QVLBI Doppler Demonstrations Conducted During Pioneer 11 Encounter and Solar Conjunctions

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During the Jupiter encounter of Pioneer 11 in December 1974, a limited amount of simultaneous two-way and three-way doppler was obtained. It was demonstrated in this study that, based on a very short arc (two weeks) of differenced doppler (quasi very long baseline interferometry or QVLBI doppler), the B-plane predictions were as good as 200 km at E–1 day and 400 km at E–3 days.

During the two solar conjunctions of Pioneer 10 and 11, which occurred in March 1975, several passes of QVLBI doppler were obtained and analyzed. The data quality of QVLBI doppler was found to be two to three times better than the conventional two-way doppler when the Sun–Earth–probe angle was less than 5 degrees.

I. Introduction

Studies in Ref. 1 have shown that using differenced two-way and three-way (QVLBI) doppler data rather than the conventional two-way doppler data may significantly improve the accuracy with which the trajectory of a spacecraft can be determined in the presence of process noise. Process noise describes the effect of unmodeled spacecraft accelerations due to attitude control gas leaks and solar radiation pressure anomalies, etc. This data type has been successfully demonstrated using the radio metric data of Pioneer 10 (Ref. 2) and that of Mariner 10 (Ref. 3). The results of the Pioneer 10 demonstration indicate an order of magnitude improvement at Jupiter *B*-plane in the presence of large unmodeled accelerations (10^{-8} km/sec^2) due to the four massive Galilean satellites. The results of the later demonstration conducted with Mariner 10 conclusively showed that this new data type can reduce the effects of moderate unmodeled spacecraft accelerations (10^{-10} km/sec^2) by an order of magnitude and reduce the effects of the solar corona by a factor of five when the Sun–Earth–probe (SEP) angle is less than 5 degrees.

Unmodeled spacecraft accelerations and solar plasma effects will be two major difficulties in navigation of future space missions such as Mariner Jupiter–Saturn and the Saturn flyby of Pioneer 11. The latter effect is even more important because solar conjunction will occur during many of the critical periods of planet encounter of Mariner Jupiter–Saturn and Pioneer 11 missions. The order of magnitude increase in data noise due to the solar corona makes the orbit determination (OD) extremely difficult. During the solar conjunction of Mariner 10, the doppler data noise became so large (1.1 Hz) that neither the S-band-X-band (S-X) dual-frequency technique nor the sequential estimation method was able to calibrate or remove this effect. Therefore, the OD strategy relied heavily on the solutions based on QVLBI doppler data. By comparing short arc solutions with that from conventional data, a factor of 4 improvement in *B*-plane uncertainties was found (Ref. 3).

During the Pioneer 11 encounter of Jupiter, one month of simultaneous two-way and three-way doppler data were received. The two-way doppler data during this period were relatively clean, and the accelerations due to Galilean satellites had been correctly modeled. Therefore, we do not expect significant improvement in data quality from the QVLBI doppler data. Consequently, the Pioneer encounter demonstration emphasized the orbit determination capability of this new data type.

Later in the spring of 1975, both Pioneer 10 and Pioneer 11 were in solar conjunction, and a few passes of two-way and three-way doppler were obtained. Because of very limited data coverage, data quality improvement was demonstrated with no attempt at studying the OD improvement.

II. Pioneer Encounter

Similarly to previous demonstrations (Refs. 2,3), the results of orbit determination based on this new data type will be compared with those from conventional data types. In the meantime, both of them will be compared with the true values determined from both pre- and post-encounter data. The simultaneous two-way and three-way doppler data coverage was little less than a month during encounter, with 18 days before and 10 days after the closest approach of Jupiter. Figure 1 shows the data distribution of two-way and three-way simultaneous doppler for that period. On most of the days, the coverage was less than 2 hours, which is relatively poor compared with the continuous coverage of conventional two-way doppler data.

During this period, the conventional doppler data was relatively quiet. Consequently, we do not anticipate significant improvement in data quality from the new data type as we did in previous demonstrations. Instead, we emphasize the actual capability for navigation of this two-way and three-way differenced doppler. Besides, the ephemerides of the four massive Galilean satellites, which were turned off in the previous Pioneer 10 demonstration (Ref. 2), were included in the orbit determination program this time.

