

Forthcoming Close Angular Approaches of Planets to Radio Sources and Possibilities to Use Them as GR Tests

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Abstract—During close angular approaches of solar system planets to astrometric radio sources, the apparent positions of these sources shift due to relativistic effects and, thus, these events may be used for testing the theory of general relativity; this fact was successfully demonstrated in the experiments on the measurements of radio source position shifts during the approaches of Jupiter carried out in 1988 and 2002. An analysis, performed within the frames of the present work, showed that when a source is observed near a planet's disk edge, i.e., practically in the case of occultation, the current experimental accuracy makes it possible to measure the relativistic effects for all planets. However, radio occultations are fairly rare events. At the same time, only Jupiter and Saturn provide noticeable relativistic effects approaching the radio sources at angular distances of about a few planet radii. Our analysis resulted in the creation of a catalog of forthcoming occultations and approaches of planets to astrometric radio sources for the time period of 2008–2050, which can be used for planning experiments on testing gravity theories and other purposes. For all events included in the catalog, the main relativistic effects are calculated both for ground-based and space (Earth–Moon) interferometer baselines.

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INTRODUCTION

Apart from the theory of general relativity (GR), generally accepted among physicists and astronomers, alternative theories of gravitation have been suggested. The most serious of them do not contradict the available observational data, but predict deviations from GR for circumstances that have not been observed so far or for accuracies higher than those that have been already achieved. Therefore, the testing of gravity theories on the basis of different methods and more and more precise observations is an urgent astronomical and physical problem.

Among the proposed GR tests are the Very Long Baseline Interferometry (VLBI) observations of radio sources at the time instants when solar system planets closely approach them (Treuhaft and Lowe, 1991; Kopeikin, 2001; Fomalont and Kopeikin, 2003, 2008). In particular, these papers present the observations of relativistic time delays of radio source signals at the instances of close approaches of Jupiter in 1988 and 2002. Similar observations of Jupiter and Saturn are planned at O.A. Titov's proposal by the International VLBI Service for Geodesy and Astrometry (Schlüter and Behrend, 2007) in 2008–2009 (<http://ivscc.gsfs.nasa.gov/program/opc.html>). However, the reduction of already available experimental data showed that some formulated problems still have no unambiguous answer, in particular, because the achieved accuracy proved to be insufficient, mostly as a result of the fairly large angular distances between the radio sources

and Jupiter. Therefore, further observations are necessary, which should be performed in the most favorable conditions, first of all, during the closest approaches (further, we imply apparent approaches) and occultations.

Note that so far the observations have been carried out in an irregular way, i.e., an experimenter used the closest in time approach of a planet to a known astrometric radio source. Another researcher who decided to perform a similar experiment has to search for forthcoming approaches himself. In this situation, the most interesting phenomena, i.e., the closest angular approaches, may be missed. In addition, the observations of relativistic effects caused by light deflections and gravitational time delays near a planet require significant, usually international, resources and should be planned well in advance. Therefore, the possibility of early planning of the experiments that can be performed in the most favorable conditions is highly desirable.

In the present work, we tried to create a catalog of approaches of solar system planets to astrometric radio sources for the convenient and reliable planning of observations. During the work, we found that two characteristics of such experiments, which are currently treated as obvious, are wrong. First, we found that such events occur much more often than it had been considered before. Second, one of the most interesting relativistic effects related to the speed of gravity propagation proved to be observable not only in the case of giant planets, but in the case of all other planets, including

Table 1. The maximum values of relativistic effects for the case of observations at the edges of a planet's disks, ns

Baseline, thousand km	Effect	Mercury	Venus	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto
8	Δ	0.01	0.06	0.02	2.1	0.77	0.27	0.33	0.00
	Δ_p	0.15	0.32	0.13	1.2	0.68	0.73	1.14	0.09
400	Δ	0.5	3.2	0.75	110	39	14	16	0.05
	Δ_p	7.3	16	6.7	62	34	37	57	4.3

Table 2. The values of relativistic effects for a 30-arcsec angular distance between the planet center and the source, ns

Baseline, thousand km	Effect	Mercury	Venus	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto
8	Δ	0.00	0.01	0.00	1.1	0.20	0.02	0.01	0.00
	Δ_p	0.00	0.01	0.00	0.33	0.04	0.00	0.00	0.00
400	Δ	0.04	0.51	0.05	56	9.8	0.78	0.60	0.00
	Δ_p	0.05	0.41	0.03	17	2.2	0.12	0.08	0.00

Pluto. In addition, the development of space technology makes it possible to perform VLBI experiments with baselines of several hundred thousand kilometers; with these baselines, the main relativistic effects can be observed in the case of all planets, including the largest among the minor planets.

