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## EXPERIMENTAL TESTS OF RELATIVISTIC GRAVITATION THEORIES

Final Report of Research Accomplished at the California Institute of Technology (January 1, 1971 - December 31, 1971) and Jet Propulsion Laboratory (September 15, 1970 - July 1, 1971) with support from

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## I. INTRODUCTION

The NASA and DDF funds, which supported the research described herein, were "seed money" to help generate new research programs at Caltech and JPL on experimental tests of relativistic gravity. Although the funds actually granted (\$50 k) were well below the funds originally requested (\$107 k), a large fraction of the original goals were achieved. This report describes our achievements. For more detailed descriptions, see the references in §IV.

The research at Caltech focussed on theoretical aspects of experimental tests, including (i) theoretical frameworks for interpreting past and future tests; (ii) the invention of new tests; (iii) comparative analyses of theories with each other and with experiment.

The research at JPL focussed on feasibility studies for various experimental tests, with particular emphasis on determining the potential uses of future deep space missions in studies of relativistic gravity.

We chose to maintain a loose coordination between these two efforts as a means of strengthening each. The Caltech theoretical effort is helped greatly by contact with the "hard-nosed" realities of the JPL feasibility studies; all too often the starry-eyed theorists at Caltech underestimate the difficulties of future experiments. The JPL feasibility studies are strengthened by having a theorist look over the mathematical methods, to be sure the reality has been "done right"; and by having theorists provide ideas for new experiments and opinions on the relative priorities of various measurements.

Although NASA has chosen to cease its joint funding of the Caltech and JPL efforts, we shall continue to maintain our close interaction and

## II. SUMMARY OF CALTECH RESEARCH RESULTS\*

### A. Theoretical Frameworks for Interpreting Past and Future Experiments

Our Caltech effort began in 1969-70 with NSF funding. The chief accomplishment of that effort was the construction of a "Parametrized Post-Newtonian Framework", by Clifford M. Will (then graduate student, now Instructor). This PPN framework is a powerful tool in comparing theories of gravity with each other, in analyzing the significance of experimental tests, and in devising new experiments. It is an improved version of earlier frameworks devised by Nordtvedt and by Eddington, Robertson and Schiff. In essence, it is a parameterization of Chandrasekhar's post-Newtonian approximation to General Relativity. Parameters are inserted into Chandrasekhar's post-Newtonian formalism, and new terms are added to it, so it can encompass the post-Newtonian limit of every metric theory of gravity. Each metric theory has particular values for the post-Newtonian parameters of Will's framework. The task of experiments, from the PPN viewpoint, is to measure the PPN parameters and thereby determine which metric theory (general relativity, Dicke-Brans-Jordan, ...) is correct.

During the last year the PPN framework was extended, by Will and Nordtvedt (ref. A.6) to take explicit account of the motion of the solar system's center of mass relative to the mean rest frame of the Universe. This was necessary because earlier in the year Will (ref. A.1) had shown that in many theories of gravity the "universal rest frame" exerts Machian-type forces on objects which move relative to it.

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Will (ref. A.1) also showed that a given theory exhibits such Machian forces at the post-Newtonian level if and only if one of the following combination of PPN parameters is nonzero:

$$4\beta_1 - 2\gamma - \xi - 2 \quad , \quad \Delta_2 + \xi - 1 \quad , \quad 7\Delta_1 + \Delta_2 - 4\gamma - 4.$$

In related work Will (ref. A.1) proved that a metric theory of gravity possesses post-Newtonian integral conservation laws for energy, momentum, angular momentum, and center-of-mass motion if and only if its PPN parameters satisfy the seven constraints:

$$\beta_1 = \frac{1}{2} (\gamma + 1) \quad , \quad \beta_2 = \frac{1}{2} (3\gamma - 2\beta + 1) \quad , \quad \beta_3 = 1 \quad , \quad \beta_4 = \gamma \quad ,$$

$$\Delta_1 = \frac{1}{7} (4\gamma + 3) \quad , \quad \Delta_2 = 1 \quad , \quad \xi = 0.$$

In such a theory there are only two unconstrained PPN parameters: the Eddington parameters  $\beta$  and  $\gamma$ .

In 1971 an attack was begun (ref. B.5 and B.6) on the task of developing a framework, analogous to PPN, for analyzing nonmetric theories of gravity. But this is such a difficult task that we do not expect significant results until the end of 1972 or later.

## B. The Invention of New Experiments

1971 was a fruitful year for the invention of new experimental tests of relativistic gravity. Clifford Will (ref. A.3) discovered a Machian effect of motion relative to the Universal rest frame: such motion produces

an anisotropy in the locally-measured Newtonian gravitational constant. The anisotropy in  $G$  causes the local gravitational acceleration, measured by a gravimeter at a fixed point on Earth, to vary with a period of 12 sidereal hours as the Earth rotates. Will showed that gravimeter data (measurements of "Earth tides") put a limit of  $1/10^9$  on the amplitude of any such anisotropy; and he showed (ref. A.3 and A.7) that this limit disproves several theories of gravity that were previously considered viable (e.g., two theories due to Papapetrou).

Will (ref. A.3) also showed that in Whitehead's theory of gravity the mass of the galaxy, by a Machian type influence, produces an anisotropy in  $G$  at the Earth. The same gravimeter data as disprove Papapetrou's theory then also disprove Whitehead.

Will and Nordtvedt (ref. A.7) later discovered several other Machian effects produced by the solar system's motion relative to the Universal rest frame. These include contributions to the perihelion shift of Mercury ( $\sim 600''/\text{century}$  for some theories), periodic perturbations in the Earth-Moon distance (some with amplitudes  $\sim 20$  meters), periodic effects on the precession of an orbiting gyroscope, a periodic effect on the rotation rate of the earth, and further effects measurable by earth-bound gravimeters. These new effects have not yet been explored thoroughly; but already they have managed to disprove more than half of the theories of gravity which were considered viable at the beginning of 1971.

Wei-Tou Ni (graduate student) has discovered that, according to some theories, the motion of a star relative to the Universal rest frame can produce a Machian driving force which acts on stellar pulsations. He

is now studying the influence of that force on the pulsations of realistic stellar models. We hope that comparison with observations (e.g., of Cepheid variable stars) will yield useful tests of relativistic gravity.

On the negative side, Will (ref. A.2) has shown that anisotropies in the Earth's passive gravitational mass (one aspect of the "Nordtvedt effect") are too small to produce an observable influence on the Earth-Moon orbit.

