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The Search for Reference Sources for ΔVLBI Navigation of the Galileo Spacecraft

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A comprehensive search has been made in order to identify celestial radio sources that can be used as references for navigation of the Galileo spacecraft by means of ΔVLBI observations. The astronomical literature has been searched for potential navigation sources, and several VLBI experiments have been performed to determine the suitability of those sources for navigation. This article reports on the results of such work performed since mid-1983. We present a summary of the source properties required, the procedures used to identify candidate sources, and the results of the observations of these sources. The lists of sources presented are not meant to be taken directly and used for ΔVLBI navigation, but they do provide a means of identifying the radio sources that could be used at various positions along the Galileo trajectory. Since the reference sources nearest the critical points of Jupiter encounter and probe release are rather weak, it would be extremely beneficial to use a pair of 70-m antennas for the ΔVLBI measurements.

I. Introduction

The Galileo spacecraft is scheduled to be launched in May 1986 on a mission to explore Jupiter and its satellites. On the way to Jupiter, it will fly past the asteroid Amphitrite. In July 1988, an atmospheric probe will be released from the main spacecraft bus. This passive probe will follow a path that diverges slightly from that of the orbiter. Both the probe and the orbiter are scheduled to arrive at Jupiter in December 1988. While the orbiter will make a tour of the Jovian system that is scheduled to last for approximately two years after the planetary encounter, the probe will enter the atmosphere and survive for about an hour.

Current plans call for ΔVLBI (VLBI = Very Long Baseline Interferometry) navigation to be used to help determine the spacecraft trajectory precisely The ΔVLBI observables are sensitive to position in the plane of the sky rather than to radial distance or velocity. As such, they can be complementary to the more traditional Doppler and ranging data. The increased accuracy afforded by including the ΔVLBI data will help conserve fuel during the tour of the Jovian system and will be especially useful in reconstructing the trajectory of the atmospheric probe. The more accurate trajectory reconstruction will allow a more detailed specification of the properties of Jupiter's atmosphere.

The basic principle of ΔVLBI navigation is to use two widely separated Deep Space Network (DSN) stations to find the angular separation between a spacecraft and a natural radio source, usually a quasar. The two stations are used as an interferometer and can acquire observables (phase and phase-delay rate) that depend on the geometry of the baseline connecting the stations, the quasar and spacecraft positions, the station clocks, and the Earth's atmosphere. Observed phase is used to reconstruct signal path delay, which in turn is a measure of source angular position. Observations from two baselines are needed to determine both components of angular position. By making sequential VLBI observations of the spacecraft and a quasar, the effects of a number of imperfectly known quantities can be reduced by differencing the observables. Since the quasar position has been determined previously in an inertial frame of radio sources, the JPL VLBI catalogue (Ref. 1), the angular position of the spacecraft is tied to an inertial frame. An important point to recognize is that the accuracy of the ΔVLBI results depends nonlinearly on the angular separation between the spacecraft and the natural radio source. Larger separations imply less complete cancellation of some errors and a less precise determination of the spacecraft position.

II. Searching for Suitable ΔVLBI Reference Sources

A. Identification of Candidate Sources

Jupiter's sidereal period of revolution is nearly 12 yr. Therefore, both Jupiter and the Galileo spacecraft will traverse a large portion of the ecliptic plane during the approximately 4-yr lifetime of the mission. Since the most accurate ΔVLBI navigation requires radio sources as close as possible to the spacecraft, a net of reference sources located along the ecliptic plane is needed.

A set of criteria for suitable reference source candidates is based on the properties of the ΔVLBI navigation system. The system in use is called the Block I system. It involves the recording and real-time transmission of VLBI data in a 250-kHz observing channel. This bandwidth, the maximum achievable coherent integration time (about 10 min), and the properties of the DSN 70-m antennas (to be upgraded from 64 m) can be combined to estimate the minimum correlated flux density for a usable VLBI navigation source; detailed error analysis has been performed in JPL Engineering Memorandum 335-26.[1] If corrections for propagation errors caused by charged particles in the ionosphere are to be made, observations at both S and X bands (2.3 and 8.4 GHz, respectively) are needed. This requires the reference source's correlated flux density to be at least 0.25 Jy (1 Jy = 10^{-26} W · m^{-2} · Hz^{-1}) in each band for a pair of 70-m antennas. For the combination of a 70-m and a 34-m antenna, the required correlated flux density would be close to 0 5 Jy.