Three different data types are included in this analysis: the conventional two-way doppler (F2), the two-way and three-way differenced (QVLBI) doppler (F3C) and the ramped range (ETR). The selected data arc starts from 30 days before Jupiter encounter, with conventional doppler loosely weighted (Table 1). Six ramped range data were evenly distributed in this interval, and they are weighted at 10 km. Three cases of OD solutions at three different data arcs were obtained. In the first case, six state parameters and two parameters for the constant frequency bias for the DSS 14–43 baseline (A1001) and the DSS 43–63 baseline (A1002) were estimated. In the second case, two more parameters for the relative frequency drift (A2001, A2002) were added to the estimated list. The third case is the state only solution without QVLBI doppler and with two-way doppler weighted normally at 0.045 Hz and ramped range (10 km). Table 2 shows all the estimated and considered parameters, together with a priori and nominal values used in the OD analysis. Those a priori values are standard values used by the Pioneer 10–11 navigation team.

The three data arcs give solutions at 5, 3 and 1 days before encounter. The *B*-plane values shown in Fig. 2 indicate an excellent agreement in the **B** · **T** component between that predicted by QVLBI doppler (solid and empty triangles) and the post-encounter best estimate (less than 60 km). The **B** · **R** component, which is the out-of-plane component and usually is difficult to predict, has a spread of 1000 km in the solutions from QVLBI data. This is not surprising because at E–5 days, the QVLBI doppler only sparsely covered an arc of about 10 days. At E–3 days, the **B** · **R** prediction missed the best estimate by less than 400 km. The best prediction from QVLBI data was good to 200 km, which is at E–1 day with only a 16-day arc of QVLBI doppler. The predictions based on continuous two-way doppler (case 3) at E–5, E–3 and E–1 day agree with the best estimate within 120 km. It is estimated that the QVLBI doppler data coverage actually obtained during this time span (E–30 days to E–1 day) is less than 15 percent of the possible QVLBI doppler covered during the same time interval (based on 7-hour two-way and three-way overlap per 24 hours). Had we had all the possible two-way and three-way data during that time span, considerable improvement in *B*-plane accuracy would have been expected.

The difference between the solid and empty triangles (Fig. 2) tends to indicate the effect due to the drift between frequency standards (new Rb maser 5065A). The estimated values for frequency biases are shown in Fig. 3. The bias between DSS 14 and DSS 43 was as large as 33.9 mHz, which is consistent with the estimated value from the Mariner 10 QVLBI doppler demonstration (Ref. 3). The slope of the frequency drift between DSS 14 and DSS 43 for this period is unusually small at 0.1 mHz per month. The slope between DSS 43 and DSS 63 is also small during this interval. It is seen from Fig. 3 that the estimated values of bias (case 1 solution) differed from the values when slopes were estimated at the same time (case 2 solutions). This is true particularly for the E–5 day solution. It may be responsible for the large error in *B*-plane predictions. When both bias and slope are estimated from a short arc of data, the two parameters are highly correlated and thus degrade the uncertainty of estimated biases. By comparing results (covariance) of case 1 and case 2, the bias may be determined from 2 weeks of QVLBI data within a few tenths of a mHz if slopes are not estimated and station location has no error, while in case 2, when slopes are estimated, the uncertainty of estimated bias becomes as large as 20 mHz. The above fact strongly suggests that better frequency standards such as H-masers with long-term drift less than one tenth of a mHz or better are highly desirable for QVLBI doppler tracking. If we had H-masers as frequency standards, with the constant bias properly removed either by estimating in the Orbit Determination Program or other independent methods such as VLBI or SITT[1], the *B*-plane solution would be improved significantly.

Figure 4 shows the sensitivity of *B*-plane components to various parameters for the three different data arcs. It is as expected that the QVLBI data type is much less sensitive to errors in the mass and ephemerides of Jupiter than the conventional data type. QVLBI doppler is more sensitive to errors in station location and frequency standards.

As a research effort, only the simultaneous two-way and three-way doppler data (without differencing) from E–18 days to E + 10 days were used together with the six ramped range data to estimate the dynamic constants of the Jupiter system. It was hoped that the common error sources would be implicitly removed from the simultaneous data. Those estimated values for the mass of Jupiter, J2, and J4 and the masses of the four Galilean satellites have good agreement with earlier determinations (Ref. 4) and are shown in Table 3.

[1]SITT is the Simultaneous Interference Tracking Technique which, as has been demonstrated, can estimate the relative frequency offset good to a few parts of a mHz.

III. Solar Conjunctions of Pioneer 10–11

The two Pioneer 10–11 spacecraft had solar conjunctions in late March and early April 1975. Since the celestial longitude is approximately the same for both spacecraft, the minimum Sun–Earth–probe angle occurs approximately at the same time—March 24 for Pioneer 11 and April 4 for Pioneer 10. This minimum angle reaches a little less than 2 degrees for both spacecraft.