All of the above experiments were invented and analyzed using Will's version of the PPN framework.

### C. Comparative Analyses of Theories with Each Other and with Experiment

Graduate student Wei-Tou Ni has begun a project of perusing, evaluating, and classifying all respectable twentieth-century theories of gravity. Questions asked of each theory are: (i) is it self-consistent? (ii) is it complete? (iii) is it compatible with all experiments performed in the past? Ni is examining the ability of current and future experiments to distinguish between the currently viable theories, thereby getting a measure of the relative value of various experiments. His preliminary results are spelled out in reference A.5. We estimate that two more man-years of work by graduate students in our group will be needed to produce a complete evaluation and classification of all twentieth-century theories. This winter Ni will probably be joined or replaced on the project by one other graduate student.

The method by which relativistic effects are included in the JPL ephemeris is being reviewed and checked by Thorne (professor), Will (instructor), and Kovacs (graduate student); see reference B.3. Currently the ephemeris includes the PPN parameters  $\beta$  and  $\gamma$ . A proposal

for adding Nordtvedt-effect parameters has been made by Estabrook (JPL). Many other PPN parameters and effects can and should be added in the future. PPN "point-particle equations" containing these parameters and effects are being derived and put into a form appropriate for addition to ephemeris computer codes.

Kovacs (ref. B.3) has used the PPN Formalism to check the method by which experimenters are trying to extract the value of the PPN parameter  $\gamma$  from pulsar timing data. (The principal experimental effort in this area is by Reichley at JPL.)

### III. SUMMARY OF JPL RESEARCH RESULTS

#### A. Frank B. Estabrook

Theoretical studies at JPL by Frank B. Estabrook included derivation of a relativistic n-body Lagrangian containing the relativity parameters  $\beta$  and  $\gamma$  and Nordtvedt-effect parameters. This is based on the n-body equations of C. M. Will (Caltech) in the case when a full set of classical integral conservations laws exists, and generalizes a previously given Lagrangian involving only  $\gamma$  (for Brans-Dicke theory). Estabrook also critically analyzed some published work of A. Anderson (Uppsala), which had appeared in NATURE 229, (1971), and which claimed to show that certain anomalies in JPL Mariner 6 and 7 tracking data might be due to gravitational waves, correlated with Weber's ground observations. Such a discovery would indeed be momentous, but our analysis demonstrated its extreme improbability; radar range tracking in the solar system does not, in the reasonably foreseeable future, offer possibilities for that kind of testing of relativistic gravity. Other relativistic theoretical

contributions by Estabrook and Hugo D. Wahlquist (not supported by this NASA contract) were a paper on "Hamiltonian Cosmology", in PHYSICS LETTERS, 1971, in which new quantum equations were derived for the initial "big-bang" phase of the universe (when extreme anisotropy may have existed prior to the clotting out of matter and galaxies), and a report on this work at the VI International Conference on GRG, Copenhagen. These equations imply, for the first time, that quantum gravity theory may escape the singularity of classical cosmology, and allow re-expansion after any "inverse big-bang" collapse.



### III-B. John D. Anderson and Colleagues

The work at JPL commenced on September 15, 1970 with funds from the DDF. Later, on December 15, 1970, these funds were supplemented by NASA and the JPL activity was increased appropriately. On July 1, 1971, all funding of the JPL effort was terminated, and the feasibility studies came to a halt.

Because the potential of planetary landers and orbiters as instruments for precise measurements of the PPN parameters was almost completely unknown at the start of the studies, an early goal was the simulation of extended tracking for the MM'71 and Viking missions and the computation of reasonably realistic standard deviations on the two Eddington parameters  $\beta$  and  $\gamma$ .

The studies on the Viking mission were performed by Dan L. Cain and were completed in time for the Caltech Relativity Conference (Reference C.1) Cain showed that tracking of the Viking orbiter and lander at S and X-bands over a full synodic period of Mars (780 days) would yield  $\gamma$  to  $\pm 3\%$  and  $\beta$  to  $\pm 16\%$  when both parameters were estimated together. If the parameter  $\gamma$  were assumed known, from superior conjunction experiments for example, then the parameter  $\beta$  could be determined to an accuracy of  $\pm 7\%$  from the orbital motions of the Earth and Mars.

Other studies, which were partially supported by the DDF funds, were reported at the Caltech conference. David W. Curkendall and his colleagues demonstrated that nongravitational forces on an interplanetary spacecraft such as Mariner 6 are a very serious error source for superior conjunction experiments (Reference C.2). The 1970 Mariner experiment, which was described at the Caltech conference and elsewhere (References C.3, C.4, C.5, C.6), made use of Curkendall's studies to show that the nongravitational forces were the limiting error source on the experiment and that the corresponding limiting error on the relativity test from a single spacecraft was about  $\pm 3\%$ . More recent work by Pasquale B. Esposito (unpublished) has shown that a combination of data from Mariner 6 and Mariner 7 can reduce the error below  $\pm 3\%$ , perhaps to a level of  $\pm 1.5\%$ .

Results of a study by Donald W. Trask were also presented at the Caltech conference. Trask showed that errors in the rotation rate of the Earth, the location of the tracking stations, and the propagation of the radio signal in the Earth's atmosphere and ionosphere have a relatively minor effect on superior conjunction experiments of the Mariner type. All error sources investigated by Trask contributed less than  $\pm 1\%$  to the error of the relativity test.

Another study which received partial support from the DDF was that of Louis D. Friedman (Reference C.7). In this study a series of probable interplanetary space missions for the 1970's was surveyed in order to determine whether further refinements in relativity testing could be expected from deep-space missions. Although detailed covariance analyses were not performed, Friedman's survey demonstrated quite convincingly

that the pioneering tests with the Mariner 6 and 7 spacecraft would be outdated within a very few years.

Subsequent to the Caltech conference, the error analyses at JPL were directed toward the computation of covariance matrices for simulated future missions. A computer program for this purpose was developed by William Burke, now a student in the Harvard Law School. Burke computed partial derivatives of simulated range and Doppler data with respect to orbital elements of the spacecraft and planets, and with respect to corona and relativity parameters. All derivatives were computed by means of literal expressions in order to avoid the time consuming numerical integration of a system of variational equations. Variations with respect to the orbital elements of the planets and spacecraft were obtained from standard conic formulae. The derivatives for the corona parameters were taken from the work of Duane O. Muhleman (Reference C.8). The derivatives for the relativity parameters ( $\beta$ ,  $\gamma$ ) were obtained from an approximate analytical solution to the relativistic equations of motion. Both the solution and the derivatives were formulated by Radmilo Georgevic (References C.8, C.9).