Counts of sources as a function of total flux density at different frequencies have been made by astrophysicists studying the distribution and evolution of radio sources in the universe (e.g., Ref. 2). In the strip of sky within 10° of the ecliptic plane, there should be a source with a total flux density of at least 0.25 Jy at 5 GHz about every 0.7° in ecliptic longitude. (Most radio astronomy surveys and source counts have been made at 1.4 or 5 GHz, not at the 2.3- and 8.4-GHz frequencies used by the DSN.) However, most natural radio sources are heavily resolved by interferometers with intercontinental separations. The fringe spacing (resolution element) of an interferometer with a 10,000-km baseline is about 0.7 milliarcseconds (3 6 nanoradians) at X band. Only sources having more than 0.25 Jy in structure that is unresolved by such an interferometer are suitable as Block I ΔVLBI navigation references Since very few extragalactic radio sources have more than half their total flux density in such compact structure, and most have considerably less, the density of reference sources is much lower than indicated by the total flux densities alone.

Typical extragalactic radio sources have "steep" spectra in which the flux density decreases with increasing frequency. However, some sources have relatively "flat" or "inverted" spectra, with the total flux density remaining fairly constant or even increasing with increasing frequency in the 1- to 10-GHz spectral range. It has long been known that such sources have a far higher probability of being very compact than do the steep spectrum sources, so these sources are the best candidates for ΔVLBI navigation. However, the most compact sources are also the most variable at X band (S band fluxes remain relatively constant).

The selection of candidate ΔVLBI reference sources proceeded based on the knowledge of system and source characteristics outlined above. Surveys of the northern and southern skies complete to flux densities of 0.5–0.6 Jy at 2.7 or 5 GHz were made in the 1960s and early 1970s (e.g., Refs. 3 and 4). Objects that appeared in these surveys were potential candidates for use as Block I ΔVLBI navigation sources. The astronomical literature was searched in order to find any available information on the radio structure and spectrum of the sources within 20 deg of the Galileo trajectory. Many were found to have most of their flux in components resolved on scales of arcseconds to arcminutes. Of the remaining sources, some had little structural information available, while some were known to have more than 0.25 Jy in components less than about an arcsecond in size. These sources were chosen as potential ΔVLBI navigation sources deserving further investigation.

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[1] Thomas, J.B., "An Error Analysis for Galileo Angular Position Measurements with the Block I ΔDOR System," JPL Engineering Memorandum 335-26, 1981 (JPL internal document).

Preference was given to sources with flat radio spectra, as they are most likely to contain very compact components.

B. VLBI Observations of Candidate Radio Sources

Some of the candidate sources were already part of the JPL VLBI catalogue, and others had been observed prior to mid-1983. Thus, accurate positions and typical correlated flux densities were known. The other candidate sources were observed in several short baseline Mark II VLBI experiments, using the 40-m antenna at Caltech's Owens Valley Radio Observatory (OVRO) and the 26-m DSS 13 in the Goldstone complex as the two observing stations. Data were eventually obtained on all the good candidate sources along the Galileo trajectory. Typically, the available data on a given source include two or three observations of about 10-min duration at different hour angles on a single day. Since OVRO's S/X receiver is uncooled, its system temperatures were about 6 times the system temperature of 25 K for DSS 13. The Mark II system has a usable bandwidth of 1.8 MHz, so the OVRO–DSS 13 baseline was about a factor of two less sensitive than a baseline with two 70-m DSN antennas and the Block I VLBI system.

Data from the observations were processed on the Caltech/JPL Block 0 VLBI correlator. The main information extracted from post-correlation software was correlated flux densities at S and X bands and improved positions for the detected sources. The OVRO–DSS 13 baseline is approximately 250 km in length, yielding a fringe spacing of about 30 milliarcseconds at X band. Thus, presence of a correlated flux density greater than 0.25 Jy at both S and X bands on this baseline is a necessary but not a sufficient condition for a source to be deemed suitable for ΔVLBI navigation. Instead, those radio sources with at least 0.25 Jy in correlated flux on the 250-km baseline need to be observed on an intercontinental baseline to see if they have enough correlated flux on a 10,000-km baseline. As expected, the limiting factor for most sources is their weakness at X band. The total flux density at that frequency is less than at S band for the typical steep radio spectra, and the smaller fringe spacings at X band usually resolve a larger fraction of the total flux than at S band.

