal investigator, and the other at The Massachusetts Institute of Technology (MIT) with I. I. Shapiro as principal investigator. Data acquisition was the responsibility of the DSN with data validation and preliminary processing

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carried out at JPL. The subsequent analysis and interpretation was accomplished cooperatively, with complementary efforts at JPL and MIT.

The radio data for Mariner 9 were similar to those obtained from Mariner 6 and Mariner 7. More than 300,000 two-way Doppler measurements at a one-minute sample rate and more than 1300 independent acquisitions of round-trip range were achieved over a period from November 14, 1971 to October 27, 1972, when the orbiter ran out of the attitude control gas needed to keep its high-gain antenna pointed at Earth. The Mu ranging system provided the data for the relativity tests. The determination of the orbit of Mariner 9 about Mars was a critical factor in obtaining accurate range data to the center of mass of the planet. J. F. Jordan of JPL lead an orbit determination effort that reduced a set of pseudo range measurements (normal points) between the center of Earth and center of Mars. Both Doppler and range data were used for this purpose. The primary data processing mode was to first determine the spacecraft orbit relative to the center of mass of Mars from short spans of Doppler data, (usually a single revolution of the orbiter) and then to combine the resulting spacecraft position vectors relative to Mars at the times of the ranging acquisitions with the ranging measurements to the spacecraft, thereby obtaining the round-trip range to Mars. The limiting error in the resulting normal points was not the uncertainty introduced by the Mu ranging equipment, but instead the uncertainty from two other sources: (1) the orbit determination error on the orbiter caused primarily by uncertainties in the martian gravity field, and (2) as in the case of Mariner 6 and Mariner 7, the solar coronal effect on the 13 cm radio signal near conjunction.

The Mu ranging data were obtained with the 64-meter antenna at Goldstone, California. During the conjunction period from August 29 to September 14, 1972, a programmable local oscillator was used to tune the receiver to the downlink spacecraft signal, a technique that was used successfully on Mariner 6 and Mariner 7. Without this technique, the receiver could not have been kept in phase lock with any of the three spacecraft at conjunction. A plot of the residuals in a set of 803 normal points (observed minus computed) about a least squares fit to the orbits of Earth and Mars is shown in Figure 3 (Anderson et al., 1978). The effect of the solar corona near the end of the data is obvious. The RMS ranging residual near conjunction is about 2.5 μs or about 375 meters in the distance to Mars. Near opposition the RMS residual is 0.25 μs or about 38 meters in distance, a good indication of the ultimate accuracy of normal points from an orbiter with a Mars-centered orbit similar to Mariner 9.

The improvement in the Mariner 9 relativity tests over the Mariner 6 and 7 test was not particularly impressive (Reasenberg and Shapiro, 1977; Anderson et al., 1978). The Mariner 6 and Mariner 7 test at the 3% level was improved to the 2% level, again with no contradiction of the prediction of Einstein's theory. It was pointed out, however, that the real power of the Mariner 9 normal points would be realized when they were combined with range data from future missions to Mars, in particular the Viking orbiters and landers (see also, Jordan, Melbourne, and Anderson, 1972). It would then be possible to test not only the relativistic range delay, but also some orbital predictions of

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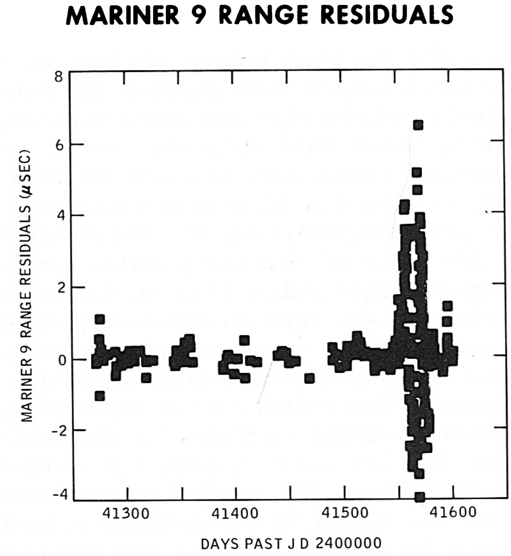

Figure 3. Mariner 9 Range Residuals

general relativity, somewhat along the lines of the classical test of the precession of the perihelion of Mercury, but to much greater accuracy. This goal was later realized with the Viking landers.

Subsequent to the Mariner 6 and 7 mission, an operational planetary ranging assembly (PRA), capable of either sequential or pseudo noise range coding, was developed and implemented throughout the DSN. For several years, it was possible to obtain ranging data with either the R&D Mu machine or with the PRA. Today only the PRA is in use.

