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Source and Event Selection for Radio-Planetary Frame-Tie Measurements Using the Phobos Landers

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The Soviet Phobos Lander mission will place two spacecraft on the Martian moon Phobos in 1989. Measurements of the range from Earth-based stations to the landers will allow an accurate determination of the ephemerides of Phobos and Mars. Delta VLBI between the landers and compact radio sources nearby on the sky will be used to obtain precise estimates of the angular offset between the radio and planetary reference frames. The accuracy of this frame-tie estimate is expected to be in the vicinity of 10 nrad, depending on how well several error sources can be controlled (calibrated or reduced). Many candidate radio sources for VLBI measurements have been identified, but additional work is necessary to select those sources which have characteristics appropriate to the present application. Strategies for performing the source selection are described below.

I. Introduction

The technique of Very Long Baseline Interferometry (VLBI) allows very precise navigation of spacecraft [1]. Radio transmissions from the spacecraft are received at two widely separated radio telescopes on the earth, and recorded on magnetic tape. The data from the two telescopes are later correlated. This allows the measurement of the delay in arrival time between the two telescopes of wavefronts from the spacecraft. This delay can be measured very accurately (much less than 1 nsec error). A compact extragalactic radio source nearby (typically 10 degrees or less away) on the sky is observed immediately before or after (or both before and after) the spacecraft observation. This procedure allows the location of the spacecraft on the sky to be measured very accurately (5–50 nanoradians) with respect to the radio source. Extensive VLBI observations at JPL over the last ten years have led to the development of a catalog of compact radio sources over the northern 75 percent of the sky, with positions accurate to 5–15 nanoradians (nrad), as described in [2]. The set of radio sources in this catalog forms what is known as the "radio frame." Because of the enormous distances (mostly more than 1 gigaparsec: 3×10^{22} km) of the objects in this catalog (the majority of which are quasars), their angular motions are negligible. Therefore, the radio frame is believed to be inertial and is stable at the approximate level of the measurement accuracy.

A VLBI measurement of a spacecraft with respect to any one of these compact radio sources (ΔVLBI) establishes the spacecraft position in the radio frame to an accuracy δ, where δ is the vector sum of the spacecraft–radio source measurement error and the source position error in the radio source catalog. The value of δ is as small as 15-25 nrad currently [1], with values of 5-10 nrad expected within 5 years. Most deep space navigation purposes require the location of a spacecraft with respect to a planet or natural satellite. To make optimum use of ΔVLBI for navigation, it is therefore necessary to measure the location of solar system objects in the radio frame, thus performing a "radio-planetary frame-tie." Currently, the accuracy of this frame-tie is approximately 200 nrad for the inner planets, and somewhat poorer for the outer planets [3]. An improvement in this value is critical for high-accuracy target-relative navigation by ΔVLBI.

II. The Phobos Lander Mission

The Soviet Phobos Lander Mission, scheduled for dual launches in July 1988, will land two spacecraft on the Martian moon Phobos in the spring of 1989. The spacecraft lifetime is estimated at 2-3 years. Ranging measurements between Earth and the landers will determine the orbit of Phobos around Mars (orbital period 7 hr 39 min) very precisely (much better than 5 nrad as seen from the earth). In addition, these measurements will improve our knowledge of the Martian orbit, which has been most accurately measured by ranging to the two Viking landers. Ranging measurements to a spacecraft fixed on the surface of a planet or a natural satellite are more useful than ranging measurements to a free-flying spacecraft because non-gravitational forces on a planet or natural satellite are negligible. This greatly reduces the number of parameters and the magnitude of systematic errors in the orbit determination process. With ranging data to the Viking Landers starting in 1976 and similar data to the Phobos Landers as late as 1991 or 1992, secular and long-period terms in the orbit of Mars can be well measured. This should allow the Martian orbit to be determined to about 5 nrad relative to the orbit of the earth around the sun.

The orbits of the earth and Mars will then form a planetary frame which is as accurate and stable as the radio frame, except for a very slow rotation of the planetary frame due to unmodeled effects such as unknown asteroid masses [4]. The orbits of other planets will be tied to this frame to variable accuracy (15-30 nrad for Venus; 200-400 nrad for the gas giants).