III. Observational Results

Results from the search for suitable ΔVLBI sources are presented in Tables 1 through 3. The sources in these tables are arranged in order of increasing right ascension, with the zero point shifted to be near the beginning of the Galileo trajectory. Table 1 lists sources currently in the JPL VLBI catalogue that might be usable reference sources for Galileo navigation. Included in the table are the source names, their positions, the typical correlated flux densities at S and X bands on intercontinental baselines, and the minimum angular distance between each source and the spacecraft trajectory. It should be noted that some of these sources may not be suitable ΔVLBI references. Most have variable flux densities that may fall below the flux density threshold at which consistent detection can be expected, and some have structure that can cause them to have insufficient correlated flux densities when observed with some projected baselines.

Table 2 lists sources observed on the OVRO–DSS 13 baseline. In addition to the columns used in Table 1, the epoch of the short baseline observations is given here. The correlated flux densities listed are those found on the baseline within California and are larger than the correlated flux densities that would be found on intercontinental baselines. Table 2 is divided into two parts. First, we list those sources that were detected at both bands; then we list the sources that were undetected in one or both observing bands. The latter radio sources definitely will not have sufficient flux on intercontinental baselines to be used for navigation. Sources in the top half of the table cannot be ruled out on the basis of the short baseline observations alone, but further information is required to determine whether they can be used as navigation references. Separations from the Galileo trajectory are listed only for sources that were detected in at least one of the two observing bands. Typical position errors in this table are on the order of 5 arcseconds, compared to the milliarcsecond positional accuracy for most of the sources listed in Table 1.

Table 3 lists the sources that were selected from previous short baseline observations or from the astronomical literature and were observed in a long baseline experiment between DSS 13 and DSS 63 (the 64-m antenna in Spain) in November 1983. Several of these sources are part of the JPL VLBI catalogue and are also listed in Table 1. The correlated flux densities listed in Table 3 are those that were found on the nearly east–west intercontinental baseline. Values on the baseline between California and Australia could be higher or lower, depending on the structures of the individual sources. Positions listed in Table 3 have a typical accuracy of several tenths of an arcsecond

A shortage of suitable ΔVLBI sources still exists near some critical parts of the Galileo trajectory. Figure 1 displays the Galileo trajectory from 1986 through 1991. The hatched regions are those within 10° of a radio source that has a high probability of being a usable navigation reference. Figure 2 is a blow-up of the section of the trajectory including probe release and Jupiter encounter, with 10°-radius circles plotted for the reference sources that can be used with a reasonable expectation of success. The radio source GC 0406+12 (not plotted) is the candidate reference source for ΔVLBI nearest the positions of probe release and Jupiter encounter, but it often has a correlated flux density below 0.2 Jy at X band. We have concentrated our greatest efforts on finding reference sources in this region, but the results are not encouraging. Another region of potential importance is near the position of Jupiter in late 1989 and early 1990. This area is in a part of the ecliptic which intersects the galactic plane. Since regions within 10 deg of the galactic plane generally have not been surveyed for radio sources, few potential navigation sources have been identified in this area. It is a region that would be very important if the Galileo launch were delayed by about 18 months, as it would then be the location of probe release and initial Jupiter encounter.

It must be re-emphasized that navigation sources should not be selected from these tables without consultation with the VLBI Systems Group. The natural radio sources have variable flux densities; new information about the sources is being acquired by a variety of means; and positions of the sources are frequently updated and refined.

IV. Continuing Investigations

Two approaches are being taken currently in an effort to find more ΔVLBI navigation sources for Galileo. These approaches utilize radio source surveys which have been and are being made by astronomers not connected with JPL. A few of the sources identified in these surveys have some potential as navigation reference sources, so we are attempting to investigate them further. Neither of the ongoing investigations is very likely to yield any sources that would be better than those already known. However, the effort is continuing because of the high value of even a single usable navigation source if it is located in the right place.

The first of the continuing investigations utilizes a sensitive sky survey being performed by the radio astronomy group of the Massachusetts Institute of Technology (MIT) using the 91-m telescope of the National Radio Astronomy Observatory (NRAO), located in Green Bank, West Virginia. This survey will be complete to a limiting total flux density of about 0.1 Jy at 5 GHz. The MIT-Green Bank survey includes many sources that were not previously known because they are weaker than the 0.5–0.6 Jy completeness limits of previous surveys. Conceivably, one or more of these sources could have enough compact flux to be suitable navigation reference sources. The survey also includes some sources that have increased their flux densities in the last 10–20 yr, and now have somewhat more than 0.5 Jy at 5 GHz.