Burke's error analysis program was completed shortly before the termination of the funding for the JPL effort, and a few error studies were performed by Burke and Eunice Lau, who joined JPL in June of 1971. These studies were not published because it was felt that they were too preliminary in nature. However, results were obtained for six future missions and for the Mariner Mars '69 mission. The future missions included the Mariner Mars '71 orbiter, the Viking mission, hypothetical orbiters of Mercury and Venus, the Helios mission, and the Mariner Venus-Mercury extended mission after the encounter with Mercury. Burke and J. Frank Jordan determined that for the orbiter missions it should be possible to obtain daily measurements of the distance between the Earth and the planet to an accuracy on the order of  $\pm 40m$ . They assumed that the orbiter was equipped with a Doppler and ranging transponder for this purpose. As it turned out, the limiting error source for the Earth-planet distance measurement was not the error in the ranging system, but instead the error in the location of the orbiter with respect to the center of mass of the planet. Uncertainties in the gravity field of the planet and random nongravitational forces on the spacecraft were responsible for the orbital error of  $\pm 40m$  along the line of sight. In performing the error analyses for the orbiters it was decided that the distance error of  $\pm 40m$  should be increased to  $\pm 100m$ . This was done to allow for possible errors which might be introduced by unfavorable tracking patterns or by signal propagation effects in the interplanetary medium.

The results for orbiters of Mercury, Venus, and Mars are displayed in Figures 1., 2., and 3. respectively. Curves for the standard deviation on the two Eddington parameters are shown as a function of the duration of time that the orbiter has been tracked. The parameter  $\gamma$  in the Eddington formalism has been replaced by the parameter  $\gamma^* = (1 + \gamma)/2$ . This represents directly the error in a test of the relativistic time-delay effect at superior conjunction.

Results for three interplanetary spacecraft missions are shown in Figures 4., 5., and 6. Here, the ranging accuracy to the spacecraft is assumed equal to  $\pm 500\text{m}$ . Over a period of six months, this is a reasonably realistic corruption of the ranging accuracy, if one takes into account the nongravitational forces acting on a spacecraft of the Mariner type. The resulting curves for the Mariner Mars '69 extended mission are given in Figure 4. This mission was included in the error analysis in order to compare the predicted error in a superior conjunction experiment with the actual error obtained from an analysis of real data. The predicted error of  $\pm 2.4\%$  is sufficiently close to the actual error to give us confidence in the ability of Burke's program to yield realistic error estimates.

Results for the Mariner Venus-Mercury mission are shown in Figure 5. The improvement in the predicted error over that from Mariner Mars '69 is caused by the more rapid passage of the Venus-Mercury spacecraft through superior conjunction. The nongravitational forces do not have as long to build up a position error at conjunction as they do for a Mariner '69 spacecraft. However, the closer approach of the Venus-Mercury spacecraft to the Sun could introduce larger random accelerations from the solar wind and radiation pressure. More analyses are needed in this area.

The expected errors in the relativity tests for the Helios mission are shown in Figure 6. The tracking pattern is selected here in such a way that the six months duration encompasses three superior conjunctions. In addition, two more months of tracking are indicated by the dashed curves. This is done for the reason that the lower area to mass ratio of Helios, plus its spin stabilization, could make the random forces less serious than for a Mariner spacecraft. It may be realistic to track Helios for eight months with an effective ranging accuracy of  $\pm 500\text{m}$ . If this is so, then some information on the parameter  $\beta$  is obtained. However, the time delay test is not improved beyond the six months level of  $\pm 0.95\%$ .

A summary of the error analyses for the six missions shown in the figures as well as for Cain's analyses of the Viking mission is given in Table 1. The fundamental conclusions which can be drawn from this table are:

1. A time delay test could be performed within the next few years to an accuracy of  $\pm 0.6\%$  with either Mariner Mars '71 or the Viking orbiters.
2. The parameter  $\beta$  could be determined by the Viking lander. However, the probability that the lander and orbiter can be tracked for a period of two years at both S and X-bands seems very small. Because an extended tracking assumption is basic to Cain's analysis, we cannot seriously consider Viking a useful device for measuring  $\beta$ .
3. Of all the future missions that are listed, only the orbiter of Mercury emerges as an obvious candidate for a significant measurement of  $\beta$ .

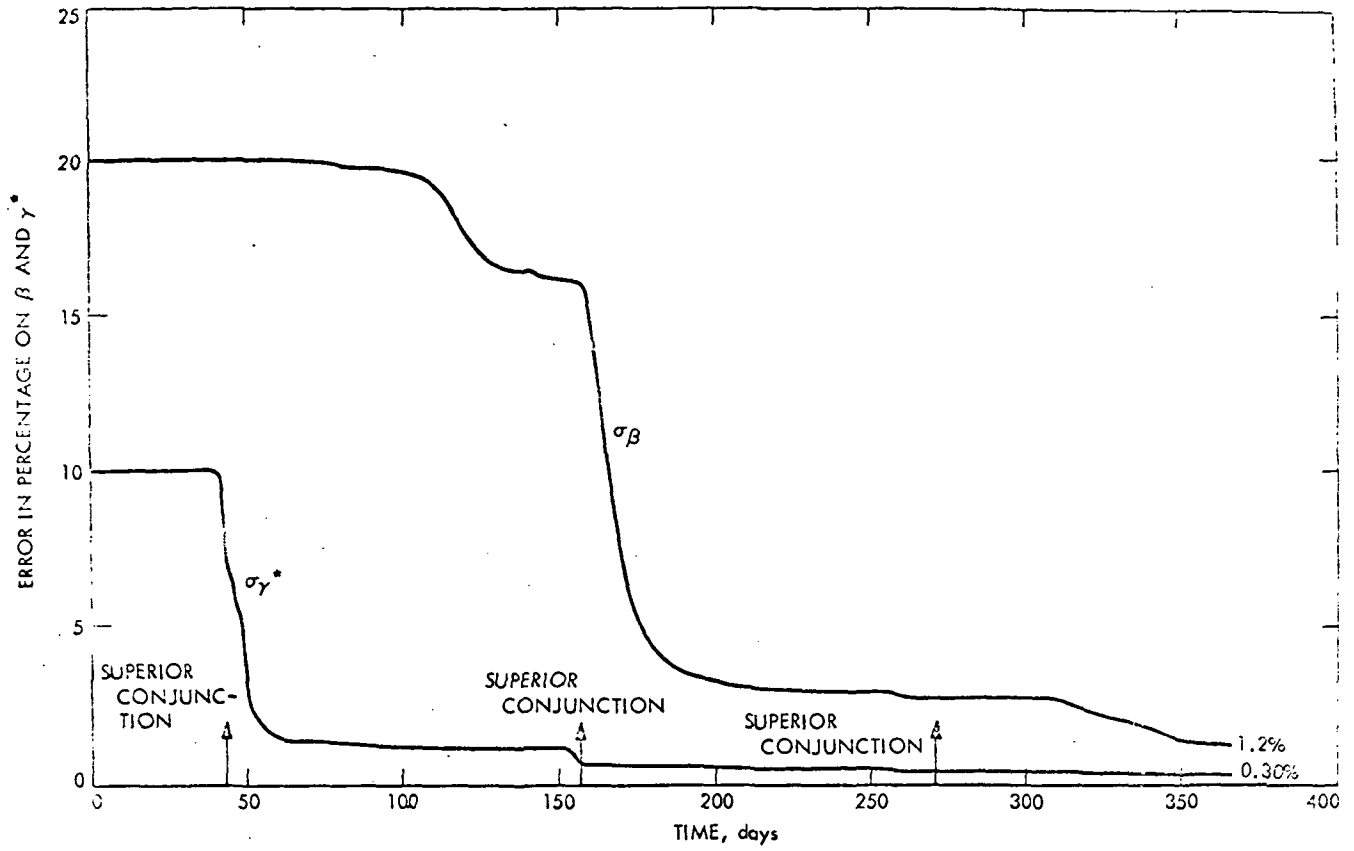
Although the studies of six individual missions give us some insight into what to expect from spacecraft tracking data in the area of relativity testing, more work should be done before results of the covariance analyses are published. In particular we would like to answer the following questions:

1. What relativity information is included in a combination of data from several missions? For example, what can be learned from combining data from the MM'71 orbiter with data from the Viking mission, or from combining data from Mariner 2 and Mariner 5 with data from an orbiter of Venus?
2. What is the usefulness of combining spacecraft tracking data with the ground based radar and optical observations of the planets?
3. Do the new spacecraft tracking techniques (VLBI, simultaneous tracking of two spacecraft from one station, simultaneous tracking of one spacecraft from two stations, on-board optical data) provide any useful relativity information?
4. Are there spacecraft missions which will measure relativistic effects which arise from the nonlinear superpositioning of gravitational fields or that will place a limit on the constancy of G or on the equivalence of inertial and gravitational mass?

Also, there are a number of parameters which are important to a complete covariance analysis of the relativity problem, but which were not included in Burke's preliminary version of his error analysis program. These parameters could be added with little difficulty by means of analytical formulae. They are:

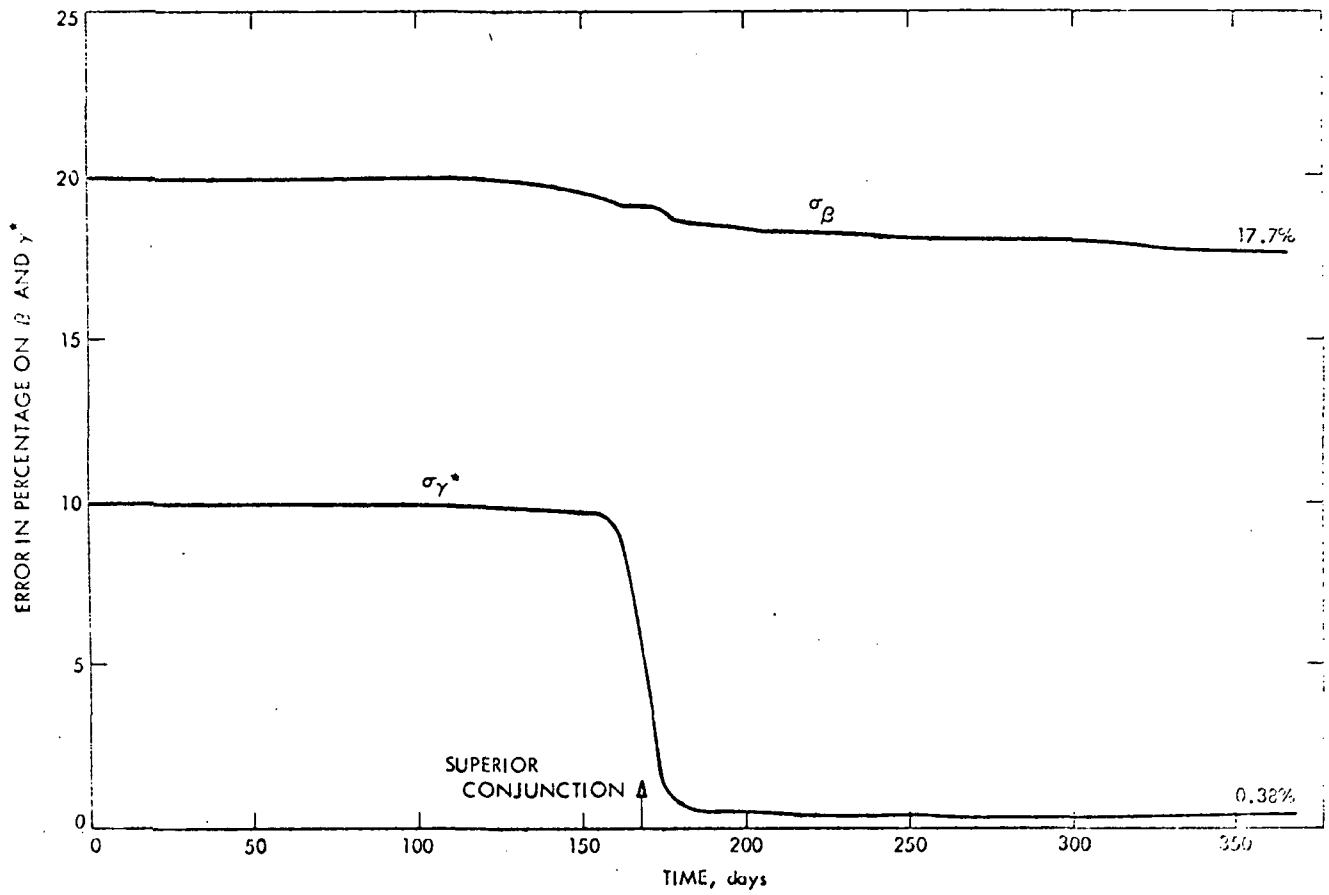
1. The second order zonal harmonic coefficient  $J_2$  for the Sun.
2. The astronomical unit.
3. A radiation pressure coefficient for interplanetary spacecraft.
4. A parameter for the total amount of material in the asteroid belt.
5. A parameter  $\dot{G}$  for a time variation in the gravitational constant.