In addition to ephemeris improvement, the Phobos Lander Mission also provides the opportunity for accurate radio-planetary frame-tie measurements. Each lander will have a "VLBI broadcast mode," with two coherent tones spaced 14.71425 MHz apart on the downlink frequency of 1.7 GHz. Delta VLBI measurements of a lander and a compact radio source nearby on the sky can locate the lander and therefore Mars in the radio frame (this is possible because the positions of Phobos and Mars will be tied together to much less than 5 nrad). A cursory error analysis concludes that a measurement with an accuracy of 5-10 nrad can be obtained with a lander-radio source separation of 2 degrees or less, if adequate accuracy can be achieved in the calibration of instrumental phase errors in the ground system.[1] The error analysis assumed one measurement each of the lander and radio source, closely spaced in time. This separation is much less than for most current ΔVLBI measurements. Phobos Lander transmissions will be at a single frequency, which precludes direct calibration of the ionosphere or solar plasma. Furthermore, that frequency (1.7 GHz) is sufficiently low that phase errors due to charged particles in the ionosphere or solar plasma are large. For ΔVLBI measurements these errors are reduced, approximately by the spacecraft-radio source separation in radians.

Restricting ΔVLBI measurements to lander-radio source separations of less than 2 degrees is the most obvious technique for achieving high accuracy. However, it is not the only possible technique. Larger separations, with well-studied compact radio sources, could be used if several error sources (e.g., the troposphere, or charged particles) can be accurately calibrated. One possible technique is the local network approach [5], in which observations are made of several compact radio sources that are near the spacecraft on the sky. This process allows several atmospheric, earth orientation, and clock parameters to be determined from the data. These techniques (other than that of using small lander-source separations) will not be discussed further in this article. However, a careful error analysis is needed to determine their potential accuracy for Phobos Lander frame-tie measurements. A hybrid technique with fairly small lander-source separations and some calibration methods may prove to be optimum.

If small lander-source separations are used, it is necessary to begin the source selection process now. The Soviets will fix the lander transmission times in November 1987. Close passes between Mars and radio sources last for approximately 1 day or less time, and we must therefore determine all potential sources soon. There will be time between November 1987 and the arrival at Phobos to decide which of these sources (and what strategies) to use. For sources far (>5 degrees) from the path of Phobos, the lander-source distance changes proportionately much more slowly. The scheduling of observations is therefore much more flexible.

III. Source Selection

The ideal compact radio source for VLBI astrometry would be very strong (flux density >10 Jy), with all its emission concentrated within a region on the sky much smaller than 1 nrad

[1]C. E. Hildebrand, "First Cut at Phobos Lander VLBI Errors," IOM 335.1-87-29 (internal document), Jet Propulsion Laboratory, Pasadena, California, February 3, 1987.

diameter. In practice, there are no such sources. The extent to which actual radio sources deviate from this ideal introduces two types of error into VLBI measurements: statistical error and error due to source structure effects. The flux density (total power received at the earth per unit area and frequency interval) and the size of a radio source both influence the S/N of a VLBI measurement. For VLBI, the appropriate measure of source strength is the correlated flux density. Very approximately (usually within a factor of 2–3), the correlated flux density is the power received from a strip on the sky with a width one-half the fringe spacing and oriented perpendicular to the vector between the two telescopes (the baseline vector). For a pair of telescopes separated by a distance d, the fringe spacing is $\lambda/(d|\sin\theta|)$, where λ is the observing wavelength, and θ is the angle between the source direction and the baseline vector [6].

The ratio of correlated flux density to total flux density is defined as the visibility. The visibility is always between 0 and 1, with the larger values implying more compact sources. Many radio sources have visibilities of 0 on intercontinental baselines (source sizes much larger than the fringe spacing), a few have visibilities only slightly less than 1.0 (source sizes less than half a fringe spacing), and many others have values somewhere in between. The visibility is a function of baseline length, orientation, and observing frequency. It will not be the same on the two primary Deep Space Network (DSN) baselines (Spain–California and California–Australia). Actual visibilities can only be determined by VLBI observations, although other information (e.g., source spectral index or connected-element interferometry) can help in predicting visibilities.

The flux densities of compact radio sources vary with time, typically on time scales of a few years. At 8.4 GHz, this is an important effect, as sources can strengthen or weaken by a factor of 2 in 1–2 years. However, at 1.7 GHz, source variability is comparatively weak. In a period of 5 years, almost no sources will vary by more than 20 percent. Therefore, we need not worry about source variability for the Phobos Lander Mission.

The observing frequency for the Phobos Landers is 1.7 GHz. All of our VLBI catalog observations are at X-band (8.4 GHz) and S-band (2.3 GHz). Correlated flux densities of radio sources at 1.7 GHz will usually be within a factor of two of correlated flux densities at 2.3 GHz. For Phobos Lander frame-tie measurements, a source with 50 mJy correlated flux density provides an acceptably small statistical error, if we have two 70 m antennas and receivers with 56 MHz bandwidth. We have set a requirement of 100 mJy correlated flux density on intercontinental baselines, with a preference for sources with correlated flux densities of 200 mJy or greater.