The Mariner Venus Mercury (MVM) 1973 mission was the first to employ a coherent 13 and 3.6 cm downlink,W. L. Martin and A. I. Zygielbaum upgraded the Mu machine to a simultaneous dual frequency device (the Mu II machine) that measured the range at both frequencies to obtain the differential group delay and with it the total columnar electron content (Martin and Zygielbaum, 1977). The Mu II ranging machine was successfully demonstrated on the MVM mission with occultation measurements of the ionosphere of Venus and the establishment of an upper bound for the ionosphere of Mercury (Levy, 1973).

4. SOLAR SYSTEM TESTS OF RELATIVISTIC CELESTIAL MECHANICS

It is recognized by many scientists that the relativistic contribution to the orbits of the Moon and inner planets should to be determined as accurately as possible with modern spacecraft and ground-based DSN radio instrumentation. In 1981, the Committee on Gravitational Physics of the Space Science Board, as approved by the Governing Board of the National Research Council, made a recommendation along these lines, providing in addition an excellent justification for carrying out the

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observations (Shapiro et al., 1981). The thrust of their recommendation was to include piggyback gravitational experiments on future space missions that are particularly suitable for a study of the relativistic aspects of celestial mechanics and astrometry, thereby gaining the greatest scientific return for a minimal expenditure of technological and financial resources.

Two outstanding examples of the success of the piggyback approach are provided by (1) the lunar laser ranging to optical corner reflectors left on the Moon by Apollo astronauts and Lunakhod II, and (2) the six years of coherent transponded radio ranging to the Viking landers on Mars. As early as 1976, analysis of the lunar laser data yielded a significant contribution to experimental relativity by placing a limit of three percent or less on a possible breakdown of the Weak Equivalence Principle for massive self-gravitating bodies (Shapiro et al., 1976; Williams et al., 1976). Such a breakdown could not occur in general relativity, but it was shown by Nordtvedt (1968) that if general relativistic predictions were wrong on this point, a polarization of the Moon's orbit about the Earth would occur. The failure of the lunar laser data to detect this polarization resulted in one of the best modern tests of general relativity. A definite limit was placed on a linear combination of parameters in a generalized post-Newtonian metric theory of gravity that includes general relativity as a special case, the PPN formalism (Misner, Thorne and Wheeler, 1973; Will, 1981 and references therein). In the future, the continued acquisition and analysis of lunar laser ranging data after 1976 will eventually lead to an even better determination of this "Nordtvedt effect", perhaps with an improvement by a factor of three in accuracy (Reasenberg, 1985).

Coherent ranging to the Viking orbiters and landers on Mars yielded other tests of general relativity. The most accurate test of the theory to date was published in 1979 by a group representing the Viking Radio Science Team (Reasenberg et al., 1979). Again the DSN provided the data acquisition and the preliminary data reduction and processing. Both the Mu II and the upgraded dual frequency planetary ranging assembly were used for the Viking mission.

A value for the PPN parameter γ of 1.000 ± 0.002 was obtained from the increased ranging signal round-trip times caused by solar gravity. The dual frequency downlink from the Viking orbiters was used to measure the total electron content in the ray path. This was essential for correcting the range of the landed spacecraft, which had a single-frequency turnaround ranging system at 13 cm.

The landers were fixed with respect to the center of mass of Mars; unlike the Mariner 9 orbiter, the limiting accuracy of the range fixes depended only on the accuracy of the radio ranging link between the Earth and the landers. A new model for the rotation of Mars (Reasenberg and King, 1979) was developed and included in the data analysis. The precession and nutation caused by solar torques was represented by series that included all terms causing a maximum Mars surface displacement of at least 1 cm after 10 years.

There are six years of reduced Viking lander ranging data currently available, over 1000 measurements in all, from the first landing in

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July, 1976 to the demise of the second lander in July, 1982. Preliminary reports of new results on the PPN parameters have been given at meetings (Hellings, 1984; Reasenberg, 1985), and a new result has been published on a possible time variation in the gravitational constant G (Hellings et al., 1983), or actually two limits depending on how the effect is formulated. The limit for a variation in G as it appears in the Newtonian equations of motion is (0.2 ± 0.4) x 10^{-11} yr^{-1}. The limit for the alternative formulation, expressed in terms of a drift between atomic clocks and the implicit ephemeris time in the relativistic dynamics, is (0.1 ± 0.8) x 10^{-11} yr^{-1}. This is the first result on G that limits its variation below a level where the effect was presumed to exist ($\sim$5 x 10^{-11} yr^{-1}).