The credibility of the covariance analyses would be enhanced by including a capability to assign variable error estimates to the tracking data which would depend on the amount of plasma along the ray path and on the assumed carrier frequency of the tracking signal. This is being done in the analysis of the real data from Mariner 6 and 7, and it would not be difficult to include the same scheme in the error analyses for future missions.



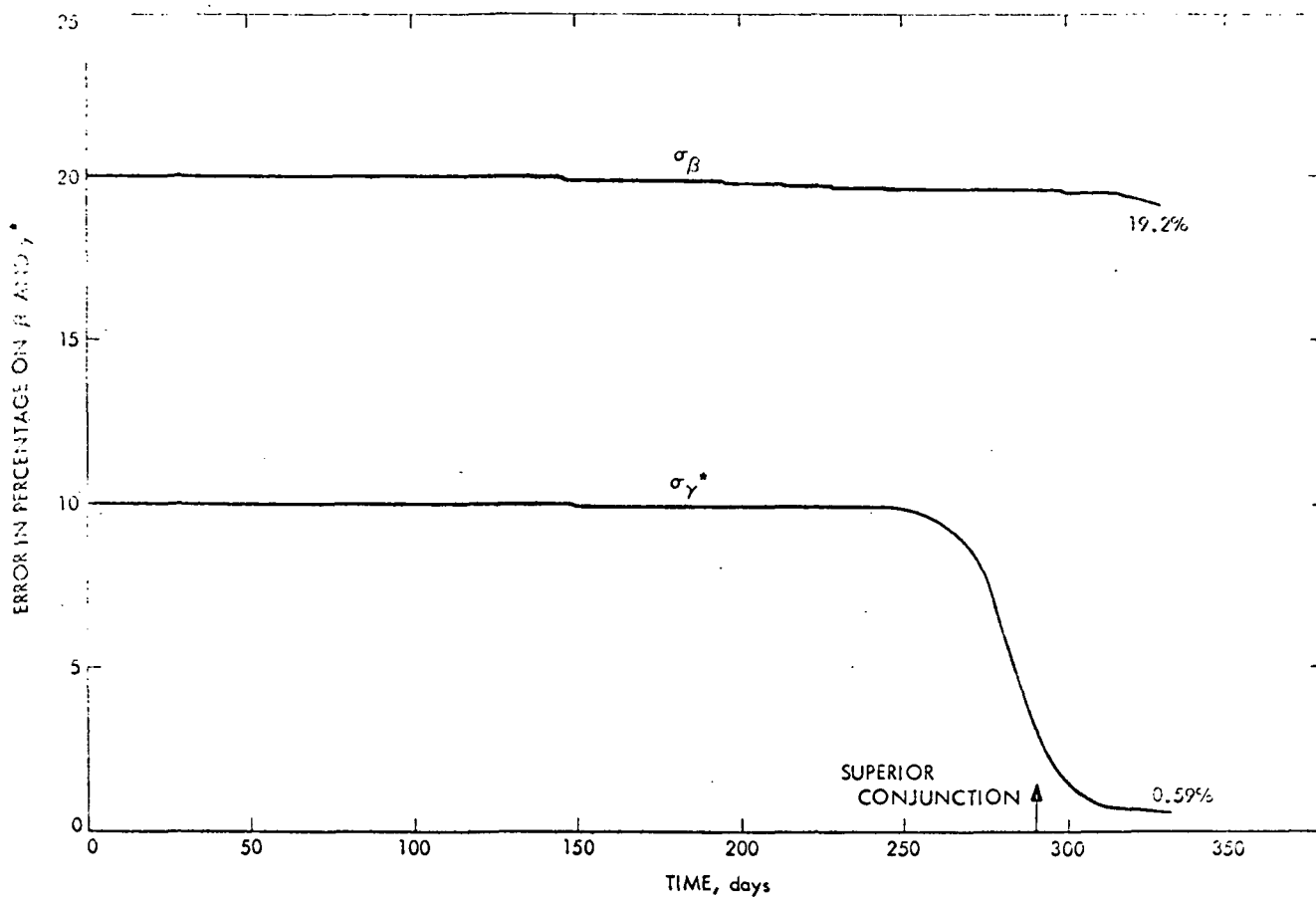
Errors on  $\beta$  and  $\gamma^*$  for Ranging Accuracy  
of  $\pm 100$  m to the Center of Mercury