A total of 4 passes of QVLBI doppler were obtained in late March during the solar conjunction of Pioneer 11. A summary of these data is shown in Table 4. Unfortunately, one pass of three-way doppler received at DSS 44 was bad, and another pass of three-way doppler at DSS 42 on March 23, when the 2-degree minimum angle occurred, was questionable because the three-way data were found to be 60 percent more noisy than those of the two-way doppler received at the same time at DSS 14. According to earlier observations (Ref. 3), it is unlikely that the 60 percent increase in data noise is due to the gradient in the solar corona. A possible explanation for the noise in the three-way data is that during that time, the 26-meter antenna of DSS 42 was at only 9 dB, which was very marginal to receive useful doppler data. Two good passes of QVLBI doppler were received on March 29 and 31. On March 29, the SEP angle was about 4 degrees and the data noise of both two-way and three-way doppler was around 0.026 Hz (60-second count time). After differencing the simultaneous doppler, the data noise became 0.0098 Hz, a factor of 3 improvement (Fig. 5). Two days later, the SEP angle was about 5 degrees, and the data noise was improved from 0.0177 Hz to 0.0089 Hz after differencing (Fig. 6).

During the Pioneer 10 solar conjunction, two passes of QVLBI doppler were received on March 22 and March 30. On March 22, the SEP angle was about 10 degrees and the data noise of two-way doppler received at DSS 12 was 0.0134 Hz (see Table 5). There is no noticeable improvement in the differenced data, which have a data noise of 0.0132 Hz. This is about the normal data noise of two-way doppler at 60-second count time. Comparison with the two-way doppler data noise (0.0144) during the Pioneer 11 conjunction, when the SEP angle was 15 degrees, seems to indicate that solar corona effects become less important when the SEP angle is greater than 15 degrees. The effect due to the ionosphere was not calibrated because, near local noon, it is estimated to be less than 0.002 Hz. The most interesting pass in this analysis is the one received on March 30 with two-way at DSS 14 and three-way at DSS 43. The SEP angle was at 4 degrees, and the noise seen in two-way doppler residuals was an order of magnitude higher than that found during Pioneer 11 conjunction (SEP = 4 deg). This increase strongly suggests active solar activities, particularly during the first 15 minutes of this one-hour pass, as shown in Fig. 7. After differencing, the noise is still as large as 0.28 Hz in the first 15 minutes and 0.092 Hz in the remaining 35 minutes (Table 5). The noise in the differenced doppler implies large spatial gradient and/or smaller-scale (less than the DSS 14–43 distance of 7000 km) inhomogeneities in the solar plasma. This particular pass of data may be useful in studying solar activities.

It is also interesting to see the integrated doppler residuals due to solar plasma. Figure 8 shows the equivalent range residuals after integrating the two-way and differenced doppler residuals as shown in Fig. 7. It clearly indicates that the 30-meter variation in integrated two-way doppler residuals was improved to less than 5 meters after differencing. The linear drift in the differenced range residuals seems to reveal the frequency offset between the two station standards. The factor of 3 improvement in doppler quality and the improvement in range quality of nearly an order of magnitude during solar conjunction have demonstrated the importance of this differenced data type.

A summary of per pass (1σ) data noise is shown against SEP angle in Fig. 9. The improvement in the differenced doppler data noise is not as good as that of the Mariner 10 solar conjunction, which had a factor of 5 or better improvement. This difference is not well understood. A possible explanation is that the Pioneer 10 and 11 spacecraft were 8 and 5 AU, respectively, away and thus the signal-to-noise ratio was low compared to Mariner 10 data. Consequently, this tended to cause cycle slipping in the two-way or three-way doppler, which would degrade the differenced doppler.

IV. Conclusion

The results of this study have demonstrated the navigational capability based on a short arc of QVLBI doppler during Jupiter encounter and the improved data quality of this data type during solar conjunction. With only two weeks of QVLBI doppler at 3 days before encounter, the prediction at Jupiter *B*-plane was good to 400 km. This differenced doppler has improved the data noise during solar conjunction by a factor of 2 to 3. During a time of active solar activities, the integrated doppler (range) noise was reduced by nearly an order of magnitude after differencing.

Acknowledgement

The author would like to thank Anton Lubeley for his assistance in data processing.

