An Evaluation of QVLBI OD Analysis of Pioneer 10 Encounter Data in the Presence of Unmodeled Satellite Accelerations

B. D. O'Reilly and C.C. Chao
Tracking and Orbit Determination Section

Quasi-very-long-baseline interferometry (QVLBI) has been used to predict Pioneer 10 flyby B-plane coordinates from simultaneous two- and three-way doppler data in the presence of unmodeled accelerations ($\leq \sim 10^{-8}$ km/s^2) due to the four massive satellites of Jupiter. It is concluded from this study that the QVLBI technique for processing simultaneous two- and three-way doppler data is capable of predicting the encounter to within ~2000 km in the presence of unmodeled accelerations as large as 10^{-8} km/s^2. Calculations using two-way doppler data alone for the same nominal trajectory and a priori parameter statistics yielded systematic B-plane errors of the order of 100,000 km, with consequently meaningless formal uncertainties.

I. Introduction and Summary

Quasi-very-long-baseline interferometry (QVLBI) has been used to predict Pioneer 10 flyby B-plane coordinates from simultaneous two- and three-way doppler tracking data in the presence of unmodeled accelerations ($\leq \sim 10^{-8}$ km/s^2) due to the four massive satellites of Jupiter. (Fig. 1 illustrates the B-plane coordinate system.) The work presented here was carried out in two stages:

A. Preliminary Simulation Study

A preliminary simulation study was performed during October 1973 to determine the sensitivity of the QVLBI orbit determination process to the unmodeled Galilean satellite accelerations and to determine a suitable tracking pattern for acquiring simultaneous two- and three-way doppler data. Using pessimistic a priori parameter covariance values (in particular 100% mass uncertainties for the four massive satellites of Jupiter), it was found in the simulation study that QVLBI data analysis yielded a final (postencounter) value of ~2000 km for the semimajor axis of the B-plane error ellipse (SMAA). Using the same a priori parameter covariance and nominal trajectory, analysis of conventional two-way doppler data predicted a final value of ~7500 km for SMAA. In addition, the QVLBI determination of SMAA was found to be an always decreasing function of the length of the data arc, whereas SMAA predicted from two-way doppler data exhibits a peak value of ~53,000 km at one day before encounter. The corresponding QVLBI value at one day before encounter is ~12,000 km (see Fig. 2).

B. B-Plane Accuracy Analyses

B-plane accuracy analyses were performed using both two-way doppler and QVLBI tracking data from the Pioneer 10 spacecraft during the encounter phase of its trajectory. The parameters modeled in the encounter study are listed in Table 1. The epoch and initial state vector and the a priori parameter statistics used in the encounter study appear in Tables 2, 3, and 4. The best B-plane target coordinate values inferred from each data type were obtained by estimating the spacecraft state vector at epoch and the mass, ephemeris parameters, and oblateness of Jupiter. The quality of the final results was ascertained by comparing them to the best estimates of $\mathbf{B} \cdot \mathbf{R}$ and $\mathbf{B} \cdot \mathbf{T}$ obtained by the JPL Pioneer Navigation Team processing almost continuous two-way doppler data with the dynamics of the Galilean satellites accounted for explicitly. (The reference values of $\mathbf{B} \cdot \mathbf{R}$ and $\mathbf{B} \cdot \mathbf{T}$ obtained in this manner are given in Table 5.) The QVLBI estimates of both $\mathbf{B} \cdot \mathbf{T}$ and $\mathbf{B} \cdot \mathbf{R}$ exhibit maximum deviations of ~4000 km from the reference values, with their final values deviating by ~1500 km (see Figs. 3 and 4). The corresponding final statistical uncertainties were $\sigma_{\mathbf{B} \cdot \mathbf{R}} = 133$ km and $\sigma_{\mathbf{B} \cdot \mathbf{T}} = 188$ km (see Fig. 5). By contrast, the two-way doppler estimates of $\mathbf{B} \cdot \mathbf{T}$ and $\mathbf{B} \cdot \mathbf{R}$ show maximum deviations of ~35,000 and 85,000 km from their reference values with final values ~27,000 and ~2000 km (see Figs. 3 and 4). Their deviations from the reference values plotted as functions of the length of the data arc exhibit large amplitude variations which render any interpretation of their formal statistics meaningless.

It is concluded from this study that the QVLBI technique for processing simultaneous two- and three-way doppler data is capable of predicting the encounter coordinates of a spacecraft on a planetary flyby trajectory to within ~2000 km in the presence of unmodeled accelerations as large as 10^{-10} km/s^2.

Since the simultaneous tracking data for this study came almost exclusively from one pair of stations, DSS 14 and DSS 43, and it spans a somewhat limited time period (see the tracking schedule in Table 6), it would appear that 2000 km represents a conservative upper limit to the attainable accuracy for the estimation of targeting coordinates for flyby missions comparable to Pioneer 10. It should be noted especially that there was an irretrievable loss of critically important simultaneous data for several hours surrounding encounter because of improper synchronization between a pair of tracking stations. With better tracking coverage, it is likely that the accuracy limit could be lowered significantly.