The portion of the sky survey between $-0.^{\circ}5$ and $+19.^{\circ}5$ declination has been completed by the MIT group (Ref. 5). This includes the region south of the ecliptic near the position where Galileo encounters Jupiter. The survey has been used by JPL to select many of the sources that were investigated on the OVRO–DSS 13 baseline in August 1985. It is encouraging that the two sources nearest the critical encounter and probe release position, 0341+158 and 0342+147, were both detected at S and X bands in each of three scans. Observations of these sources have been made recently (in September 1985) on intercontinental baselines; the data from that experiment have not yet been analyzed. Intercontinental-baseline observations of several of the other sources listed in Table 2 are tentatively planned for the future.

The second ongoing investigation involves a recent low-frequency survey for scintillating sources in some regions of the galactic plane. This survey was made by a non-JPL group using the Ooty radio telescope in India (Ref. 6). Sources that were found to scintillate by the Ooty group are those that contain components less than an arcsecond in size. It is possible that one or several of these sources could be used for VLBI navigation in the region where the ecliptic intersects the galactic plane. The Indian group has already observed some of the sources with sub-arcsecond resolution at NRAO's Very Large Array (VLA) in New Mexico. We have collaborated with them on a proposal to observe the remaining sources with the VLA. The proposed observations would provide enough knowledge about the radio sources to judge whether any have enough potential as ΔVLBI navigation sources to be investigated on intercontinental baselines.

V. Summary and Speculations for the Future

An extensive search for potential ΔVLBI navigation sources for the Galileo spacecraft has been performed. This search has involved both investigation of the astronomical literature and new interferometric observations of a number of natural radio sources. The investigation of many radio sources in the ecliptic has also provided information that could be used in the navigation of other planetary exploration spacecraft in the future. Unfortunately, the distribution of strong, ultra-compact radio sources is such that there is apparently a lack of strong navigation sources near some critical parts of the Galileo trajectory. It is unlikely that any more suitable sources will be found in these critical regions. Since it is desirable to have reference sources near the spacecraft trajectory in order to provide the best navigation accuracy, it may be advantageous to use some sources whose correlated flux densities are too low to be detected consistently with the combination of a 34-m and a 70-m antenna. Therefore, it will be necessary to use two 70-m antennas if ΔVLBI observations utilizing these weak sources are attempted.

Improved navigation of future missions by the use of reference sources within a few degrees of the spacecraft would require increased sensitivity of the ΔVLBI observations. Such an improvement in sensitivity could be achieved either with larger receiving antennas or by using a wider bandwidth VLBI system. The Mark III system currently used in astronomy has a maximum bandwidth of 56 MHz, more than 200 times that currently employed in the Block I system. This bandwidth is too high for a real-time VLBI system with satellite transmission of data. However, it could be useful for non-real-time work in such tasks as reconstructing trajectories of spacecraft and probes after the fact. A real-time system with an intermediate bandwidth of 5 MHz would provide nearly 5 times the sensitivity of the Block I system. This would allow ΔVLBI to be done with two 70-m antennas for sources having correlated flux densities above 0.05 Jy.

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Table 1. Potential Galileo ΔVLBI sources in the JPL VLBI catalogue