References

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Table 1. Data summary during Pioneer II encounter

Station ID	Data type	Time of earliest point		Time of latest point		Total points
DSN-43	F2—S	03 NOV 74	10:10:32.00	12 DEC 74	12:55:32.00	919
DSN-63	F2—S	03 NOV 74	17:35:32.00	12 DEC 74	22:30:32.00	831
DSN-14	F2—S	06 NOV 74	02:09:32.00	13 DEC 74	00:59:32.00	588
DSN-14	ETR—S	07 NOV 74	02:30:30.00	01 DEC 74	03:20:30.00	3
DSN-43	ETR—S	13 NOV 74	08:55:30.00	10 DEC 74	07:05:30.00	3
DSN-63	F3C—S	15 NOV 74	14:37:32.00	12 DEC 74	12:59:02.00	71
DSN-14	F3C—S	15 NOV 74	22:47:32.00	12 DEC 74	21:13:32.00	135
DSN-43	F3C—S	18 NOV 74	04:45:32.00	13 DEC 74	03:38:32.00	152

QVLBI: Data	Weight
F3C	0.005 Hz
ETR	10 km
F2	0.5 Hz

Table 2. Estimated and consider parameters and the a priori values

Name	DX	Sigma	A priori sig.	New value	Previous	Nominal
			Estimated parameters			
X	−0.20963859+003	0.12816+005	0.10000+005	−0.2616640180689983+008	−0.26166192+008	−0.26166166+008
Y	0.94837902+003	0.52173+005	0.10000+005	0.2884050131638451+008	0.28839553+008	0.28839064+008
Z	−0.29388873+004	0.16898+006	0.10000+005	0.1040944516061885+008	0.10412384+008	0.10413440+008
DX	0.39066160−004	0.33225−002	0.10000+001	0.6129445346992491+001	0.61294063+001	0.61294066+001
DY	−0.22425842−003	0.13698−001	0.10000+001	−0.6547890364795064+001	−0.65476661+001	−0.65476163+001
DZ	0.62536468−003	0.43661−001	0.10000+001	−0.2471630467680742+001	−0.24722558+001	−0.24723309+001
A1001	0.13401015−010	0.30045−010	0.10000−010	0.1340101533576107−010	0.00000000	0.00000000
A1002	−0.62326979−011	0.23034−009	0.10000−010	−0.6232697922876701−011	0.00000000	0.00000000
A2001	0.10147428−020	0.31975−019	0.31623−017	0.1014742772031248−020	0.00000000	0.00000000
A2002	0.48452651−020	0.15498−018	0.31623−017	0.4845265095899446−020	0.00000000	0.00000000
			Consider parameters			
GM5	Mass of Jupiter		0.25000+004			0.12671303+009
J502	J2 of Jupiter		0.44159−003			0.14730637−001
J504	J4 of Jupiter		0.60000−003			−0.59322944−003
501GM			0.75000+002			0.59369039+004
502GM	Masses of the four satellites		0.75000+002			0.32476577+004
503GM			0.10000+003			0.98766103+004
504GM			0.21500+003			0.71323529+004
LO14			0.10000−003			0.24311052+003
LO43	Station longitude		0.10000−003			0.14898130+003
LO63			0.10000−003			0.35575202+003
CU14			0.10000−001			0.52039962+004
CU43	Spin axis distance		0.10000−001			0.52052508+004
CU63			0.10000−001			0.48624504+004
DMW5			0.70520−006			0.44149977−006
DP5			0.53292−006			0.16706886−006
DQ5			0.52240−006			0.26149561−006
EDW5	Set III ephemerides of Jupiter		0.26653−006			−0.58308401−007
DA5			0.28634−007			−0.15887297−007
DE5			0.26127−006			−0.24894730−006

Table 3. Summary of estimated values of the dynamic constants of the Jupiter system

	Sampson (1921)	de Sitter (1931)	Pioneer 10, Anderson, et al.	Pioneer 11, simultaneous 2-way and 3-way doppler
GM_5			126,713,600 ± 2500	126,714,027 ± 4000
J_2			$(1.4720 \pm 0.0040) \times 10^{-2}$	$(1.4754 \pm 0.0022) \times 10^{-2}$
J_4			$(-6.5 \pm 1.5) \times 10^{-4}$	$(-5.97 \pm 3.66) \times 10^{-4}$
GM_{Io}[a]	4.497	3.81 ± 0.40	4.696 ± 0.06	4.606 ± 0.03
GM_{Europa}	2.536	2.48 ± 0.07	2.565 ± 0.06	2.519 ± 0.13
$GM_{Ganymede}$	7.988	8.17 ± 0.13	7.845 ± 0.08	7.878 ± 0.48
$GM_{Callisto}$	4.504	5.09 ± 0.53	5.603 ± 0.17	5.637 ± 0.11

[a]The satellite masses are in units of the mass of Jupiter $\times 10^{-5}$.