II. Background

Previous articles by V. J. Ondrasik and K. H. Rourke have shown that using differenced two-way/three-way doppler and range data rather than two-way data of these types may significantly improve the accuracy with which the trajectory of a spacecraft can be determined in the presence of process noise (see Refs. 1 and 2). Process noise describes the effect of unmodeled spacecraft acceleration on the processing of tracking data. In many cases it has been observed that unmodeled accelerations change the estimates of the spacecraft velocity and position by tolerably small amounts. However, they tend to degrade the statistical confidence in the trajectory estimate severely so that, for example, position uncertainties of many thousand kilometers may result.

Nearly identical process noise signatures appear in the down-link signals received simultaneously by both the transmitting station and a second station separated from the transmitter by a long baseline. Hence, differencing the data taken simultaneously from a pair of such stations tends to cancel the very similar process noise signatures in the simultaneous tracking signals received by them, thus producing a new data type which is, to high order, free of process noise effects. In a similar manner the effects of charged particles in space plasma can be reduced by using QVLBI.

In the present study of the Pioneer 10 spacecraft orbit determination accuracy during its encounter phase, we consider a somewhat surprising candidate for treatment using the QVLBI data type, namely the unmodeled spacecraft accelerations due to the gravity fields of the four massive satellites of Jupiter (Io, Callisto, Ganymede, and Europa). In the data analysis carried out by the Pioneer Navigation Team, the accelerations were modeled. In the present study they were purposely left unmodeled in order to gauge the ability of QVLBI data analysis to remove the errors in the estimates of the spacecraft orbit parameters due to the presence of their signatures in the two- and three-way tracking data before differencing.

It should be noted here that unmodeled accelerations up to the order of 10^{-8} km/s^2 are considered in this study.

Other studies are in progress to ascertain the ability of QVLBI to remove unmodeled gas leak and solar pressure signatures due to accelerations of the order of 10^{-11} km/s^2 acting on the Mariner 10 Venus/Mercury spacecraft (Ref. 3).

III. Scheme for Data Analysis

The QVLBI massive satellite analysis of the Pioneer 10 spacecraft's encounter has been carried out in two stages:

(1) In advance of the onset of the encounter phase (which has been set at E-30 days), accuracy analysis studies were carried out to determine what errors would result from ignoring the effects of the Jovian satellites' gravity fields. The errors were expressed in terms of the axes of the Jovian B-plane error ellipse as a function of time from encounter (data arc length) using both conventional two-way doppler data and differenced simultaneous two-way/three-way doppler (QVLBI) data.

(2) Using the results of the simulation study for guidance, a tracking schedule for taking simultaneous two- and three-way data was set up. The resulting two-way and QVLBI data were then processed using first the SATODP orbit determination program (Ref. 4) and then the ATHENA filter program to calculate the spacecraft state and B-plane covariance matrices.

A. Simulation Analysis

The simulation study used continuous two-way data from Stations 14, 51, and 61 with simultaneous three-way data between Stations 61 and 51. Attention was focused on solutions for the state at epoch (E-30 days) in the two-way doppler cases and for the state vector plus frequency bias between Stations 51 and 61 for the QVLBI cases. For two-way doppler simulation the standard deviation of the data noise was assumed to be 0.015 Hz (1 mm/s for range rate). To avoid complete loss of geocentric range rate information due to data differencing, the simulated two-way data, with noise standard deviation set to a very large value of 3.75 Hz, was included along with the QVLBI data (for the reasons given in Ref. 5). In all cases, the simulated data spanned the interval from E − 30 to E + 7 days. The list of error sources (consider parameters) and their sizes (a priori uncertainties), used to evaluate the accuracy of the solution for the state vector at epoch, appear in Tables 7, 8, and 9. The epoch and initial state vector for these calculations are given in Table 10.

Each of the values of the B-plane error ellipse semi-major axis plotted in Fig. 1 was obtained by an appropriate time/coordinate mapping and subsequent diagonalization of the state vector covariance matrix obtained for the indicated time of encounter.

B. Encounter Analysis

A tracking schedule for both two-way and simultaneous two- and three-way doppler data was arranged as dictated by the results of the simulation study and the availability of antenna time. (A summary of data types and corresponding time spans actually used appears in Table 6.) The dominant influence of station location uncertainties on the quality of the simulated B-plane solutions prior to E − 3 days dictated the use of geocentrically sensitive two-way doppler data from E − 30 to E − 10 days. The shift from dominance of station location uncertainties to satellite mass uncertainties after E − 3 days inferred from the simulation study pointed to the use of QVLBI data from that time forward.