OBSERVABLE EFFECTS

When a planet approaches a radio source, one can observe two relativistic effects which contribute into the measured interferometric delay, defined as the difference between the instants of electromagnetic wave front arrivals to two VLBI antennas. These effects are the Shapiro time delay Δ and the delay of gravity propagation Δ_p caused by the ray propagation near a moving body, i.e., near a planet in our case. Kopeikin (2001) showed that their measurement makes it possible to determine two fundamental relativistic parameters: γ , which is equal to unity in GR, and the parameter of gravity propagation δ , which is equal to zero in GR, i.e., the gravity speed is considered to be equal to the speed of light. The values of these effects can be estimated from the formulas derived by Kopeikin (2001; Eq. 13), which after the obvious transformations take the form

$$\Delta \cong \frac{2(1+\gamma)GMrB}{c^3 R d}, \quad \Delta_p \cong (1+\delta)\frac{\Delta v}{cd}, \quad (1)$$

where GM is the planetocentric gravitational constant, B is the interferometer baseline, r is the apparent angular radius of the planet, d is the angular distance between the source and the planet center for a station, R is the planet radius, v is its orbital speed, and c is the speed of light. One can see that Δ and Δ_p achieve their maxima at the edge of the planet's disk, i.e., when $d = r$. In

this case, Eq. (1) within the frames of GR can be rewritten in the form

$$\Delta \cong \frac{4GMB}{c^3 R}, \quad \Delta_p \cong \frac{\Delta v}{cr}. \quad (2)$$

Equation (2) shows that at the edge of the disk, Δ does not depend on the apparent size of the disk, i.e., on the planet distance, and Δ_p reaches its maximum when the distance between the Earth and the planet becomes the largest. The maximum values of the observable relativistic effects are present in Table 1 for ground-based and space-based (Earth–Moon) interferometer baselines. Taking into account the linear dependence of the considered effects on B , these values can be easily recalculated for any baseline.

Note that the relativistic effects that are of the order of Δ_p can be measured using the simplest interferometric technique of the group delay measurements. At the same time, the effects of the order of Δ_p require differential phase measurements in carefully planned observations. One can reasonably expect a significant increase of the accuracy of relativistic effect measurements with setting in operation the new VLBI 2010 stations (Behrend et al., 2008).

Calculations show that nearly all planets during their closest approaches to radio sources provide relativistic effects, especially for Δ_p , that can be observed even with ground-based interferometers. However, with an increase of the angular distances between the planets' centers and radio sources to 30 arcsec, the relativistic effects become so weak that ground-based interferometers can produce sufficient accuracy only for Jupiter and Saturn (Table 2).