IAU name	Other name	Position (1950.0)		Correlated flux, Jy		D_{min}, deg
		Right ascension, 00^h 00^m 00.^{s}0000	Declination, 00° 00’ 00 ”000	S band	X band	
2155–152	OX-192	21 55 23.2414	–15 15 30 070	0.55	0.49	16 8
2216–038	P 2216–03	22 16 16.3814	–03 50 40.606	0.74	1.78	11.2
2223–052	3C 446	22 23 11 0774	–05 12.17.778	0.78	1.15	9.1
2243–123	OY–172.6	22 43 39.7925	–12 22 40.273	1.24	0.79	5 4
2320–035	P 2320–035	23 20 57.5248	–03 33 33.613	0.52	0.29	1.8
2345–167	P 2345–16	23 45 27.6822	–16 47 52.585	1.8	0.42	12 5
0019+058	P 0019+058	00 19 58.0233	05 51 26 473	0.43	0.41	4 7
0048–097	P 0048–09	00 48 09.9825	–09 45 24.237	0.83	0 73	12 7
0106+013	P 0106+01	01 06 04 5175	01 19 01.161	2.51	0.76	4.3
0119+041	GC 0119+04	01 19 21.3925	04 06 44.012	0.74	0.55	2.5
0202+149	P 0202+14	02 02 07.3961	14 59 50.961	1.00	1.33	3.6
0234+285	CTD 20	02 34 55.5896	28 35 11.426	1.48	1.97	13 7
0235+164	GC 0235+16	02 35 52.6301	16 24 04.033	1.65	1.82	2.1
0239+108	OD 166	02 39 47.0897	10 48 16.295	0.35	0.40	3.7
0333+321	NRAO 140	03 33 22.4049	32 08 36.674	0.60	0 40	13 3
0336–019	CTA 26	03 36 58.9525	–01 56 16.878	1.4	1.0	19 9
0406+121	GC 0406+12	04 06 35.4765	12 09 49.322	0.4	0.2	7.6
0420–014	P 0420–01	04 20 43.5393	–01 27 28.691	1.5	1.5	21.6
0528+134	P 0528+134	05 28 06.7590	13 29 42 295	0.86	0.74	9 4
0552+398	DA 193	05 52 01.4076	39 48 21.949	0.6	1.0	16.5
0735+178	P 0735+17	07 35 14.1262	17 49 09.254	0.50	0 69	4.1
0738+313	OI 363	07 38 00.1785	31 19 02.054	1.40	0.81	9 5
0742+103	DW 0742+10	07 42 48.4643	10 18 32.648	0.5	0.4	11 2
0745+241	B2 0745+24	07 45 35.7253	24 07 55.494	0.81	0.40	2 7
0748+126	P 0748+126	07 48 05.0601	12 38 45.468	0.75	0 30	8 6
0827+243	B2 0827+24	08 27 54.3987	24 21 07.646	0.8	0.26	4.4
0851+202	OJ 287	08 51 57.2503	20 17 58 402	1.32	2.00	1 9
1004+141	GC 1004+14	10 04 59.7838	14 11 10.893	0.27	0.30	1.6

Table 1 (contd)

IAU name	Other name	Position (1950.0)		Correlated flux, Jy		D_{min}, deg
		Right ascension, 00^h 00^m 00.^{s}0000	Declination, 00° 00' 00."000	S band	X band	
1038+064	OL 064.5	10 38 40.8845	06 25 58 514	0.58	0.42	3.0
1040+121	3C 245	10 40 06 0002	12 19 14.953	0.24	0.38	2.8
1055+018	P 1055+01	10 55 55.3130	01 50 03.518	1 00	0.88	5.8

Table 2. Short baseline source observations

IAU name	Other name	Position (1950.0)		Correlated flux, Jy		D_{min}, deg	Epoch
		Right ascension, 00^h 00^m 00.^{s}0	Declination, 00° 00' 00"	S band	X band		
A. Sources Detected at Both Frequencies:							
0259+121	P 0259+12	02 59 46.4	12 07 11	0.59	0.29	3.9	1985.6
0341+158	..	03 41 33.7	15 50 19	0 46	0.27	2.8	1985.6
0342+147	...	03 42 18.0	14 44 26	0.30	0.32	3.9	1985.6
0411+054	4C+05 14	04 11 58.3	05 27 14	0.6	0.25	14.4	1985.6
0425+048	P 0425+04	04 25 08 7	04 50 30	0.66	0.65	15.6	1985 6
0536+145	...	05 36 51.5	14 32 14	0.38	0.55	8 5	1985 6
0544+273	...	05 44 26.0	27 20 43	0.51	0.47	4.3	1984 2
0554+242	.	05 54 03 0	24 13 15	1.43	0 97	1.4	1984.2
0556+238	...	05 56 28.0	23 53 25	0.45	0.61	0.9	1984.2
0600+177	...	06 00 16 0	17 43 00	0.59	0.56	5.5	1984.2
0610+260	3C 154	06 10 43.8	26 05 30	0.56	0.3	7.1	1984.2
0629+104	. .	06 29 29.4	10 24 13	1.6	0.3	12 6	1985 6
0629+160	. .	06 29 50.3	16 02 25	1.2	0 6	7 0	1984.2
0657+172	...	06 57 07.7	17 13 37	0.95	1.4	5.8	1984 2
1011+250	..	10 11 06 1	25 04 06	0.53	1.05	12 2	1984.2
B. Sources Not Detected at One or Both Frequencies:							
0320+053	4C+05 14	03 20 41.4	05 23 37	1.12	<0.24	...	1985 6
0332+078	GC 0332+07	03 32 12.4	07 50 16	0.49	<0.25	.	1984 2

Table 2 (contd)