To improve the accuracy of orbit determination calculations performed with QVLBI data, care was taken to treat the frequency bias between DSS 14 and DSS 43 as a solve-for parameter and the frequency biases between DSS 43 and DSS 63 and between DSS 63 and DSS 14 as consider parameters (error sources). This was done in light of the fact that it was learned that the relative bias between station frequency standards appears to be the major error source in the QVLBI data type (Ref. 6). The frequency system for this demonstration using the new rubidium standards has a long-term instability of about $\Delta f/f = 3 \times 10^{-12}$ (Ref. 7). It should be noted that the unmodeled accelerations due to Jupiter's inner satellites are as large as 10^{-8} km/s^2. Such acceleration is equivalent to a long-term noise of $\Delta f/f \approx 3 \times 10^{-8}$. Thus the biases characteristic of the current frequency system are several orders of magnitude below the level which would mask the signature of the satellite accelerations.

The following rationale was used to determine the ratio of the standard deviations of the noise distributions belonging to two-way doppler and QVLBI data. From the short baseline QVLBI study of Chao, Wong, and Lubeley using Pioneer 10 and Pioneer 11 tracking data taken during the spring of 1973 (Ref. 5), it was inferred that a reasonable value for the ratio of two-way-doppler-to-QVLBI noise standard deviations is

$$\sigma_{2\text{-way}}/\sigma_{\text{QVLBI}} \approx 3$$

Thus, the two-way doppler and QVLBI noise sigmas used to analyze the data discussed here were

$$\sigma_{2\text{-way}} = 0.045 \text{ Hz } (3 \text{ mm/s})$$

and

$$\sigma_{\text{QVLBI}} = 0.015 \text{ Hz } (1 \text{ mm/s})$$

The relatively smaller noise level of the QVLBI data is attributed to cancellation of process and transmission medium noise.

The sequence of calculation processes to which the encounter data were subjected is described below. The numerical results of the calculations and the conclusions drawn therefrom have been presented above in the study summary.

IV. Computational Tools and Data Processing

Below we give a brief account of the computational tools and data processing procedures which were used to obtain the results presented above. A list of computer codes used, their functions, and their authors appears in Table 11.

A. Sequence of Computations for the Encounter Simulation Study

(1) A modified version of the REVA link of the ATHENA filter program called MACK was used to generate simulated range-rate REGRES and PATH-VARY files for a continuous tracking pattern using Deep Space Stations 51, 61, and 14, spanning the period from E − 30 to E + 10 days. MACK accounts for the accelerations due to the four massive satellites of Jupiter. The output REGRES file from this calculation describes very nearly the information contained in conventional two-way doppler data for the same spacecraft tracking history.

(2) The code DERIVE was used to augment the two-way range-rate REGRES and VARY files with effective simultaneous differenced two-way/three-way REGRES and VARY files. In particular, partial derivatives of the differenced range rate observable with respect to an assumed constant frequency bias between DSS 51 and DSS 61 were calculated and used in the formation of the additional files.

(3) The TOSCA link of the ATHENA filter was used in batch mode to combine the a priori statistics of the parameter sets described in Tables 8 and 9 with the statistical information contained in the simulated REGRES files for both conventional two-way and differenced data types to obtain both "consider" and "estimate" covariance matrices for the heliocentric EME (Earth mean equator) 1950 Cartesian state vector at epoch for a selection of print times ranging from E − 10 to E + 7 days. "Print time" refers to the time of the last data point included in the data batch under consideration.

(4) The SCANB link of the ATHENA program was used to map the estimate and consider covariance matrices of the state vector at epoch to the B-plane at encounter. An important ancillary result of the consider covariance mapping is the calculation of the perturbation matrix, which provides a direct measure of the relative importance of the confidence degrading influence of the a priori uncertainties of the consider (unmodeled) parameters on the covariance of the B-plane parameters.

B. Sequence of Computations for Analysis of Pioneer 10 Encounter Data

(1) With the aid of the orbit data editor (ODE), IBM 360 tracking data tapes obtained from the Mission Operations Analysis Tracking Team (MOATRK) were decoded (converted for processing by the UNIVAC 1108), and two- and three-way doppler data, taken at 60- and 10-s sample rates (mostly at the former rate), were extracted to form a preliminary orbit data file.

(2) These data were examined to locate blunder points by direct visual inspection.

(3) The ODE was then exercised to purge the data file of blunder points, and the remaining data points were compressed to ≤11-min count-times. Care was taken to align simultaneous sequences of two- and three-way data points to produce simultaneous two- and three-way compression intervals whenever station overlaps were available for three-way reception.

(4) The edited and compressed data files obtained from individual tracking tapes were then merged into a single data file using ODE.

(5) The merged data file was then processed through the links ODINA, PATH, VARY, ODINB, REGRESS,

and ACCUME of the double-precision-orbit-determination processor SATODP/Version D[1] to produce:

(a) A PATH-VARY file containing the partial derivatives of the state vector with respect to the trajectory parameters listed in Table 1 (excluding frequency biases between stations).