Table 3. Occultations of astrometric radio sources by planets

Planet	Date, y m d	Source	Source α and δ , J2000		Notes, seeing
			h min s	deg arcmin arcsec	
Venus	2011 02 26.6	1946–200	19 49 53	–19 57 13	S. America, Australia, Antarctica
Mars	2011 05 03.8	0127+084	1 30 28	+8 42 46	America
Venus	2012 12 24.4	1631–208	16 34 30	–20 58 26	Africa, S. America, Antarctica
Venus	2015 08 06.8	0947+064	9 50 03	+6 15 04	America
Venus	2020 01 16.7	2220–119	22 22 56	–11 44 26	Europe, Africa, S. America
Venus	2020 07 17.7	0446+178	4 49 13	+17 54 32	America
Jupiter	2025 09 18.6	0725+219	7 28 21	+21 53 06	America, Antarctica
Saturn	2028 10 24.8	0223+113	2 25 42	+11 34 25	Annular occultation, Asia, Africa, Europe
Jupiter	2033 02 04.2	2104–173	21 07 27	–17 08 10	S. America, Australia, Antarctica
Venus	2035 07 03.3	0558+234	6 01 47	+23 24 53	Europe, Asia, Africa
Venus	2037 01 03.8	1734–228	17 37 02	–22 51 55	S. America, Australia, Antarctica
Jupiter	2043 02 01.1	1734–228	17 37 02	–22 51 55	Antarctica, Asia, Africa, Antarctica
Venus	2043 02 15.6	1858–212	19 01 04	–21 12 01	America
Venus	2043 02 17.7	1908–211	19 11 54	–21 02 44	America, Australia
Jupiter	2045 09 24.4	2221–116	22 24 08	–11 26 21	S. America, Australia, Antarctica
Venus	2049 01 13.5	2243–081	22 45 49	–7 55 19	Asia, Europe, Africa
Venus	2049 11 02.2	1333–082	13 36 08	–8 29 52	Africa, Antarctica

PRECOMPUTATION OF OCCULTATIONS AND APPROACHES

On the basis of the results presented in the previous section, one can conclude that the instants of occultations should be precomputed for all planets from Venus to Neptune, and for Jupiter and Saturn the circumstances of the approaches should be precomputed in more detail. In this case, all of the approaches of planets to radio sources that provide the most noticeable relativistic effects of signal propagation will be taken into account. Their amount makes it possible to plan experiments not involving Mercury, Mars, and minor planets, for these planets’ relativistic effects can be measured, but with fairly large relative errors. However, the data omitted in this paper can be easily supplied by the authors at the request of interested parties.

Most computations of the circumstances of planet approaches to radio sources were performed using the codes APPROACH and OCCULT, which utilize the Ephemeride Package for Objects of the Solar System (EPOS; L’vov et al., 2001) data and environment. Source coordinates were taken from the Goddard center of space flight’s catalog (Petrov, 2008), adding sources from the ICRF-2 catalog (Fey et al., 2004). The total number of sources proved to be 3958; their list and optical characteristics are available at the website http://www.gao.spb.ru/english/as/ac_vlbi/sou_car.dat.

The list of source occultations by planets is presented in Table 3, and the circumstances of Jupiter and

Saturn approaches to radio sources are given in Tables 4 and 5, respectively. The tables exhibit the circumstances of all occultations and approaches closer than 10’ over the time interval from September 2008 (the time of writing this paper) to 2050. There is no occultation for Uranus and Neptune over this time interval. An interesting feature of the list is the presence of multiple approaches due to the retrograde apparent motion of the planets. In this case, a planet approaches a radio source from different directions, which may have a particular interest for studying the influence of a moving planet on the signal delay (Δ_p term).

The apparent angular diameters of planets in Tables 4 and 5 are calculated from their mean radii. The Δ and Δ_p values are calculated for a 8000-km long baseline. In this case, we used an equation which obviously follows from Eq. 1 (GR case)

$$\Delta = \frac{4GMB}{c^3 Dd}, \tag{3}$$

where D is the distance between the Earth and the planet. Data for other baselines, including space-based ones, can be easily obtained by proportionally recalculating the present values. The results of the experiment performed in 2002 (Fomalont and Kopeikin, 2003) showed that the relativistic time delay $\Delta_p \approx 6$ ps (more precisely, an equivalent light deflection of 51 μ s) proved to be measurable with an accuracy of 20% using the VLBA interferometer supplemented by the 100-