Figure 1



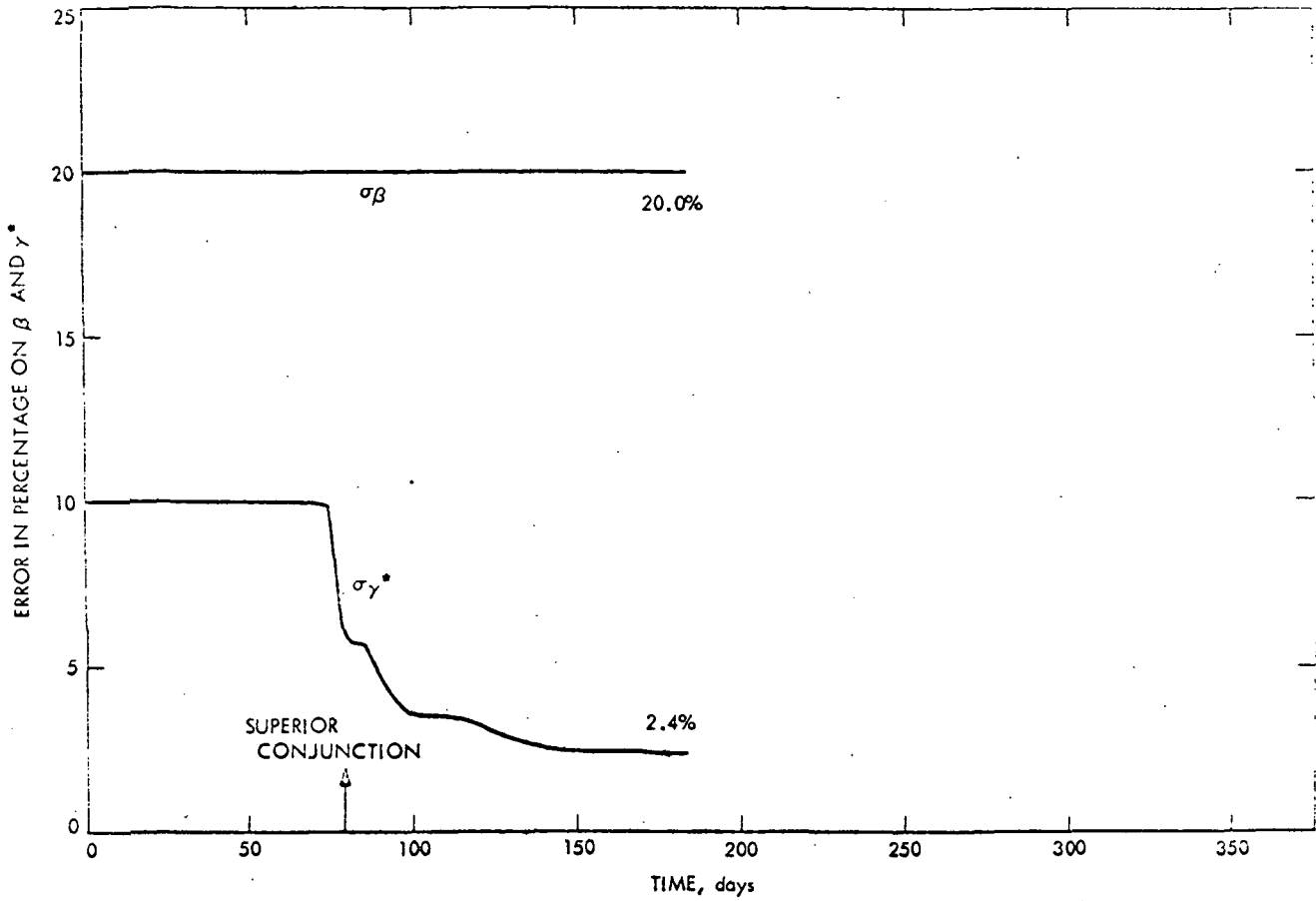
Errors on  $\beta$  and  $\gamma^*$  for Ranging Accuracy of  $\pm 100$  m to the Center of Venus

Figure 2



Errors on  $\beta$  and  $\gamma^*$  for Ranging Accuracy of  $\pm 100$  m to the Center of Mars

Figure 3

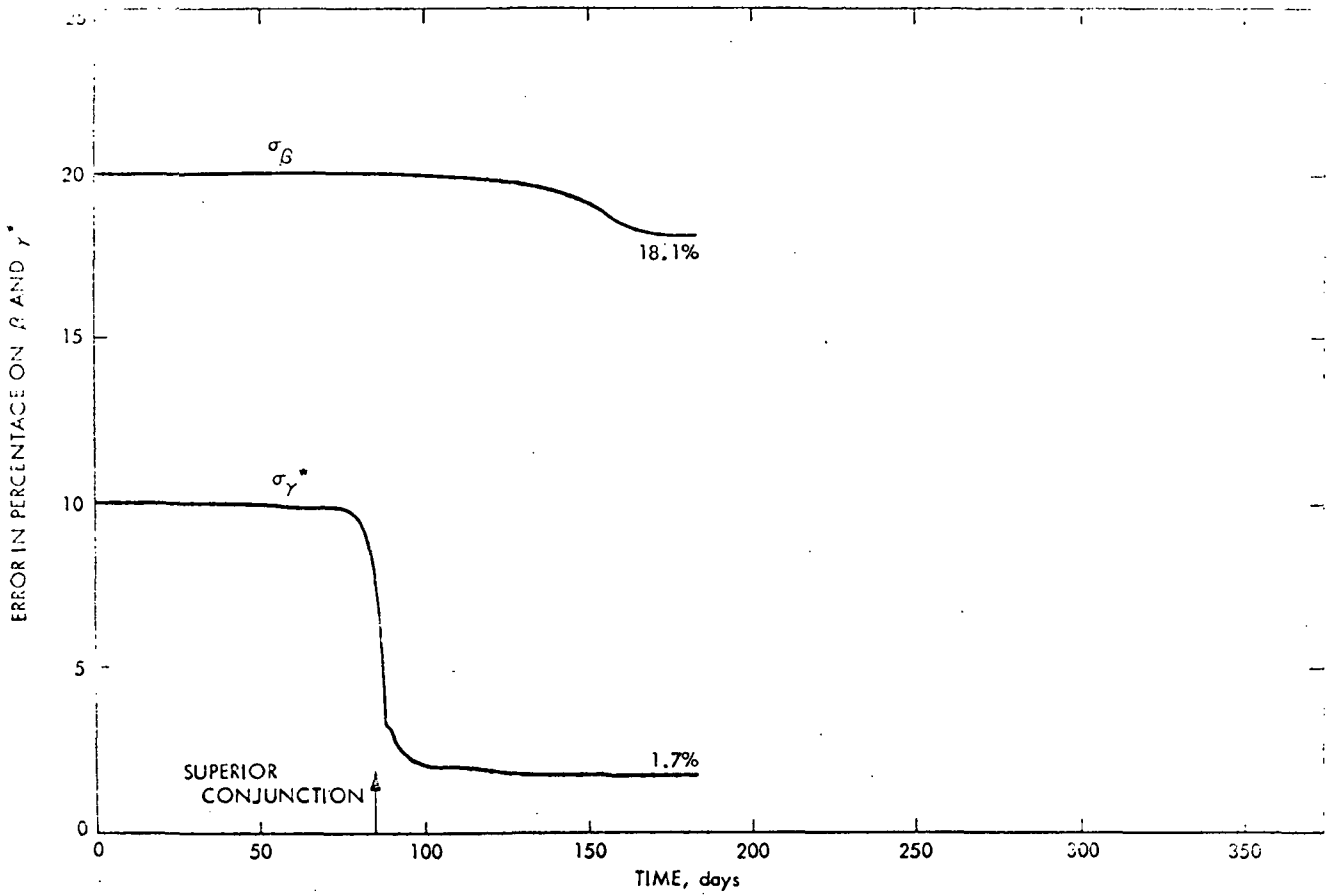


Errors on  $\beta$  and  $\gamma^*$  for Effective Ranging Accuracy of  $\pm 500$  m to the Spacecraft