In addition to reduction in S/N, a non-zero source size introduces systematic error. VLBI observations of a compact radio source will measure a source position that depends on baseline length and orientation. The dependence is complicated [7], but the magnitude of the effect can be estimated within a factor of 3–4 by making measurements of the correlated flux density at several hour angles on the baselines that will be used for frame-tie measurements. In general, sources with high visibilities (greater than about 0.5) have small source structure effects on astrometry: less than 5 nrad at 1.7 GHz. Sources with lowei visibilities may or may not have significant structure problems; it depends on the details of the structure. Correlated flux density measurements can be done during astrometric experiments on these sources, although extrapolating the effect from 2.3 GHz to 1.7 GHz introduces some uncertainty. We expect to discard between 10 percent and 30 percent of the candidate sources that have adequate correlated flux density, because those sources have structures which could cause unacceptable systematic errors.

A potential problem related to the source structure effect discussed above is the dependence of source position on observing frequency. Physically, this is due to the fact that lower frequency radiation arises from regions of lower particle energy and lower magnetic fields. Because there are strong spatial gradients of these properties in compact radio sources, and because most compact radio sources are strongly asymmetrical, the emission centroid varies with emission frequency. This effect has been observed to be as large as 10–15 nrad for 3C 273 between 10.7 GHz and 1.7 GHz. This is an extreme case (perhaps the largest of any source in the sky), and for almost all sources the effect will be less than 2–3 nrad. A source like 3C 273 can be identified (and removed from the catalog) by its low visibility ($\approx$0.1) on intercontinental baselines. We therefore expect that position shifts due to the lower observing frequency will not pose a major problem.

If the radio frame were based on astrometric observations at 1.7 GHz, this effect would not be important. However, the radio frame is based on 8.4 GHz observations (with 2.3 GHz observations for ionospheric calibration), so the position off set between 8.4 GHz and 1.7 GHz is important. More analysis is needed to estimate the magnitude of this effect, and to determine if it can be calibrated. It may be possible to hold the effect to an acceptable level by selecting very compact sources, which are identified by their high visibilities.

If a candidate source lies within 1–2 degrees of the path of Phobos on the sky and has acceptable correlated flux density and structure, it is suitable for a frame-tie measurement. However, before the final data analysis can be performed, it is necessary to determine the source position to 5–10 nrad by astrometric VLBI observations. This is a time-consuming process, and requires a large amount of antenna time. With the advent of wide-bandwidth recording capability at the DSN sites, substantially less antenna time will be needed. We may be able to obtain 5–10 nrad source positions for all successful candidates in 1–2 years, given adequate manpower and antenna time. However, accurate astrometry of candidate sources remains a problem, and obtaining 10 nrad source positions for all of them will be very difficult. We will probably have to settle for less accurate positions, or concentrate on a subset of the candidate sources.

Sources in the DSN Astrometric Catalog [2] have adequate correlated flux density on intercontinental baselines (greater than 250 mJy at S-band), and have positions known to 5–15 nrad. Table 1 presents the sources from that catalog which lie within 2 degrees of the path of Phobos between March 15, 1989, and May 1, 1992. Because Phobos is always within 30 sec of Mars on the sky, the ephemeris of Mars was used for this and all other source searches presented here. In Table 1, the epoch and distance of closest approach are given, along with the source name. The angular separation between Mars and the Sun at this epoch is also given. The relevance of this quantity is discussed in the section "Selection Among Candidate Events." The angular rate of motion of Mars on the sky at the epoch of closest approach is also listed. This value allows the Mars–radio source separation at nearby times to be easily calculated by the Pythagorean rule. (The path of Mars on the sky can be approximated as a straight line for short times.)

For several technical reasons, as discussed in the section "Selection Among Candidate Events," many apparently suitable candidate events may not be usable for frame-tie measurements. It is therefore desirable to search additional radio source catalogs in order to get more candidate events.

As a result of searches for navigation sources for various JPL missions (Voyager, Galileo, and Magellan), an ecliptic catalog of compact radio sources has been developed [8], [9]. These sources are compact, with correlated flux densities greater than about 100 mJy at S-band on intercontinental baselines. They should nearly all have greater than 100 mJy correlated flux density at 1.7 GHz, and are suitable for ΔVLBI measurements. However, astrometric VLBI observations have not yet been performed on these sources, and their positions are known only to about 1 arc second. Table 2 presents sources from this catalog which lie within 1 degree of the path of Mars in the period March 15, 1989, to May 1, 1992. The correlated flux densities of these sources at S-band on intercontinental baselines are given. For sources with multiple observations, the range of observed correlated flux densities is given.