IAU name	Other name	Position (1950.0)		Correlated flux, Jy		D_{min}, deg	Epoch
		Right ascension, $00^h\ 00^m\ 00.^s0$	Declination, 00° 00' 00"	S band	X band		
0333+128	4C+12.15	...	.	<0.25	<0.24	...	1985.6
0348+049	..	03 48 12.8	04 56 56	0.63	<0 25	...	1984 2
0408+070	P 0408+07	...	...	<0 21	<0 24	...	1985.6
0411+141	P 0411+14	...	...	<0.21	<0.24	...	1985.6
0417+177	P 0417+17	...	..	<0.21	<0 24	...	1985.6
0441+106	P 0441+10	04 41 26.8	10 37 17	0.65	<0 28	...	1984.2
0459+135	P 0459+13	04 59 43.8	13 33 56	0.41	<0 24	...	1985 6
0510+311	...	...	...	<0.25	<0.26	.	1984.2
0514+109	...	05 14 00.2	10 54 42	0.43	<0 26	.	1984.2
0520+244	...	...	...	<0.21	<0.24	...	1985.6
0523+327	.	...	...	<0.25	<0.26	...	1984 2
0531+194	P 0531+19	05 31 47.3	19 25 25	0 5	<0 26	..	1984.2
0538+286	..	...	..	<0.25	<0.26	...	1984.2
0539+290	...	...	...	<0.25	<0.26	..	1984 2
0548+165	..	05 48 24 9	16 35 49	1.10	<0.25	..	1984 2
0552+125	.	05 52 45.3	12 32 03	0.7	<0.25	. .	1984.2
0557+191	..	05 57 03.0	19 09 00	0.32	<0.27	...	1984.2
0559+193	..	...	..	<0.25	<0.26	..	1984.2
0600+219	..	06 00 51.1	21 59 41	0.61	<0 26	.	1984 2
0606+163	...	...	...	<0.25	<0.26	.	1984.2
0607+174	...	...	...	<0.25	<0 26	.	1984.2
0611+131	...	06 11 16.0	13 09 00	0.34	<0.25	..	1984.2
0618+145	3C 158	...	...	<0.25	<0.26	...	1984 2
0618+197	...	..	..	<0.25	<0.26	...	1984.2
0622+179	...	..	...	<0.25	<0.26	.	1984 2
0623+264	P 0623+26	...	...	<0 25	<0.26	..	1984.2
0624+176	. .	...	..	<0 25	<0 26	...	1984.2
0626+168	...	...	...	<0 25	<0 26	...	1984.2

Table 2 (contd)

IAU name	Other name	Position (1950.0)		Correlated flux, Jy		D_{min}, deg	Epoch
		Right ascension, $00^h\ 00^m\ 00.^s0$	Declination, 00° 00' 00"	S band	X band		
0631+142		06 31 55 0	14 16 00	0.32	<0 24	.	1984 2
0640+089	.	06 40 42.4	08 57 00	0.34	<0 23	.	1984.2
0645+147	.		.	<0.25	<0.26		1984.2
0648+153	...	. .	.	<0.25	<0.26	.	1984 2
0710+118	P 0710+11	. .		<0.25	<0 26	...	1984 2
0711+146	. .	...	.	<0.25	<0 26	...	1984.2
0721+161	...	.	.	<0.25	<0 26	.	1984.2
0725+147	3C 181	...	. .	<0.25	<0.26	.	1984.2
0727+153	...	. .	. .	<0.25	<0.26	. .	1984 2
0801+303	...	.	...	<0.25	<0 26	...	1984.2
0928+008	.	09 28 18 1	00 48 12	0 35	<0 26	.	1984.2
1042+071	P 1042+071	10 42 19 7	07 11 39	0.34	<0.31	.	1984.2

Table 3. Long baseline observations, 1983.9

IAU name	Other name	Position (1950.0)		Correlated flux, Jy		D_{min}, deg
		Right ascension, $00^k\ 00^h\ 00.^s00$	Declination, 00° 00' 00."0	S band	X band	
2223−114	P 2223−114	22 23 04.52	−11 28 56.7	0.40	0.43	9.1
2233−148	P 2233−140	22 33 53.99	−14 48 56 1	0.15	<0.16	8 8
2325−150	P 2325−150	23 25 11.62	−15 04 26.8	0.45	0.26	8.9
2351−006	...	23 51 35.39	−00 36 25.2	0.34	<0.11	1.5
2354−117	P 2354−11	23 54 57.22	−11 42 21.0	1.00	0.23	9.1
2355−106	P 2355−106	23 55 36.96	−10 36 50.4	0.54	0.49	8 3
0003−066	NRAO 5	00 03 40.30	−06 40 17 0	0.54	0.37	5.4
0047−051	. .	00 47 49.03	−05 08 39.4	0.15	0.26	8.5
0048−097	P 0048−09	00 48 09.98	−09 45 24.2	0 8	0.7	12.7
0234+285	CTD 20	02 34 55 59	28 35 11.4	1 40	1.97	13 7
0237+040	GC 0237+04	02 37 14.43	04 03 30.1	0.27	0.52	9 9