Table 4. Data summary of Pioneer 11 solar conjunction

	3-way doppler			2-way doppler			Differenced doppler	
Date	DSS	No. of data	Data noise, Hz	DSS	No. of data	Data noise, Hz	No. of data	Data noise, Hz
3/1	44	24	Bad	12	28	0.014	0	
3/23	42	149	0.16	14	145	0.10	145	0.16
3/29	11	14	0.025	61	106	0.026	14	0.0098
3/31	11	58	0.017	61	56	0.018	56	0.0089

Table 5. Data summary of Pioneer 10 solar conjunction

	2-way doppler			Differenced doppler		
Date	DSS	No. of data	Data noise, Hz	DSS	No. of data	Data noise, Hz
3/22	12	36	0.0134	44	36	0.0132
3/30	14	13	0.48	43	13	0.286
	14	35	0.212	43	35	0.092

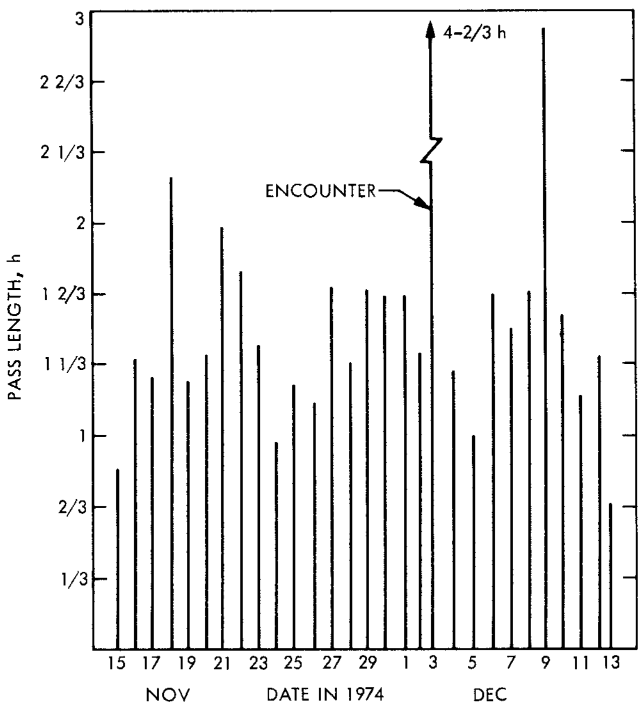

Fig. 1. QVLBI doppler data distribution

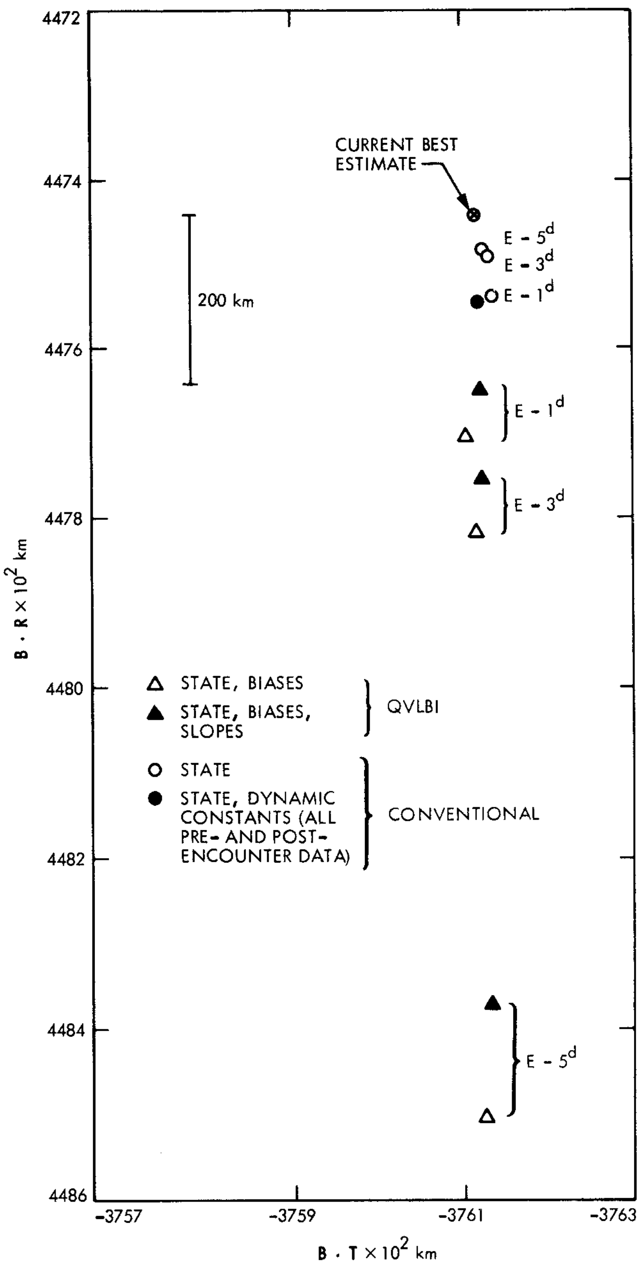

Fig. 2. Jupiter *B*-plane predictions

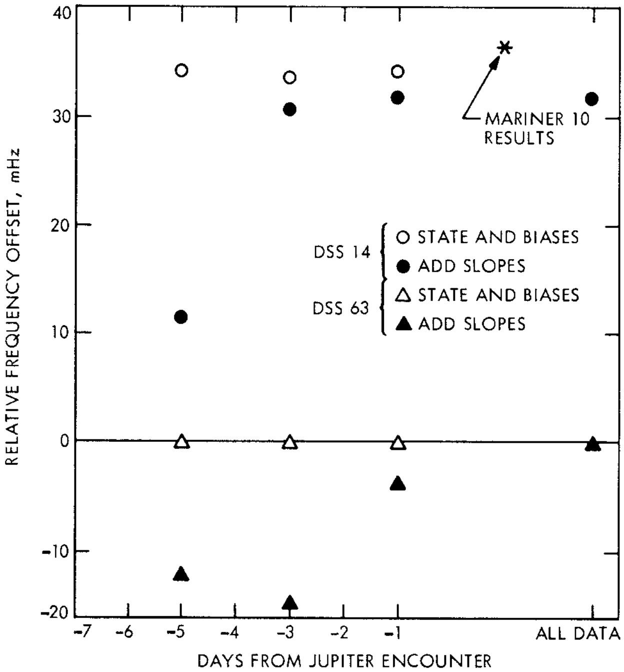

Fig. 3. Estimated values of frequency offset (all relative to DSS 43)