A third useful set of radio sources is the VLA Calibrator Catalog. These sources are strong (more than 0.5 Jy) and usually dominated by moderately compact components (less than 1 sec in size). They have positions known to 0.3 sec or better. Their correlated flux densities on intercontinental baselines will be less than the catalog flux density by an amount that cannot be predicted for any given source. However, the correlated flux density will be at least 30 percent of the catalog flux density in many cases. Therefore, many of these sources will be good candidates for Phobos Lander frame-tie measurements. Table 3 presents sources from this catalog (and from additional sets of sources which have been observed with the VLA), which lie within 1 degree of the path of Mars in the period March 15, 1989, to May 1, 1992. Their 1.7 GHz flux densities are listed.

A fourth useful catalog of radio sources is the MIT–Green Bank Catalog [10]. This consists of approximately 6000 sources in the declination band 0 to 20 degrees, with total flux density at 5 GHz greater than 60 mJy. For many of these sources, there is little or no information beyond the total source flux density and the source position (30 arc seconds 1 σ uncertainty). Table 4 lists all sources from this catalog which lie within 30 arc minutes of the Martian trajectory from March 15, 1989, to May 1, 1992. Table 5 lists sources which lie between 30 arc minutes and one degree of the Martian trajectory for the same period. In both tables, only sources with a total 5 GHz flux density greater than 150 mJy are included, and the flux density is listed. Many of these sources will have compact components too weak to use for frame-tie measurements. Only interferometric observations can determine which are suitable.

Numerous sources are in more than one of the catalogs which were searched. Those sources (if they lie close to the orbit of Mars) are listed only once: with the first catalog in which they appear. (This is the catalog for which the most source information is known.)

IV. Selection Among Candidate Events

One parameter which is listed for all candidate events is the Mars–sun angle (the arc length on the sky between Mars and the sun) at the time of the event. Because the orbit of Mars lies outside the earth, and nearly in the plane of the ecliptic, this parameter uniquely specifies the solar impact parameter of the rays from both the radio source and the spacecraft. The solar impact parameter (smallest distance between the sun and the ray paths) determines to the first order the column density of solar plasma traversed by these rays. Due to the single frequency of the lander downlink, this plasma introduces measurement errors. These errors are estimated as 5 nrad average (with a large scatter) for a Mars–sun angle of 15 degrees, and nearly always less than 5 nrad for Mars–sun angles greater than 40 degrees.[1] We will therefore discard candidate events with Mars–sun angles less than 15 degrees and will give greater weight in our data analysis to events with angles greater than 30 degrees. By avoiding all events with Mars–sun angles less than 45 or 60 degrees the effects of solar plasma would be negligible. However, this would eliminate measurements over a substantial fraction of the Martian orbit, and reduce our ability to distinguish systematic errors.

Although the ionosphere and solar plasma are expected to cause the greatest transmission media effects, the troposphere is also of concern.[1] For a 1 degree elevation difference, tropospheric errors are estimated at 5 nrad if the source elevation is 12 degrees or less at either antenna. The use of spacecraft–radio source separations of 30 arc minutes or less can greatly alleviate this problem. In addition, we should attempt to schedule observations when the spacecraft and radio source are at 15 degrees or higher elevation at both antennas. Calibrations with water-vapor radiometers may be able to reduce tropospheric errors by a factor of three.[2]

Subject to the restrictions of source structure effects (discussed above) and of transmission times (discussed below), all sources in Tables 1 and 2 with sun–Mars angles greater than 15 degrees are suitable for frame-tie observations. The sources in Tables 3-5 require additional screening. Intercontinental VLBI observations of these sources are needed to determine if their correlated flux densities at 1.7 GHz are greater than the 100 mJy requirement, and to determine the magnitude of source structure problems.

Although the antennas will have steerable beams, the Soviets want to minimize antenna movement. Therefore, the antennas will probably have fixed orientations for periods of days or weeks. Their beams will sweep across the earth once per orbital period of Phobos (7.65 hr). The gain will be variable during this sweep, with the time between 3 dB points being 45 minutes if the earth passes through the center of the beam. In addition, the landers will not always be broadcasting in VLBI mode, but will be used for ranging and telemetry much of the time. We do not yet have a schedule for transmissions from the landers, and may not have such a schedule until after the landings on Phobos. In combination with the limited mutual visibility of radio sources on intercontinental baselines, these lander broadcast restrictions will eliminate some candidate frame-tie events. It is important to select a surplus of candidate events, as a substantial fraction (perhaps 50 percent to 80 percent) will prove unusable.

[2] S. E. Robinson, R. N. Treuhaft, B. L. Gary, and C. J. Vegos, "Tropospheric Wet Delay Calibrations for Magellan Navigation," IOM 335.3-87-79 (internal document), Jet Propulsion Laboratory, Pasadena, California, June 30, 1987.