Table 3 (contd)

IAU name	Other name	Position (1950.0)		Correlated flux, Jy		D_{min}, deg
		Right ascension, $00^k\ 00^h\ 00.^s00$	Declination, 00° 00' 00."0	S band	X band	
0423+051	P 0423+051	04 23 57 26	05 11 36.3	0.52	0.25	15.2
0430+052	3C 120	04 30 31.64	05 14 58.3	0.1	0.4	15 5
0446+112	P 0446+11	04 46 21.24	11 16 17.0	0.31	0.5	10 6
0454+066	P 0454+06	04 54 26.42	06 40 28 2	0.14	0.42	15 4
0456+060	P 0456+06	04 56 08.17	06 03 32 5	0.14	0.11	16 1
0459+060	GC 0459+06	04 59 34.80	06 04 50.9	0.42	0 31	16 2
0502+049	P 0502+049	05 02 43.83	04 55 39.1	0 30	0 50	17 4
0507+179	P 0507+17	05 07 07.51	17 56 58.2	0.26	0 75	4 7
0509+152	P 0509+152	05 09 49 47	15 13 51.4	0.80	0.22	7 3
0620+389	OH 335	06 20 51.56	38 58 26.8	0 47	0 24	15.6
0650+371	GC 0650+37	06 50 35 31	37 09 26.7	0.56	0 3	14 1
0711+356	OI 318	07 11 05.62	35 39 52.2	0 72	0 1	13 0
0722+145	P 0722+145	07 22 26.99	14 31 12.1	0 45	0.35	7 8
0729+259	GC 0729+25	07 29 32.87	25 55 06.9	0.21	0 26	3 9
0733+300	GC 0733+30	07 33 04.67	30 01 04.2	0 34	0.32	8 0
0738+313	OI 363	07 38 00.18	31 19 02.1	1.4	0 7	9 5
0738+272	B2 0738+27	07 38 20.94	27 13 48.7	0 15	<0.1	5.5
0742+318	B2 0742+31	07 42 30.78	31 50 16.3	0 2	0.3	10 1
0742+103	DW 0742+10	07 42 48.46	10 18 32.6	2.4	0 3	11 2
0743+259	GC 0743+25	07 43 23.09	25 56 25 0	0.48	0.36	4 5
0748+333	GC 0748+33	07 48 41 09	33 21 03.7	0 32	<0 09	11 9
0754+100	P 0754+100	07 54 22.61	10 04 39.5	0 87	0 6	10 9
0759+183	GC 0759+18	07 59 55 32	18 18 15.4	0.30	0.21	2 6
0802+212	GC 0802+21	08 02 42 63	21 15 28 6	0 5	<0.10	0 7
0820+225	P 0820+22	08 20 28 54	22 32 45 2	0 30	0.28	2 4
0834+250	GC 0834+25	08 34 42 33	25 04 54.5	0.31	<0.18	5.5
0839+180	GC 0839+18	08 39 14.11	18 46 27.5	0.23	<0.13	0 6
0952+179	AO 0952+17	09 52 11.83	17 57 44.9	0.15	0.36	4 0

Table 3 (contd)

IAU name	Other name	Position (1950 0)		Correlated flux, Jy		D_{min}, deg
		Right ascension, $00^k\ 00^h\ 00\ ^s00$	Declination, 00° 00' 00 "0	S band	X band	
0953+254	OK 290	09 52 59.77	25 29 34.0	0.37	0.2	11 3
1004+141	GC 1004+14	10 04 59.78	14 11 10.9	0.27	0 28	1 6
1013+208	GC 1013+20	10 13 59.44	20 52 47.4	0.33	0.35	8.6
1022+194	GC 1022+19	10 22 01.49	19 27 35 2	0 31	0.26	7.9
1042+071	P 1042+071	10 42 19.48	07 11 26.2	0.20	0.22	2.0