Figure 4

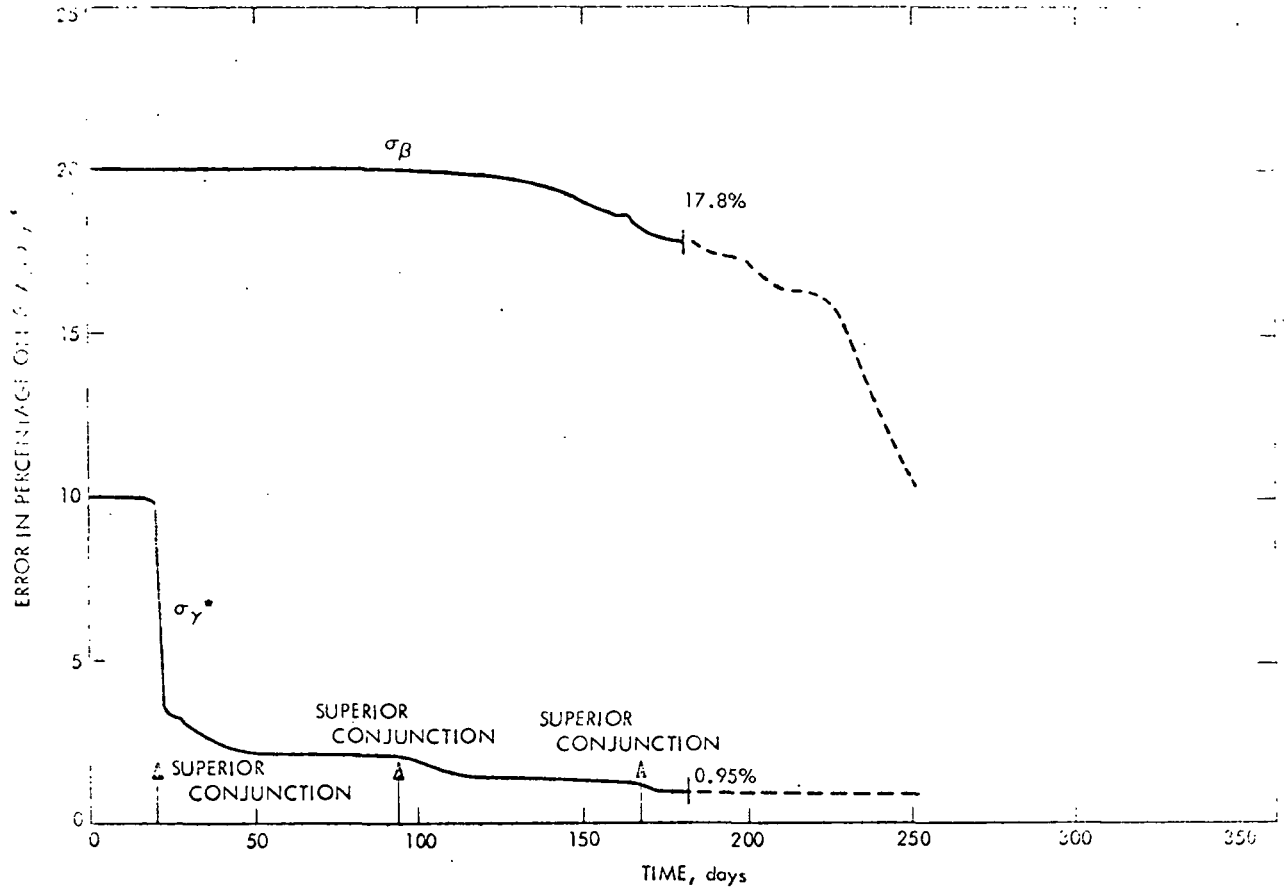


VENUS-MERCURY EXTENDED MISSION



Errors on  $\beta$  and  $\gamma^*$  for Effective Ranging Accuracy of  $\pm 500$  m to the Spacecraft

Figure 5



Errors on  $\beta$  and  $\gamma^*$  for Effective Ranging Accuracy of  $\pm 500$  m to the Spacecraft

Figure 6

MISSION	EXPECTED ACCURACY, %	
	$\gamma^*$	$\beta$
Mariner Mars '69	2.4	none
Mariner Mars '71	0.6	none
Mariner Venus-Mercury '73	1.7	none
Helios '72	1.0	none
Viking '75 (Dual Frequency)	0.1	1.0 to 7.0
Viking '75 (S-band Only)	0.6	none
Mercury Orbiter	0.3	1.2
Venus Orbiter	0.4	none

TABLE 1

Expected standard deviations in the two relativity parameters  $\gamma^*$  and  $\beta$  for Mariner Mars '69 and for six possible future missions. One year of tracking is assumed for the orbiters and two years for the Viking lander. Error contributions from nongravitational forces and from propagation effects in the solar corona are included in the estimates of uncertainty.

IV. PUBLICATIONS SUPPORTED WHOLLY OR IN PART BY THESE FUNDS

A. CALTECH - PUBLISHED PAPERS

1. Theoretical Frameworks for Testing Relativistic Gravity. III. Conservation Laws, Lorentz Invariance and Values of PPN Parameters  
Clifford M. Will  
Astrophys. J. 169, 125 (1971)
2. Relativistic Gravity in the Solar System. I. Effect of an Anisotropic Gravitational Mass on the Earth-Moon Distance  
Clifford M. Will  
Astrophys. J. 165, 409 (1971)
3. Relativistic Gravity in the Solar System. II. Anisotropy in the Newtonian Gravitational Constant  
Clifford M. Will  
Astrophys. J. 169, 141 (1971)
4. Theoretical Frameworks for Testing Relativistic Gravity - A Review  
Kip S. Thorne, Clifford M. Will, and Wei-Tou Ni  
Proceedings of the Conference on Experimental Tests of Gravitation Theories, R. Davies, ed., (NASA---JPL Technical Memorandum 33-499, 1971) p. 10.  
Also published by NORDITA (Copenhagen, Denmark) for distribution at the Sixth International Conference on Gravitation and Relativity, Copenhagen, July 1971.
5. Theoretical Frameworks for Testing Relativistic Gravity. IV. A Compendium of Metric Theories of Gravity and their Post-Newtonian Limits  
Wei-Tou Ni  
Astrophys. J., in press
6. Theoretical Frameworks for Testing Relativistic Gravity. V. Implications of White-Dwarf Stability  
Wei-Tou Ni  
Astrophys. J., in preparation
7. Conservation Laws and Preferred Frames in Relativistic Gravity. I. Preferred-Frame Theories and an Extended PPN Formalism  
Clifford M. Will and Kenneth Nordtvedt, Jr.  
Astrophys. J., in preparation
8. Conservation Laws and Preferred Frames in Relativistic Gravity. II. Experimental Evidence to Rule Out Preferred-Frame Theories of Gravity  
Kenneth Nordtvedt, Jr. and Clifford M. Will  
Astrophys. J., in preparation