One key quantity in any frame-tie measurement is the lander–radio source separation. As shown in IOM 335.1-87-29,[1] the static troposphere and the ionospheric variations can introduce errors greater than 5 nrad for elevation differences between lander and radio source as small as 1 degree. Because of the large longitude differences between the two stations of DSN intercontinental baselines, the elevation difference for at least one site will almost always be greater than one-half the spacecraft–radio source separation. Therefore, frame-tie measurements with spacecraft–radio source separations less than 1 degree are strongly preferred, and separations less than 30 arc minutes are desired.

The situation is more complicated than this, however. Unless the lander–radio source separation is less than the primary beam size of one antenna (10 min), the lander and radio source cannot be observed simultaneously. One will move across the sky due to sidereal motion (15 arc minutes per minute of time) while the other is being observed. Depending on the relative positions of the lander and radio source on the sky, this motion may increase or decrease the elevation difference. The observing sequence can be chosen to minimize the difference. Alternatively, a more complicated observing sequence (lander/radio source/lander or radio source/lander/radio source) can be used. This will allow a measurement of the linear component in the spatial and time variation in the troposphere and ionosphere.

In order to tie together two spherical coordinate systems, three parameters are needed. These can be thought of as resulting from the alignment of a reference point in the two systems (2 parameters), and then performing a rotation about this fixed point to align the remaining points (1 parameter). Two spacecraft–radio source measurements suffice, in principle, to determine these 3 parameters. However, if the two radio sources are close together (<20–30 degrees) or nearly opposite (>150–160 degrees) on the sky, the third parameter (rotation) is poorly determined. Two widely spaced measurements are needed. In practice, it is desirable to have many more than two measurements to reduce statistical measurement error. More importantly, multiple measurements over as much of the Martian trajectory as possible can allow an analysis of systematic errors, such as source structure effects, ionospheric perturbations, or even irregularities in either the planetary or radio reference frames.

V. Summary

Many candidate events for frame-tie measurements have been found. In order to determine which events to use, the following procedure will be adopted:

(1) Short-baseline VLBI observations will be performed on those sources not previously observed interferometrically. These observations will eliminate sources with sizes greater than 200 nrad, and will reduce the position errors of MIT-GB sources by a factor of about 100.

(2) Sources that have survived this sieving process will be observed on intercontinental baselines at 1.7 or 2.3 GHz. This will determine the correlated flux density, and will allow an estimate of the source structure effects on astrometry.

(3) Among sources close to the path of Mars, and which have sufficient correlated flux density, additional screening will be done. Sources with low or variable visibilities (suggesting source structure problems) will be eliminated. Preference will be given to sources with the following properties: more than 200 mJy correlated flux density, a Mars-sun angle greater than 30 degrees, a Mars-radio source separation of less than 30 arc minutes, and a source position that is already well known from astrometric VLBI measurements. Additionally, an attempt will be made to select events which are uniformly spaced along the orbit of Mars.

(4) Astrometric VLBI observations of the selected sources will be started. These observations will not be finished when some of the actual frame-tie observations are made, but will be needed for the final data analysis.

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Table 1. Close passes (<2 degrees) between Mars and the DSN Astrometric Catalog, 3/15/89–5/1/92

Date	UT	Source	Closest Approach (arc min)	Sun–Planet Angle (deg)	Angular Speed of Mars (arc min/hr)
1989 Jun. 7	18:14	B2 0745+24	93	38	1.6
1989 Jul. 3	04:58	OJ 287	82	29	1.6
1989 Aug. 1	16:48	GC 1004+14	69	20	1.6
1989 Oct. 12	15:53	3C 279	30	4	1.6
1989 Nov. 4	16:03	P 1352–104	29	12	1.7
1989 Dec. 2	02:54	P 1504–167	21	21	1.7
1990 Jan. 26	21:03	1748–253	99	39	1.8
1990 Apr. 12	05:34	OX–173	34	59	1.9
1990 Apr. 15	23:47	OX–192	65	59	1.9
1990 Jun. 28	17:50	GC 0119+04	114	76	1.7
1990 Jul. 16	15:10	P 0201+113	68	81	1.7
1990 Aug. 26	06:31	0341+158	114	96	1.3
1991 May 17	02:38	B2 0745+24	77	59	1.4
1991 Jun. 13	01:54	OJ 287	74	49	1.5
1991 Jul. 13	15:32	GC 1004+14	68	38	1.5
1991 Sep. 24	09:43	3C 279	18	14	1.6
1991 Oct. 17	06:26	P 1352–104	43	7	1.7
1991 Nov. 13	08:28	P 1504–167	36	1	1.7
1992 Jan. 6	19:09	1748–253	87	18	1.8
1992 Mar. 19	17:27	OX–173	43	36	1.9
1992 Mar. 23	08:24	OX–192	76	37	1.9
1992 Apr. 23	04:47	P 2320–035	115	43	1.9