Hellings (1984) preliminary results on the PPN parameters (also see Trimble, 1983) indicated a value for the PPN parameter β, which is unity in general relativity, of $\beta - 1 = -(2.9 \pm 3.1) \times 10^{-3}$. The preferred frame parameter that is zero in general relativity was determined as $\alpha_1 = (2.1 \pm 1.9) \times 10^{-4}$ and the coefficient of the Newtonian solar gravitational quadrupole moment was $J_2 = (-1.4 \pm 1.5) \times 10^{-6}$. The quadrupole coefficient is important because it contributes directly to the precession of the perihelion of Mercury, one of the classical tests of general relativity. According to one interpretation of solar oscillation measurements (Hill, Bos and Goode, 1982), the coefficient J_2 is equal to 5.5 x 10^{-6}, while the expected value from an assumed rigid rotation of the Sun at the surface rate is on the order of 2 x 10^{-7}. The Viking ranging data, in combination with other inner planets astrometric data obtained from radar and optical sources can resolve these conflicting claims on the value of J_2 by determining it directly from the orbital motions of the inner planets. This work is in progress.

In all data analyses dedicated to the celestial mechanics of the inner planets, ranging to the Viking landers is supplemented by other astrometric data, most importantly radar ranging performed by the DSN, the Arecibo Ionospheric Observatory, and the Haystack Observatory over the past 13 years or more. Radar ranging to Mars surface has been superceded by ranging to the Viking landers and the Mariner 9 Mars orbiter in 1971. Although the Mariner 9 orbiter range fixes are less accurate than the Viking lander fixes, they have the advantage of being removed in time from the Viking data by over four years, thus providing a unique constraint on the motions of Earth and Mars over a total of 11 years. This is an important point to keep in mind when considering the acquisition of data in the future. Effects of general relativity that characteristically accumulate linearly in time, such as the classical relativistic precession of the perihelion, will be determined to far greater accuracy by combining spacecraft range data on two or more missions separated widely in time than from any one of the single missions alone.

Solar system radar can augment spacecraft data. Radar range measurements yield only topocentric distances to the sub-radar point on the surface of the planet. However, topographic modeling can be employed to yield reasonably accurate estimates of the planetary center of mass (Reasenberg and Shapiro, 1976). The orbit of Mercury is a

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particularly important matter for radar study since there are only two good encounter orbit determinations with the Mariner Venus Mercury spacecraft; there are no known plans for another Mercury mission in the near future. Radar data can make a significant contribution to the improvement of the value of the precession of the perihelion of Mercury (Anderson et al., 1978).

5. FUTURE PROSPECTS

The important point - that tests of relativity depend on the combination of data from a number of missions - was made in the previous section. Any mission that has the potential of providing inner planets ranging data with an accuracy of better than 50 meters is of value. This potential, however, will not always lead to a relativity experiment. A relativity proposal was rejected by NASA for the Venus Radar Mapper (VRM) mission. Consequently, because there was no ranging requirement, the VRM Project used the ranging channel in their transponder for telemetry purposes, thus making it useless for any future possibility of ranging to the spacecraft. With no foreseeable spacecraft ranging to Venus, or Mercury either, because there is no firm plan for a NASA mission to that planet, our best hope is a future mission to Mars.

Outside of planetary astrometry, space missions that provide opportunities for relativity testing are important. So far, we have identified one outstanding candidate, a possible close encounter with the Sun in the mid 1990's.

One of the major limitations to range accuracy is the 13 cm uplink, which is overly susceptible to plasma effects. If the transmission path is short or the medium is very stable, the dual 13 and 3.6 cm downlink may be adequate for calibrating the uplink. Unfortunately, over interplanetary distances, especially when the ray path passes close to the Sun, the 13 cm uplink is a major source of error. A 3.6 cm uplink can reduce these effects by a factor of approximately 12. If a dual frequency uplink and downlink were used, the plasma contribution to the error could be practically eliminated.

At the last World Administrative Radio Council (WARC) meeting, a 9 mm allocation for deep space research was agreed-to. This band is particularly desirable, not only because of its greater resistance to plasma effects (a factor of 250 improvement over 13 cm) but also because of the greater spectral availability for a wideband range modulation. The 9 mm band would be particularly attractive for a solar probe type of mission where critical telecommunications must be maintained near the limb of the Sun.