(b) A file of partial derivatives of the two- and three-way observables with respect to the trajectory parameters.

(c) A file containing the square-root information matrix which results from combining the square root of the inverse a priori parameter covariance with the matrix of weighted data partials. It also contains appropriately weighted and transformed data residuals. (The initial state vector and epoch appearing in Table 2 were used to generate the nominal trajectory and its associated variational partial derivatives. They represent a converged orbit obtained from the Pioneer 10 operations orbit determination team. The data noise variances described in the preceding section and the a priori parameter covariances given in Tables 3 and 4 were used to prepare the output ACCUME file.)

[1]SATODP/version D does not account for Jovian satellite accelerations.

(6) The ACCUME and PATH-VARY files were next input into the DIFFER code, where they were used to form properly weighted differenced doppler ACCUME and data residual files. The a priori interstation frequency bias estimates, their variances, and the difference data partials with respect to the biases were incorporated into the ACCUME file at this point.

(7) The output two-way and differenced doppler ACCUME files generated by SATODP and DIFFER were next processed separately in batch mode by the TOSCA link of the ATHENA filter to obtain a set of estimates of the initial state vector and other parameters, the subsets of which belong to a selection of data arc lengths (labeled by the time of the last data point from encounter). The corresponding "estimate" and "consider" covariances of the various parameter estimates are also computed along with a file of partial derivatives of the state vector with respect to its own components at epoch to be used subsequently to perform time-coordinate mappings.

(8) Finally, the SCANB link of ATHENA was used to map the initial state vector estimates and their covariances to the B-plane at encounter for a selection of print times ranging from E − 5 to E + 2.6 days. Corresponding perturbation matrices were produced to show the influence of the a priori consider covariance on the B-plane statistics.

References

1. Ondrasik, V. J., and Rourke, K. H., "Applications of Quasi-VLBI Tracking Data to the Zero Declination and Process Noise Problems," AAS No. 71-399, Astrodynamics Specialists Conference, Ft. Lauderdale, Fla., Aug. 1971.

2. Ondrasik, V. J., and Rourke, K. H., "Application of New Radio Tracking Data Types to Critical Spacecraft Navigation Problems," Quarterly Technical Review, Vol. I, No. 4, Jet Propulsion Laboratory, Pasadena, Calif., Jan. 1972.

3. Chao, C. C., "Report of QVLBI Doppler Demonstration Conducted with Mariner 10," EM 391-584, Jet Propulsion Laboratory, Pasadena, Calif., July 1974 (an internal document).

4. Moyer, T. D., *Mathematical Formulation of the Double-Precision Orbit Determination Program*, Technical Report 32-1527, Jet Propulsion Laboratory, Pasadena, Calif., July 15, 1971.

References (contd)

5. Nishimura, T., and Nead, M., "ATHENA Filter Sequential Orbit Determination Program with General Evaluation Capability," 900-605 (a JPL internal document), Mar. 8, 1973.
6. Mulhall, B. D., Chao, C. C., Johnson, D. E., and Zielenbach, J. W., "Report of the Two-Station Doppler (VLBI) Demonstration Conducted with Mariner 9," in *The Deep Space Network Progress Report 42-20*, pp. 27–40, Jet Propulsion Laboratory, Pasadena, Calif., Apr. 15, 1974.
7. Chao, C. C., Wong, S. K., and Lubeley, A., "Short Baseline QVLBI Demonstrations–Part I," in *The Deep Space Network Progress Report,* Technical Report 32-1526, Vol. XVIII, pp. 47–56, Jet Propulsion Laboratory, Pasadena, Calif., Feb. 15, 1973.

Table 1. Parameters included in Pioneer 10 encounter data analysis

Parameter description	Number of parameters	2-way doppler/ Case 1		QVLBI/Case 1		2-way doppler/ Case 2		QVLBI/Case 2	
		Estimate	Consider	Estimate	Consider	Estimate	Consider	Estimate	Consider
EME 1950 Cartesian state vector at epoch	6	√		√		√		√	
Mass of Jupiter	1	√		√		√		√	
Frequency bias of DSS 43 relative to DSS 14	1	–	–	√		–		√	
Jupiter Set III ephemeris parameters	6		√		√	√		√	
Jupiter oblateness	1		√		√	√		√	
Gas leak accelerations	3		√		√		√		√
DSS 14, 43, 63 off-axis distances and longitudes	6		√		√		√		√
Frequency biases of DSS 14, 63 relative to DSS 63, 43	2		√		√		√		√
Earth-Moon barycenter Set III ephemeris parameters	6		√		√		√		√
DSS 12 off-axis distance and longitude	2		√		√		√		√

Table 2. Epoch and Jupiter-centered EME 1950 state vector for encounter analysis

Epoch = OCT. 5, 1973, $01^{h}00^{m}00^{s}.0000$
$X = -0.647705629868 \times 10^{7}$ km
$Y = 0.459338906494 \times 10^{8}$ km
$Z = 0.171826623342 \times 10^{8}$ km
$DX = 0.105757364142 \times 10^{1}$ km/s
$DY = -0.821591385146 \times 10^{1}$ km/s
$DZ = -0.311665562776 \times 10^{1}$ km/s