Table 2. Close passes (<1 degree) between Mars and the DSN Ecliptic Catalog, 3/15/89–5/1/92

Date	UT	Source	Closest Approach (arc min)	Sun–Planet Angle (deg)	Angular Speed of Mars (arc min/hr)	Correlated Flux Density at S-band (mJy)
1989 Mar. 20	02:02	0409+22	34	66	1.5	210
1989 Mar. 25	10:42	0423+233	23	64	1.5	170
1989 Apr. 28	18:41	0556+238	55	51	1.5	240
1989 Apr. 30	18:16	0601+244	19	51	1.5	100
1989 Jun. 14	20:39	GC 0802+21	30	35	1.6	240
1989 Jun. 29	05:35	GC 0839+18	54	30	1.6	420
1989 Sep. 19	14:15	P 1158+007	17	3	1.6	140
1989 Sep. 20	21:02	P 1203+011	34	3	1.6	110
1989 Sep. 26	18:43	1216–010	11	1	1.6	150
1989 Oct. 2	03:39	P 1229–021	12	1	1.6	120
1989 Nov. 5	12:58	P 1354–107	21	12	1.7	90
1989 Nov. 22	10:16	P 1437–153	20	18	1.7	110
1989 Nov. 24	20:52	P 1443–162	47	19	1.7	330
1989 Nov. 25	14:01	P 1445–16	28	19	1.7	(350,530)
1990 Apr. 6	20:52	P 2126–15	30	57	1.9	130
1990 Apr. 20	17:56	P 2208–137	41	61	1.9	(130,260)
1990 Apr. 26	04:06	2223–114	13	62	1.9	(250,400)
1990 May 6	09:41	2252–090	3	64	1.9	(140,380)
1990 Jun. 5	01:26	0013–00	5	71	1.8	(230,330)
1990 Jun. 17	06:53	P 0047+023	30	74	1.8	(140,210)
1990 Jul. 27	09:51	0229+13	34	84	1.6	(220,480)
1990 Aug. 15	19:16	CTA 21	9	91	1.4	122
1990 Sep. 21	20:11	P 0428+20	7	109	0.9	130
1990 Nov. 19	08:25	GC 0423+23	41	168	0.9	170
1990 Nov. 27	23:36	0409+22	26	178	0.9	210
1991 Feb. 8	10:22	0409+22	25	106	0.9	210
1991 Feb. 17	03:06	GC 0423+23	32	101	1.0	170
1991 Mar. 8	02:25	0459+252	21	90	1.2	240
1991 Apr. 4	22:39	0601+244	51	76	1.3	100
1991 May 24	17:40	GC 0802+21	44	56	1.5	240
1991 Sep. 1	07:19	P 1158+007	8	21	1.6	140
1991 Sep. 2	14:09	P 1203+011	43	21	1.6	110
1991 Sep. 8	12:28	1216–010	1	19	1.6	150
1991 Sep. 10	09:11	P 1218–02	59	19	1.6	120
1991 Sep. 13	21:35	P 1229–021	22	18	1.6	120
1991 Oct. 18	03:09	P 1354–107	34	7	1.7	90
1991 Nov. 1	18:42	P 1430–155	52	2	1.7	(120,230)
1991 Nov. 3	19:32	P 1437–153	5	1	1.7	110
1991 Nov. 6	05:16	P 1443–162	33	1	1.7	330
1991 Nov. 6	22:08	P 1445–16	14	1	1.7	(350,530)
1992 Mar. 14	13:29	P 2126–15	23	35	1.9	130
1992 Mar. 27	22:41	P 2208–137	55	38	1.9	(130,260)
1992 Apr. 2	04:30	2223–114	3	39	1.9	(250,400)
1992 Apr. 12	01:01	2252–090	24	41	1.9	(140,380)

Table 3. Close passes (<1 degree) between Mars and VLA Catalog sources, 3/15/89–5/1/92