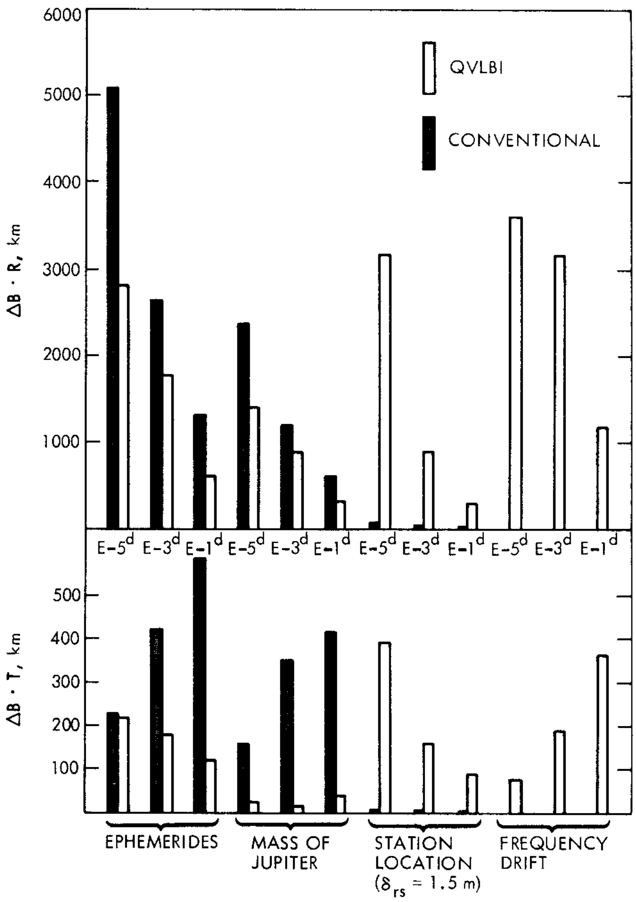

Fig. 4. Sensitivity at *B*-plane due to various error sources

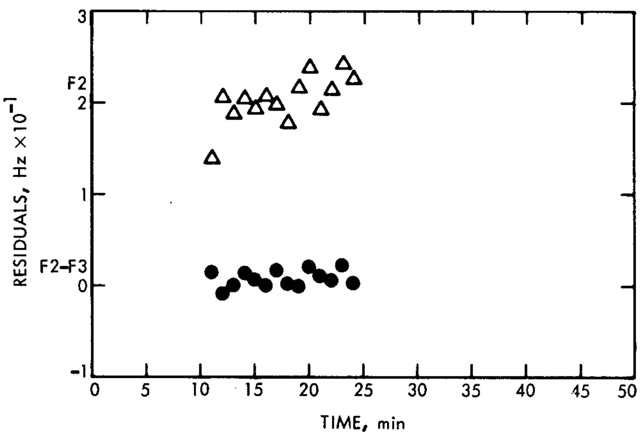

Fig. 5. Residuals of 2-way and differenced doppler on March 29 (Pioneer 11), when SEP = 4 deg

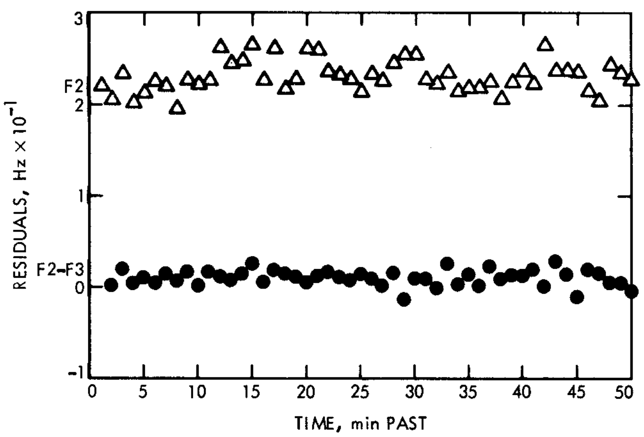

Fig. 6. Residuals of 2-way and differenced doppler on March 31 (Pioneer 11), when SEP = 5 deg

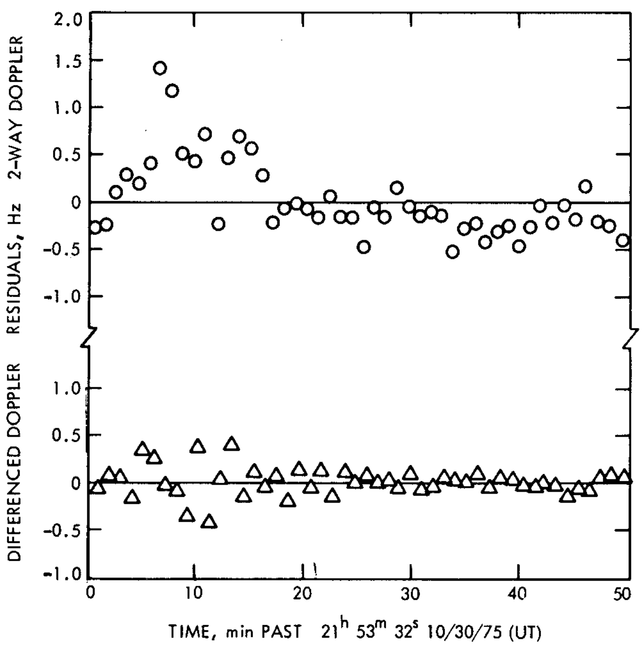

Fig. 7. Residuals of 2-way and differenced doppler during Pioneer 10 solar conjunction (SEP = 4 deg)