Table 4. Apparent approaches of Jupiter to astrometric radio sources

Date, y m d	Source	Source α and δ , J2000		d , arcsec	r , arcsec	Δ , ps	Δ_p , ps
		h min s	deg arcmin arcsec				
2008 11 19.0	1922 – 224	19 25 40	–22 19 35	83	17	443	48
2009 03 08.6	2104 – 173	21 07 27	–17 08 10	277	16	127	4.1
2011 07 03.6	0210 + 119	2 13 05	+12 13 11	341	18	116	3.0
2011 09 13.1	0229 + 131	2 31 46	+13 22 55	149	23	328	20
2012 02 04.0	0201 + 113	2 03 47	+11 34 45	490	19	83	1.5
2012 02 20.3	0210 + 119	2 13 05	+12 13 11	342	18	114	3.0
2013 02 28.1	0420 + 210	4 23 02	+21 08 02	216	19	191	8.0
2013 10 23.0	0723 + 219	7 26 14	+21 53 20	123	20	343	25
2013 11 07.0	0725 + 219	7 28 21	+21 53 06	388	21	114	2.6
2013 11 22.1	0723 + 219	7 26 14	+21 53 20	351	21	132	3.4
2017 10 13.7	1352 – 104	13 54 47	–10 41 03	69	15	471	62
2019 10 28.4	1723 – 229	17 26 59	–22 58 02	184	16	192	9.4
2020 08 02.0	1922 – 224	19 25 40	–22 19 35	79	23	631	72
2020 10 24.2	1922 – 224	19 25 40	–22 19 35	355	18	112	2.8
2021 02 19.9	2104 – 173	21 07 27	–17 08 10	149	16	232	14
2022 11 13.8	2354 – 021	23 57 25	– 1 52 16	159	22	304	17
2022 12 04.1	2354 – 021	23 57 25	– 1 52 16	177	21	257	13
2023 06 11.1	0210 + 119	2 13 05	+12 13 11	28	17	1321	426
2023 11 05.4	0229 + 131	2 31 46	+13 22 55	199	24	261	12
2024 01 02.1	0210 + 119	2 13 05	+12 13 11	396	21	117	2.6
2025 09 15.4	0723 + 219	7 26 14	+21 53 20	215	17	174	7.3
2025 10 25.0	0741 + 214	7 44 47	+21 20 00	30	19	1374	406
2025 11 29.1	0741 + 214	7 44 47	+21 20 00	274	22	169	5.5
2029 03 15.3	1333 – 082	13 36 08	– 8 29 52	432	21	105	2.2
2029 09 28.5	1352 – 104	13 54 47	–10 41 03	47	15	704	136
2031 02 23.2	1734 – 228	17 37 02	–22 51 55	261	17	142	4.9
2031 06 07.1	1734 – 228	17 37 02	–22 51 55	55	23	877	143
2031 10 05.6	1723 – 229	17 26 59	–22 58 02	312	18	121	3.5
2033 02 27.2	2126 – 158	21 29 12	–15 38 41	417	16	83	1.8
2034 01 28.9	2245 – 091	22 47 52	– 8 50 22	342	17	105	2.8
2035 05 14.0	0201 + 113	2 03 47	+11 34 45	433	16	81	1.7
2035 05 24.1	0210 + 119	2 13 05	+12 13 11	173	17	206	11
2037 05 28.4	0558 + 234	6 01 47	+23 24 53	306	16	112	3.3
2037 08 27.9	0725 + 219	7 28 21	+21 53 06	159	16	222	13
2037 09 19.0	0741 + 214	7 44 47	+21 20 00	29	17	1271	391
2041 09 11.6	1352 – 104	13 54 47	–10 41 03	74	16	455	55
2045 01 20.1	2104 – 173	21 07 27	–17 08 10	192	16	180	8.4
2045 02 12.0	2126 – 158	21 29 12	–15 38 41	283	16	121	3.8
2045 05 29.4	2245 – 091	22 47 52	– 8 50 22	459	19	91	1.8
2045 09 20.3	2223 – 114	22 25 44	–11 13 41	228	24	224	8.9
2045 12 04.5	2223 – 114	22 25 44	–11 13 41	466	19	89	1.7
2046 01 10.7	2245 – 091	22 47 52	– 8 50 22	83	17	449	48
2047 04 28.4	0201 + 113	2 03 47	+11 34 45	294	16	118	3.6
2047 05 08.3	0210 + 119	2 13 05	+12 13 11	308	16	113	3.3
2049 05 11.4	0558 + 234	6 01 47	+23 24 53	129	16	272	19
2049 08 29.5	0741 + 214	7 44 47	+21 20 00	179	16	196	9.9