Date	UT	Source	Closest Approach (arc min)	Sun–Planet Angle (deg)	Angular Speed of Mars (arc min/hr)	Sub-arc-sec Component Flux Density (mJy)
1989 Jul. 6	02:36	MG0900+1831	15	28	1.6	110*
1989 Aug. 28	04:34	MG1109+0659	31	11	1.6	200*
1989 Sep. 15	04:57	MG1150+0115	40	5	1.6	130*
1989 Sep. 21	20:01	MG1208+0054	51	3	1.6	200*
1989 Oct. 7	05:16	1242–047	56	3	1.6	3400‡
1989 Nov. 24	20:45	1445–164	47	19	1.7	510†
1990 Jan. 5	12:15	1646–224	2	32	1.8	1900‡
1990 Jun. 7	07:17	0022+002	4	71	1.8	2700†
1990 Jul. 18	20:36	MG0211+1051	9	82	1.7	200*
1991 Jun. 16	03:03	MG0900+1831	8	48	1.5	110*
1991 Aug. 9	16:20	MG1109+0659	35	29	1.6	200*
1991 Aug. 27	21:27	MG1150+0115	32	23	1.6	130*
1991 Sep. 18	23:22	1242–047	45	16	1.6	3400‡
1991 Nov. 1	18:31	1433–158	52	2	1.7	400†
1991 Dec. 17	00:19	1646–224	12	12	1.8	1900‡

*Flux density in sub-arc-second component at 5 GHz.
†Flux density in sub-arc-second component at 1.7 GHz.
‡Flux density at 1.7 GHz, but not all in a compact component.

Table 4. Close passes (<30 arc min) between Mars and MIT–GB Catalog, 3/15/89–5/1/92

Date	UT	Source	Closest Approach (arc min)	Sun–Planet Angle (deg)	Total Flux Density at 5 GHz (mJy)	Angular Speed of Mars (arc min/hr)
1989 Jul. 9	17:33	MG0909+1751*	15	27	164	1.6
1989 Jul. 11	12:56	MG0914+1715*	1	26	458	1.6
1989 Jul. 12	16:55	MG0917+1717*	15	26	159	1.6
1989 Jul. 24	08:50	MG0945+1428*	14	22	237	1.6
1989 Jul. 26	03:57	MG0950+1419*	1	22	1451	1.6
1989 Jul. 26	16:38	MG0950+1344	29	21	163	1.6
1989 Aug. 2	05:48	MG1007+1248*	4	19	417	1.6
1989 Aug. 3	14:15	MG1010+1235*	9	19	164	1.6
1989 Aug. 5	10:30	MG1015+1227	28	18	292	1.6
1989 Aug. 14	11:47	MG1036+0956*	2	15	470	1.6
1989 Aug. 25	21:51	MG1104+0730	27	12	231	1.6
1989 Sep. 3	17:48	MG1124+0456*	5	9	393	1.6
1989 Sep. 7	20:38	MG1134+0358*	12	7	151	1.6
1989 Sep. 11	10:10	MG1142+0235*	17	6	172	1.6
1989 Sep. 24	10:22	MG1213–0013*	21	2	225	1.6
1990 Jun. 11	15:56	MG0034+0118*	13	72	208	1.8
1990 Jun. 21	12:08	MG0100+0417*	4	74	163	1.8
1990 Jun. 30	21:56	MG0125+0617*	26	77	206	1.7
1990 Jul. 3	04:30	MG0131+0703*	15	78	206	1.7
1990 Jul. 5	04:13	MG0135+0810*	26	78	704	1.7
1990 Jul. 10	09:04	MG0148+0927*	26	79	150	1.7
1990 Jul. 21	00:36	MG0217+1103*	27	82	480	1.6
1990 Jul. 22	11:42	MG0220+1121*	29	83	481	1.6
1990 Jul. 28	17:37	MG0235+1304	2	85	225	1.6
1990 Aug. 1	03:21	MG0244+1320	27	86	259	1.6
1990 Aug. 26	04:41	MG0342+1736*	14	95	162	1.3
1990 Aug. 28	17:40	MG0347+1749*	20	97	285	1.3
1990 Sep. 2	06:17	MG0356+1900*	19	99	371	1.2
1990 Sep. 5	04:49	MG0402+1929*	29	100	348	1.2
1991 Jun. 19	21:46	MG0909+1751*	9	46	164	1.5
1991 Jun. 21	19:00	MG0914+1715*	7	46	458	1.5
1991 Jun. 23	00:02	MG0917+1717*	10	45	159	1.5
1991 Jul. 5	02:02	MG0945+1428*	17	41	237	1.5
1991 Jul. 6	22:26	MG0950+1419*	1	40	1451	1.5
1991 Jul. 14	05:08	MG1007+1248*	4	38	417	1.5
1991 Jul. 15	14:25	MG1010+1235*	9	37	164	1.5
1991 Jul. 17	11:43	MG1015+1227	28	37	292	1.5
1991 Jul. 26	18:01	MG1036+0956*	4	34	470	1.6
1991 Aug. 16	07:39	MG1124+0456*	11	27	393	1.6
1991 Aug. 20	11:31	MG1134+0358*	19	26	151	1.6
1991 Aug. 24	01:54	MG1142+0235*	10	24	172	1.6

*VLA observations made after this article was submitted have shown that these sources have inadequate compact flux density for ΔVLBI observations.