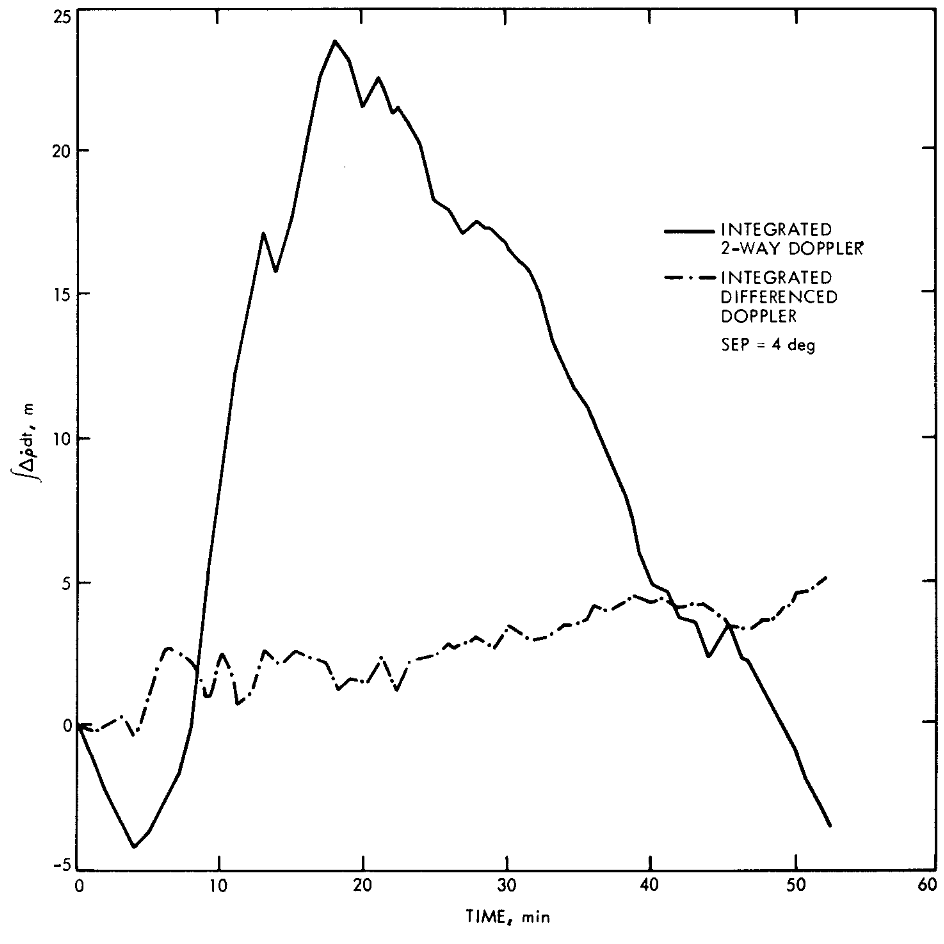

Fig. 8. Integrated doppler residuals during Pioneer 10 solar conjunction

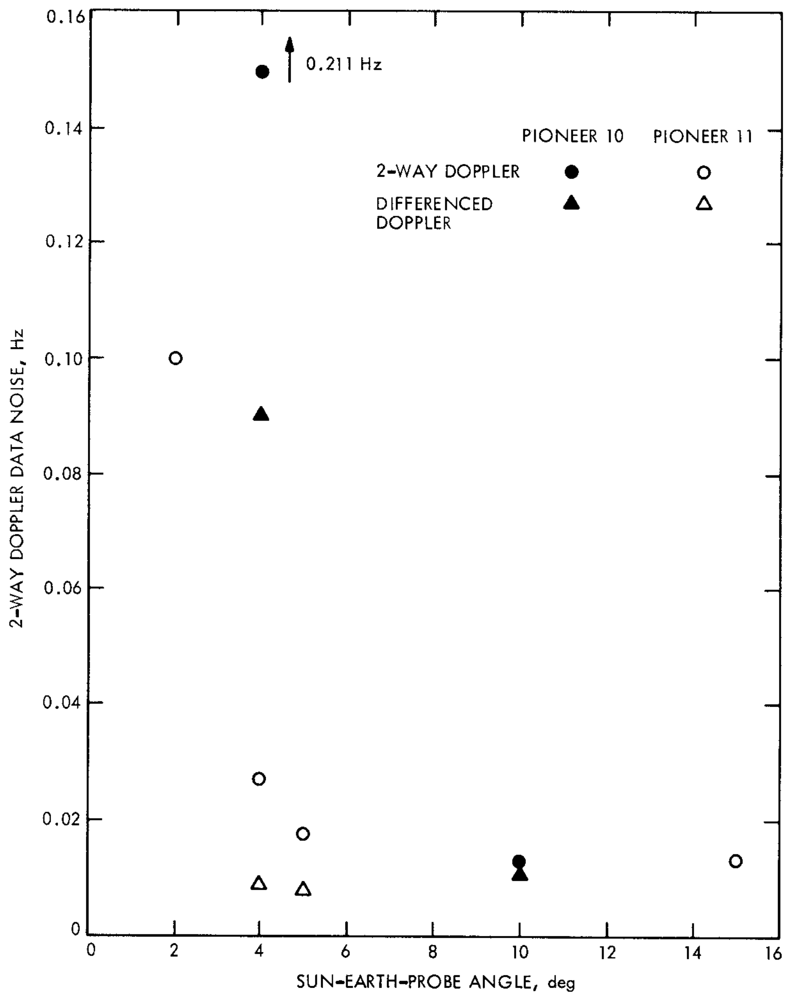

Fig. 9. Per pass 2-way and differenced doppler data noise vs. Sun-Earth-probe angle