Table 3. A priori parameter uncertainties for encounter analysis

Parameter	Estimate σ	Consider σ
Position	10^{4} km	
Velocity	1 km/s	
GM5	6×10^{3} km^{3}/s^{2}	
Off-Axis station location		3 m
Station longitude		5×10^{-5} deg
J205	1.5×10^{-4}	1×10^{-5}
Gas leak acceleration		1×10^{-11} km/s^{2}
GMM		5×10^{-2} km^{3}/s^{2}
Frequency bias	23 mHz	10 mHz

Table 4. Combined Set III Jupiter/Earth-Moon barycenter covariance for QVLBI data analysis

The combined (12 × 12) Jupiter/Earth-Moon barycenter (EMB) covariance matrix can be expressed in the partitioned form

$$\Gamma_{\text{comb}} = \begin{pmatrix} \Gamma_{\text{Jup}} & \Gamma_{\text{Jup:EMB}} \\ \Gamma^{T}_{\text{Jup:EMB}} & \Gamma_{\text{EMB}} \end{pmatrix}$$

The a priori values of the elements of the 6 × 6 submatrices Γ_{Jup}, Γ_{EMB}, and $\Gamma_{\text{Jup:EMB}}$ are tabulated below.

Γ_{Jup}

	DMW5	DP5	DQ5	EDW5	DA5	DE5
DMW5	0.497×10^{-12}	0.112×10^{-14}	-0.231×10^{-14}	-0.300×10^{-13}	-0.172×10^{-13}	-0.600×10^{-14}
DP5	0.112×10^{-14}	0.284×10^{-12}	0.153×10^{-13}	-0.345×10^{-15}	-0.555×10^{-16}	0.234×10^{-15}
DQ5	-0.231×10^{-14}	0.153×10^{-13}	0.273×10^{-12}	-0.230×10^{-15}	0.290×10^{-16}	-0.304×10^{-15}
EDW5	-0.300×10^{-13}	-0.345×10^{-15}	-0.230×10^{-15}	0.710×10^{-13}	0.186×10^{-14}	0.499×10^{-14}
DA5	-0.172×10^{-13}	-0.555×10^{-16}	0.290×10^{-16}	0.186×10^{-14}	0.820×10^{-15}	0.414×10^{-15}
DE5	-0.600×10^{-14}	0.234×10^{-15}	-0.304×10^{-15}	0.499×10^{-14}	0.414×10^{-15}	0.683×10^{-13}

Γ_{EMB}

	DMWB	DPB	DQB	EDWB	DAB	DEB
DMWB	0.134×10^{-13}	-0.153×10^{-15}	0.767×10^{-16}	0.189×10^{-15}	-0.243×10^{-16}	-0.382×10^{-17}
DPB	-0.153×10^{-15}	0.124×10^{-13}	-0.978×10^{-16}	-0.711×10^{-18}	0.327×10^{-18}	0.814×10^{-18}
DQB	0.767×10^{-16}	-0.978×10^{-16}	0.135×10^{-13}	0.222×10^{-17}	-0.132×10^{-18}	-0.525×10^{-18}
EDWB	0.189×10^{-15}	-0.711×10^{-18}	0.222×10^{-17}	0.326×10^{-17}	-0.288×10^{-18}	-0.904×10^{-19}
DAB	-0.243×10^{-16}	0.327×10^{-18}	-0.132×10^{-18}	-0.288×10^{-18}	0.830×10^{-19}	0.147×10^{-19}
DEB	-0.382×10^{-17}	0.814×10^{-18}	-0.525×10^{-18}	-0.904×10^{-19}	-0.904×10^{-19}	0.135×10^{-18}

$\Gamma_{\text{Jup:EMB}}$

	DMWB	DPB	DQB	EDWB	DAB	DEB
DMW5	0.338×10^{-14}	-0.640×10^{-16}	-0.343×10^{-17}	0.476×10^{-16}	-0.618×10^{-17}	-0.973×10^{-18}
DP5	-0.638×10^{-16}	0.286×10^{-15}	-0.363×10^{-14}	-0.126×10^{-17}	0.556×10^{-19}	0.158×10^{-18}
DQ5	-0.382×10^{-16}	0.340×10^{-14}	0.118×10^{-15}	-0.133×10^{-18}	0.810×10^{-19}	0.216×10^{-18}
EDW5	0.159×10^{-16}	-0.118×10^{-17}	0.128×10^{-17}	0.298×10^{-18}	0.280×10^{-19}	0.420×10^{-19}
DA5	-0.701×10^{-16}	0.189×10^{-17}	-0.970×10^{-18}	-0.810×10^{-18}	0.253×10^{-18}	0.453×10^{-19}
DE5	-0.809×10^{-17}	0.347×10^{-17}	-0.981×10^{-19}	-0.241×10^{-18}	0.224×10^{-19}	0.189×10^{-19}