Table 5. Close passes (30–59 arc min) between Mars and MIT–GB Catalog, 3/15/89–5/1/92

Date	UT	Source	Closest Approach (arc min)	Sun–Planet Angle (deg)	Total Flux Density at 5 GHz (mJy)	Angular Speed of Mars (arc min/hr)
1989 Jul. 5	01:48	MG0856+1739*	50	28	150	1.6
1989 Jul. 9	11:38	MG0909+1821*	44	27	306	1.6
1989 Jul. 10	13:42	MG0910+1650*	39	27	158	1.6
1989 Jul. 15	22:30	MG0925+1658	35	25	191	1.6
1989 Jul. 30	01:18	MG1000+1401*	36	20	514	1.6
1989 Jul. 31	22:09	MG1002+1215	50	20	284	1.6
1989 Aug. 1	12:19	MG1004+1207	51	20	167	1.6
1989 Aug. 8	02:01	MG1020+1039*	48	17	166	1.6
1989 Aug. 12	18:30	MG1034+1112*	58	16	464	1.6
1989 Aug. 13	17:43	MG1036+1052	52	16	201	1.6
1989 Aug. 19	16:33	MG1050+0926*	52	14	153	1.6
1989 Aug. 28	22:00	MG1109+0543	39	11	184	1.6
1989 Sep. 6	08:15	MG1131+0456*	50	8	205	1.6
1989 Sep. 12	03:42	MG1142+0154*	50	6	218	1.6
1989 Sep. 21	03:09	MG1204–0029*	53	3	184	1.6
1990 Jun. 18	13:08	MG0051+0358*	36	74	234	1.8
1990 Jun. 23	04:42	MG0103+0521	43	75	183	1.8
1990 Jul. 2	22:22	MG0131+0623*	53	77	545	1.7
1990 Jul. 17	06:38	MG0205+1134*	59	81	186	1.7
1990 Jul. 20	04:47	MG0213+1212	57	82	180	1.6
1990 Jul. 24	07:57	MG0225+1134	40	83	387	1.6
1990 Jul. 30	19:12	MG0241+1253*	39	86	189	1.6
1990 Jul. 30	20:40	MG0242+1248	45	86	161	1.6
1990 Aug. 11	06:24	MG0307+1609*	36	89	170	1.5
1990 Aug. 13	12:09	MG0314+1508*	51	90	187	1.5
1990 Aug. 23	20:51	MG0338+1634*	58	94	166	1.3
1990 Aug. 31	00:16	MG0352+1754	32	98	248	1.3
1990 Sep. 10	06:15	MG0412+1856	36	103	248	1.1
1991 Jun. 15	01:27	MG0856+1739*	58	48	150	1.5
1991 Jun. 19	15:27	MG0909+1821*	38	46	306	1.5
1991 Jun. 20	19:00	MG0910+1650*	45	46	158	1.5
1991 Jun. 23	18:22	MG0920+1753	56	45	353	1.5
1991 Jun. 26	08:31	MG0925+1658	30	44	191	1.5
1991 Jul. 7	11:38	MG0950+1344	31	40	163	1.5
1991 Jul. 10	22:24	MG1000+1401*	35	39	514	1.5
1991 Jul. 12	20:50	MG1002+1215	51	38	284	1.5
1991 Jul. 13	11:24	MG1004+1207	52	38	167	1.5
1991 Jul. 20	05:03	MG1020+1039*	47	36	166	1.5
1991 Jul. 25	23:24	MG1036+1052	54	34	201	1.5
1991 Aug. 1	01:00	MG1050+0926*	55	32	153	1.6
1991 Aug. 7	08:51	MG1104+0730	31	30	231	1.6
1991 Aug. 9	15:43	MG1107+0533*	59	29	285	1.6
1991 Aug. 10	10:13	MG1109+0543	35	29	184	1.6
1991 Aug. 15	00:23	MG1119+0410	59	27	235	1.6
1991 Aug. 18	22:39	MG1131+0456*	56	26	205	1.6
1991 Aug. 24	19:40	MG1142+0154*	42	24	218	1.6
1991 Sep. 1	01:29	MG1159–0015*	59	22	225	1.6
1991 Sep. 2	20:30	MG1204–0029*	44	21	184	1.6
1991 Sep. 6	03:53	MG1213–0013*	31	20	225	1.6

*VLA observations made after this article was submitted have shown that these sources have inadequate compact flux density for ΔVLBI observations.