Table 5. Apparent approaches of Saturn to astrometric radio sources

Date, y m d	Source	Source α and δ , J2000		d , arcsec	r , arcsec	Δ , ps	Δ_p , ps
		h min s	deg arcmin arcsec				
2009 02 10.2	1125 + 062	11 27 37	+5 55 32	80	9	92	7.7
2009 06 26.0	1109 + 076	11 12 10	+ 7 24 49	146	8	44	2.0
2015 06 19.1	1548 – 177	15 51 15	–17 55 02	156	9	44	1.9
2015 11 19.1	1614 – 195	16 17 27	–19 41 32	64	7	88	9.1
2016 11 22.9	1658 – 217	17 02 10	–21 30 03	194	7	29	1.0
2017 12 13.3	1752 – 225	17 55 26	–22 32 11	73	7	78	7.1
2021 08 10.8	2044 – 188	20 47 38	–18 41 41	20	9	347	115
2021 12 08.1	2044 – 188	20 47 38	–18 41 41	114	8	52	3
2023 04 13.3	2221 – 116	22 24 08	–11 26 21	33	8	183	37
2023 04 18.2	2223 – 114	22 25 44	–11 13 41	276	8	22	0.5
2024 01 04.6	0220 – 119	2 13 05	+12 13 11	370	8	16	0.3
2024 03 18.5	2252 – 090	22 55 04	–08 44 04	158	8	37	1.5
2026 04 01.5	0019 – 001	0 22 25	+ 0 14 56	472	8	13	0.2
2026 10 19.0	0037 + 011	0 40 14	+ 1 25 46	145	9	51	2.3
2028 05 20.6	0208 + 106	2 11 13	+10 51 35	79	8	77	6.5
2030 11 31.0	0409 + 188	4 12 46	+18 56 37	306	10	25	0.5
2032 04 03.5	0503 + 216	5 06 34	+21 41 00	71	9	93	8.8
2033 05 24.2	0620 + 227	6 23 18	+22 41 36	206	8	31	1.0
2034 06 15.7	0725 + 219	7 28 21	+21 53 06	38	8	163	28
2034 07 16.2	0741 + 214	7 44 47	+21 20 00	157	8	39	1.7
2037 01 16.1	1013 + 127	10 15 44	+12 27 07	72	10	103	9.6
2037 07 24.1	1013 + 127	10 15 44	+12 27 07	233	8	26	0.8
2043 10 18.4	1459 – 149	15 02 25	–15 08 53	220	7	26	0.8
2044 02 27.6	1548 – 177	15 51 15	–17 55 02	33	8	193	39
2045 09 20.4	1614 – 195	16 17 27	–19 41 32	46	8	132	19
2046 09 17.5	1658 – 217	17 02 10	–21 30 03	51	8	120	16
2047 10 17.1	1752 – 225	17 55 26	–22 32 11	367	8	16	0.3
2048 11 28.4	1853 – 226	18 56 36	–22 36 17	321	7	18	0.4

meter antenna at Effelsberg, Germany. Less close approaches should be observed with space interferometers for which the effect is larger proportionally to the ratio of space/ground-based interferometer baseline lengths.

Note that in the present work, the approach circumstances are calculated for the geocenter. For a real observer, the angular distances will differ from the values presented in Tables 4 and 5 up to the value of the R_0/D ratio, where R_0 is the distance from the geocenter to the mid-baseline, depending on the position angle and baseline orientation. Clearly, this difference reaches its maximum at the epochs of oppositions, and for ground-based interferometers may be as large as 3'' for Jupiter and 1'' for Saturn. The data presented in Table 3 were calculated for ground-based observations; in regard to space interferometers, the relevant calculations should be performed for their specific configurations.

CONCLUSIONS

We have calculated the circumstances of the approaches of solar system planets to astrometric radio sources for the time interval of 2008–2050. Especially interesting are the radio occultations for which the relativistic effects reach their maximum values. These occultations make it possible to measure the effects with minimum relative errors, which is a question of the utmost importance for testing gravity theories. One can efficiently use all of the planets from Venus to Saturn.

The present work demonstrates that the apparent approaches of planets to radio sources and even the radio occultations are not as rare of events as it is generally considered. The number of events in consider-

ation grows with the expansion of the list of ecliptic radio sources, thus increasing the possibilities to perform relevant experiments.

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