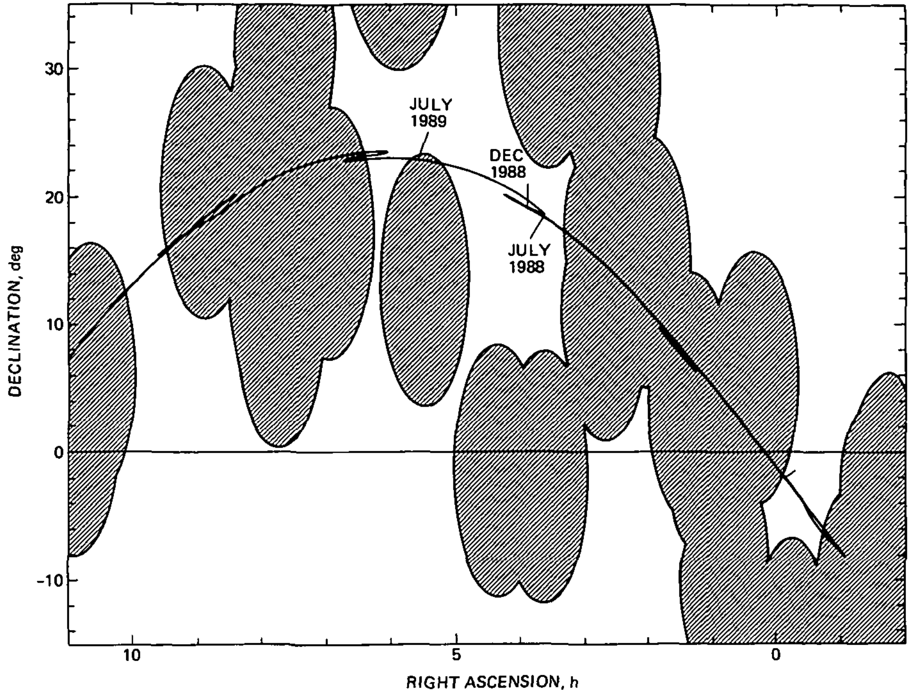

Fig. 1. Plot of the Galileo trajectory from 1986 through 1991. Hatched regions are within 10° of a potential ΔVLBI reference source that is likely to be usable in the Block I navigation system.

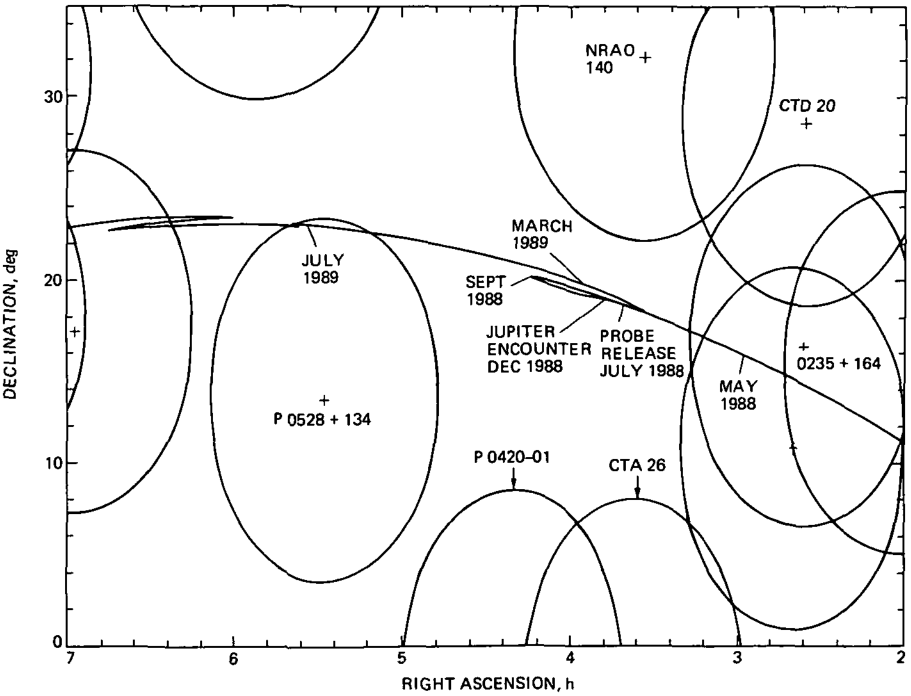

Fig. 2. Plot of the Galileo trajectory in 1988 and 1989, with several important points marked. The sources likely to be usable for ΔVLBI navigation are shown with 10°-radius circles centered on each radio source position. Note the lack of sources in the region where probe release and Jupiter encounter will occur.