Table 5. Current best estimates of encounter parameters (from S. K. Wong/JPL Pioneer Operations)

$$B \cdot R = 208887 \pm 54 \text{ km}$$

$$B \cdot T = 836151 \pm 14 \text{ km}$$

Table 6. Tracking data summary for Pioneer 10 encounter phase

Station ID	Data type	Time of first point	Time of last point	Total number of points
DSS 12	Two-way doppler	10/5/73, 02:42:32	11/16/73, 00:57:32	129
DSS 43	Two-way doppler	10/6/73, 08:52:32	12/6/73, 11:28:32	1305
DSS 14	Two-way doppler	10/12/73, 02:57:32	12/6/73, 03:09:32	443
DSS 14	Three-way doppler	11/22/73, 20:08:32	12/6/73, 03:32:32	89
DSS 43	Three-way doppler	11/23/73, 01:09:32	12/6/73, 03:09:32	159
DSS 63	Three-way doppler	11/23/73, 12:44:02	12/3/73, 12:13:32	13
DSS 63	Two-way doppler	11/26/73, 14:23:32	12/6/73, 16:13:32	329

Table 7. Parameters modeled in Pioneer 10 encounter simulation

Parameter description	Number of parameters	Range rate data Estimate	Range rate data Consider
EME 1950 Cartesian state vector at epoch	6	√	
Mass of Jupiter	1		√
Modified Jupiter Set III ephemeris parameters	6		√
DSS 51, 61, 14 off-axis distances and longitudes	6		√
Jupiter oblateness	1		√
Mass of Galilean satellites	4		√
Axial coordinates of DSS 51, 61, 14	3		√

Table 8. A priori parameter uncertainties for simulation

Parameter	A priori σ	Comments
Position	10^5 km	
Velocity	1 km/s	
GM 5	2×10^3 km^3/s^2	
Off-axis station location	5 meters	
Axial station location	10 meters	
Station longitude	10^{-4} deg	
J205	1.469×10^{-4}	1% nominal
GM Io	4.827×10^3 km^3/s^2	100% nominal
GM Europa	3.140×10^3 km^3/s^2	100% nominal
GM Ganymede	1.039×10^4 km^3/s^2	100% nominal
GM Callisto	6.449×10^3 km^3/s^2	100% nominal
Frequency bias	100 mHz	~3 × MM'71 estimate

Table 9. Modified Set III Jupiter ephemeris covariance at encounter for simulation

	DA	DE	DMW	DP	DQ	EDW
DA	2.893×10^{-13}	1.963×10^{-13}	9.996×10^{-14}	2.433×10^{-16}	-8.969×10^{-16}	-1.867×10^{-13}
DE	1.963×10^{-13}	1.946×10^{-13}	7.288×10^{-14}	8.254×10^{-16}	-1.751×10^{-15}	-1.233×10^{-13}
DMW	9.996×10^{-14}	7.288×10^{-14}	5.189×10^{-13}	2.391×10^{-15}	-4.858×10^{-15}	-1.041×10^{-13}
DP	2.433×10^{-16}	8.254×10^{-16}	2.391×10^{-15}	2.703×10^{-13}	-1.267×10^{-14}	-1.070×10^{-16}
DQ	-8.969×10^{-16}	-1.751×10^{-15}	-4.858×10^{-15}	-1.267×10^{-14}	2.952×10^{-13}	-3.723×10^{-16}
EDW	-1.867×10^{-13}	-1.233×10^{-13}	-1.041×10^{-13}	-1.070×10^{-16}	-3.723×10^{-16}	1.869×10^{-13}

Table 10. Epoch and initial heliocentric EME 1950 state vector for simulation

Epoch = Nov. 3, 1973 $03^h00^m00^s.0000$
X = $0.533909756719 \times 10^9$ km
Y = $-0.460598183846 \times 10^9$ km
Z = $-0.212212398617 \times 10^9$ km
DX = $0.101088969303 \times 10^2$ km/s
DY = 0.754694585646 km/s
DZ = 0.525514523035 km/s