B. CALTECH - ABSTRACTS OF PAPERS PRESENTED AT SCIENTIFIC MEETINGS

1. Theoretical Interpretations of Experimental Tests of Gravitation Theory: An Overview  
K. S. Thorne, C. M. Will, W.-T. Ni, S. J. Kovacs, D. Lee and A. Lightman  
Bull. Am. Phys. Soc. 17, 141 (1972)
2. Experiments to Rule Out "Preferred-Frame" Metric Theories of Gravity  
Clifford M. Will and Kenneth Nordtvedt, Jr.  
Bull. Am. Phys. Soc. 17, 141 (1972)
3. Parametrized Post-Newtonian Ephemeris  
Sandor J. Kovacs, Clifford M. Will, and Kip S. Thorne  
Bull. Am. Phys. Soc. 17, 141 (1972)
4. Relativistic Instabilities in Stars: An Empirical Approach  
Wei-Tou Ni  
Bull. Am. Phys. Soc. 17, 141 (1972)
5. The Belinfante-Swihart Theory: An Example of a Nonmetric Theory of Gravity  
Alan Lightman  
Bull. Am. Phys. Soc. 17, 141 (1972)
6. The Hoyle-Narlikar Conformal Theory of Gravity  
David Lee  
Bull. Am. Phys. Soc. 17, 141 (1972)

C. JPL - PUBLISHED PAPERS

1. Anchoring Spacecraft to Planets  
D. L. Cain  
Proceedings of the Conference on Experimental Tests of Gravitation Theories, R. W. Davies, ed., JPL TM 33-499, November 1, 1971
2. The Effects of Random Accelerations on Estimation Accuracy with Applications to the Mariner 1969 Relativity Experiment  
D. W. Curkendall, S. G. Finley, M. W. Nead, V.J. Ondrasik, and C. W. Thornton  
Proceedings of the Conference on Experimental Tests of Gravitation Theories, R. W. Davies, ed., JPL TM 33-499, November 1, 1971.
3. A Measurement of the General Relativistic Time Delay with Data from Mariners 6 and 7  
J. D. Anderson, P. B. Esposito, W. L. Martin, and D. O. Muhleman  
Proceedings of the Conference on Experimental Tests of Gravitation Theories, R. W. Davies, ed., JPL TM 33-499, November 1, 1971

4. Determination of Astrodynamic Constants and a Test of the General Relativistic Time Delay with S-Band Range and Doppler Data from Mariners 6 and 7  
J. D. Anderson, P. B. Esposito, W.L. Martin, and D. O. Muhleman  
Space Research XI, Akademie-Verlag (Berlin, 1971) pp. 105-112
5. Measurement of General Relativistic Time Delay with Mariner 6 and 7  
J. D. Anderson, P. B. Esposito, W. Martin, and D. O. Muhleman  
Paper No. 2.14, XIVth Plenary Meeting of COSPAR, Seattle, Washington, 17 June to 2 July 1971
6. Classical Least Squares and Sequential Estimation Techniques as Applied to the Analysis of the Mariner VI and VII Tracking Data  
P. B. Esposito, C. L. Thornton, J. D. Anderson, and D. O. Muhleman  
Paper AAS No. 71-384, Astrodynamics Specialists Conference, Fort Lauderdale, Florida, August 17-19, 1971
7. Applications of Presently Planned Interplanetary Missions to Testing Gravitational Theories  
L. D. Friedman  
Proceedings of the Conference on Experimental Tests of Gravitation Theories, R. W. Davies, ed., JPL-TM 33-499, November 1, 1971
8. Analytic Expressions for the Partial Derivatives of Observables with Respect to Robertson's Relativistic Parameters  
R. M. Georgevic  
JPL Space Programs Summary 37-64, Vol. III., August 31, 1970, pp. 162-169
9. Simplified Formulae for the Calculation of Perturbations of the Osculating Orbital Parameters and of the Range Rate of a Celestial Body  
R. M. Georgevic  
JPL TM 33-481, June 15, 1971
10. Application of Spacecraft Tracking Data to Experimental General Relativity  
J. D. Anderson and P. B. Esposito  
AIAA Paper No. 70-1317, October 19-22, 1970

D. JPL - ABSTRACTS OF PAPERS PRESENTED AT SCIENTIFIC MEETINGS

1. Measurement of the General Relativistic Time Delay from Mariners VI and VII Tracking Data  
J. D. Anderson, P. B. Esposito, W.L. Martin, and D. O. Muhleman  
Presented at the 133rd meeting of the Am. Astr. Soc., Tampa, Florida, December 6-9, 1970

V. INVITED LECTURES WHICH DESCRIBED RESEARCH SUPPORTED WHOLLY OR IN PART BY THESE FUNDS

A. CALTECH

1. Experimental Tests of General Relativity  
Kip S. Thorne  
134th Meeting of the American Astronomical Society, Louisiana State University, Baton Rouge, Louisiana, March 29-April 1, 1971
2. Experimental Tests of General Relativity  
Kip S. Thorne  
Lebedev Physics Institute, Moscow, USSR, June 30, 1971
3. Experimental Tests of General Relativity -- A Review  
Kip S. Thorne  
Sixth International Conference on Gravitation and Relativity, Copenhagen, Denmark, July 5-10, 1971
4. Parametrization of Gravitation Theories and Present Experimental Results  
Kip S. Thorne  
Symposium on the ESRO Gravitational Space Mission, Harlem, Holland, July 12, 1971
5. Experimental Tests of General Relativity  
Kip S. Thorne  
Leonard Schiff Memorial Session, Meeting of the American Physical Society, San Francisco, February 3, 1972

B. JPL

1. Experimental General Relativity  
J. D. Anderson  
Flight Mechanics and Control Seminar, Stanford University, April 21, 1971
2. Recent Results on the Measurement of the General Relativistic Time Delay During the 1970 Superior Conjunction of Mariners 6 and 7  
J. D. Anderson  
American Physical Society, Division of Particles and Fields, Washington, D. C., April 27, 1971

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