5.1 Solar Probe

The concept of a a solar probe was introduced to JPL in 1976 by Professor G. Colombo of Padova. Serving as a consultant, he suggested that an earlier solar probe study by the European Space Agency (ESA) could be developed jointly by ESA and NASA. This cooperative study never

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materialized, but we did publish the results of our own small study, which included Colombo's active participation (Anderson et al., 1977). A more detailed study was conducted later at JPL by an engineering team headed by J. E. Randolph (1978). A number of science study teams (Neugebauer and Davies, 1978) were organized by NASA to consider the feasibility of experiments in the areas of the solar interior and general relativity (Reasenberg et al., 1982), the solar surface, solar energetic particles, solar neutrons, solar wind, interplanetary dust, and gravitational waves. More recently, we were able to show that a solar probe, equipped with a drag-free control system, could provide the most accurate test of general relativity of any foreseeable mission (Mease et al., 1984). Study results indicate that the solar quadrupole coefficient J_2 can be determined to an accuracy of 2.5×10^{-8}. Not only would this provide valuable information on the interior of the Sun, it would effectively remove J_2 as a source of error in determining the relativistic precession of the perihelion of Mercury from the existing optical and radar data. Combining data from a solar probe with information from planetary radio and astrometric data, and from the lunar laser data, would provide a determination of the PPN parameters β and α to an accuracy comparable to the current accuracy of the Viking time-delay test (~ 0.002).

5.2 Future Missions to Mars

The NASA Mars Observer orbital mission is under development and is planned to reach Mars in 1991. Combining the one-year arc of Mariner 9 normal points and the six-year arc of Viking ranging with, say, a two-year arc of Mars Orbiter ranging acquired in 1991 through 1993 would provide the best single data base yet for studies in solar system celestial mechanics, particularly if we also had a measurement of J_2 from a solar probe. In collaboration with E. L. Lau of JPL, we have conducted a covariance analysis for Mars Orbiter, assuming a 10-meter ranging accuracy. In view of anticipated difficulties with the orbit determination, this is perhaps too optimistic; in order to compensate, we have used a worst-case error analysis where we defeat the $\sqrt{N}$ effect in the estimation of variance. This accounts for systematic errors. The following expected results assume a combination of Mars Orbiter data with other existing inner planets astrometric data and lunar laser data. We have not included the contribution of a good independent determination of J_2 from another mission at this stage.

1. Improve the determination of the PPN parameter β to an accuracy of 0.002.

2. Improve the determination of the time variation in the gravitational constant G to an accuracy of about 3×10^{-12} yr^{-1}.

3. Improve the determination of the solar gravitational quadrupole moment J_2 to an accuracy of about 10^{-6}.

In addition, new information could be obtained in the following areas.

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4. Obtain significant new tests of gravitational theories that do not fit within the PPN formalism; for example, the Nonsymmetric Gravitation Theory (Moffat, 1979) or a possible modification of Newtonian dynamics (see for example, Milgrom, 1983).

5. Search for gravitational radiation through the exchange of orbital energy and the angular momentum of Earth and Mars with the radiation field (Mashoon, 1981).

6. Determine the masses of objects beyond the orbit of Mars, such as outer planets, certain asteroids, or Planet X.

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DISCUSSION

Hill : your estimates show that $J_2\,5_r$ 10^{-6} while our estimates give J_2 of 6. 10^{-6}.

Reasenberg : the estimates of JPL seem to be too optimistic. Our group in MIT believes that the errors are much higher than presented.

Alley : what are the perspectives of improving the accuracy you achieved ?

Levy : the perspective error estimates are 2. 5 10^{-8} for J_2 . 0.002 for α_1 and 0.002 for β.

Polnarev : is there any evidence of the existence of additional planets in the solar system ?

Levy : there are some data that can be interpreted in this way, but it is not convincing.

Grishchuk : when you measure only Doppler effects (that is to say the velocity of the spacecraft), how can you detect gravitational waves, since they can only shift its position ?

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Levy : if we integrate the velocity measured by Doppler shift, we obtain a coordinate shift.

Bertotti : General Relativity is now tested to an extremely good accuracy and all doubts as to its validity are dispelled. The question arises whether there are other relativistic effects that can be tested in the future, when the accuracy in the parameters ρ and γ will be better than 10^{-3}. I wish to mention two. One is the contributions to the light deflection of order V^3/C^3 coming from preferred frame effects. The second is the effect of the solar angular momentum J on the light propagation time and the Doppler shift for rays grazing the Sun : it can be shown that the uplink and downlink Doppler shifts are different because of J.

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