Table 11. Computer codes

Code name	Reference	Comments
ATHENA	Nishimura, T., and Nead, M., 900-605, "ATHENA Filter Sequential Orbit Determination Program with General Evaluation Capability," Mar. 8, 1973	System consists of three links: (1) REVA—An orbit data simulator (2) TOSCA—A statistical filter. Accepts both simulated regress files from REVA and type 66 regress files from SATODP (3) SCAN—Routine for coordinate-time mapping
Modifications to ATHENA	Hildebrand, C. E. (unpublished)	MACK—A modified version of the REVA simulator which accounts specifically for the accelerations due to the massive Jovian satellites
DERIVE	Rourke, K. and Finley S., IOM 391.7-59 (a JPL internal document), Sep. 29, 1972	Code combines ATHENA-simulated two- and three-way regress files to produce simulated differenced (QVLBI) regress files. Accounts for frequency biases between pairs of stations. It is specifically adapted to accept regress files in the format produced by the ATHENA simulation link
ODE	Bramble, P. L., Jr., 610-188, "Mariner Mars 1971 Orbit Data Editor User's Guide" (a JPL internal document) Bramble, P. L., Jr., IOM 914.34/120 (a JPL internal document), Mar. 4, 1973	Performs following tasks: (1) Decodes IBM 360 tracking data tapes to produce raw tracking data files (2) Merges raw tracking data files (3) Edits data; removes user-selected data from file to produce file with only those data actually to be used (4) On request compresses doppler data to user-specified count-times (5) Merges edited/compressed data files
SATODP/Version D	Moyer, T. D., JPL TR 32-1527, Mathematical Formulation of the Double-Precision Orbit Determination Program, July 15, 1971	Implements an (almost) exhaustively detailed model of spacecraft motion in the solar system and uses it in conjunction with the method of differential corrections to set up and solve nonlinear regression analyses of many kinds of measured observables which depend on large numbers of parameters. Its modular (link) structure makes it possible to perform selected combinations of the basic computational tasks which together constitute a complete orbit determination calculation
DIFFER	Johnson, D. E., TM 391-333 (an internal document), June 9, 1972	Combines two- and three-way data files in SATODP (type 66) regress file format to produce QVLBI (differenced) data files in the same format. It incorporates a priori values, variances, and data partials with respect to frequency biases into the QVLBI file

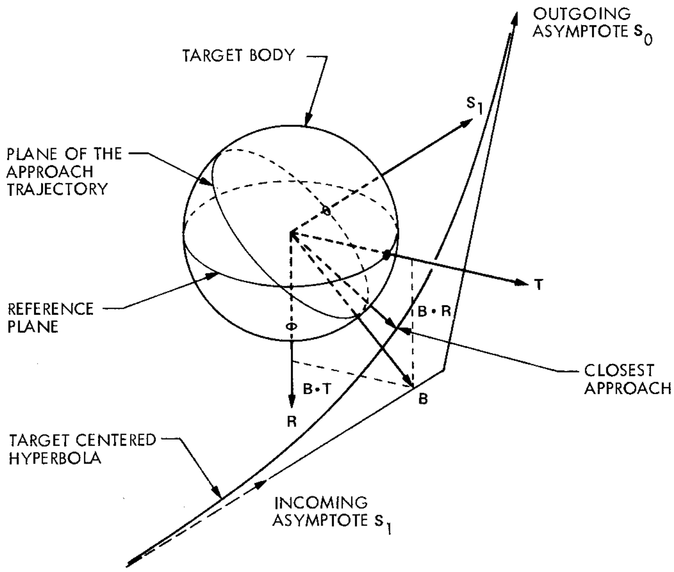

Fig. 1. Target parameters

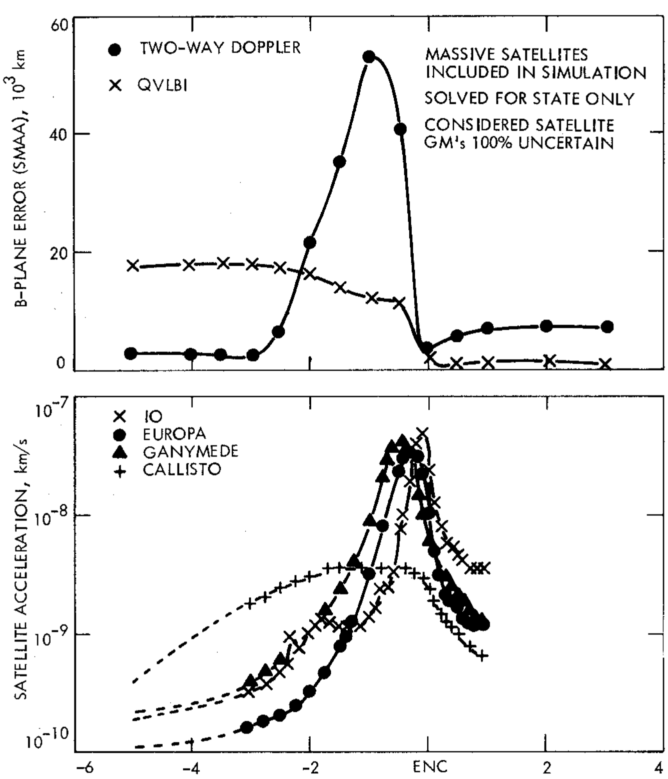

Fig. 2. Simulation study of B-plane errors

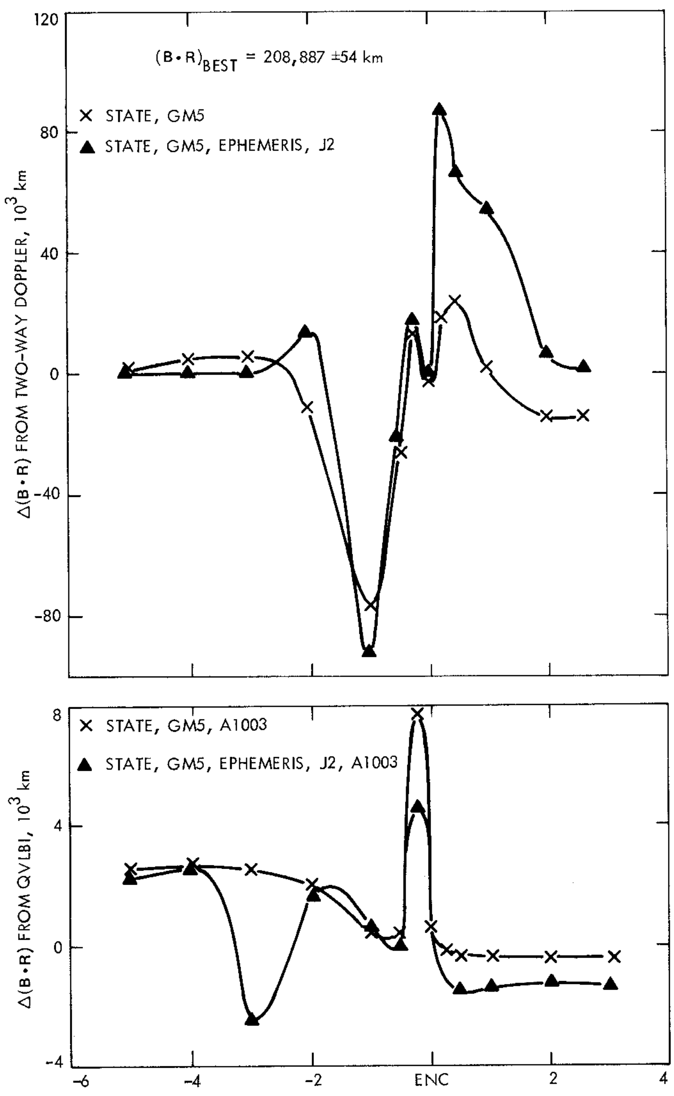

Fig. 3. $\Delta(B \cdot R) = B \cdot R - (B \cdot R)_{best}$ vs time from encounter

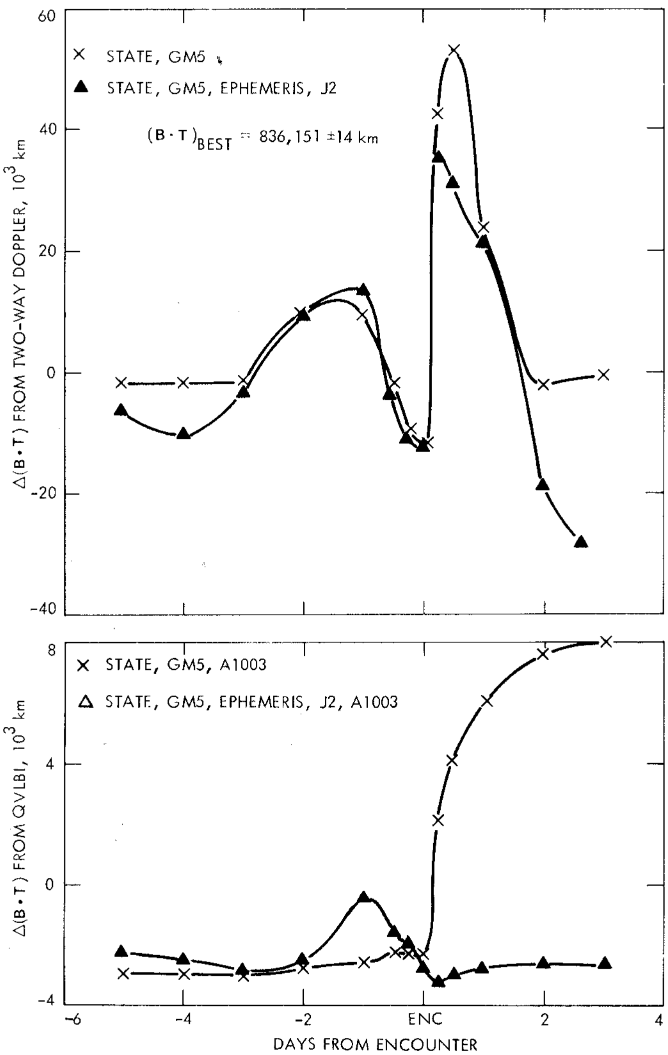

Fig. 4. $\Delta(B \cdot T) = B \cdot T - (B \cdot T)_{best}$ **vs time from encounter**

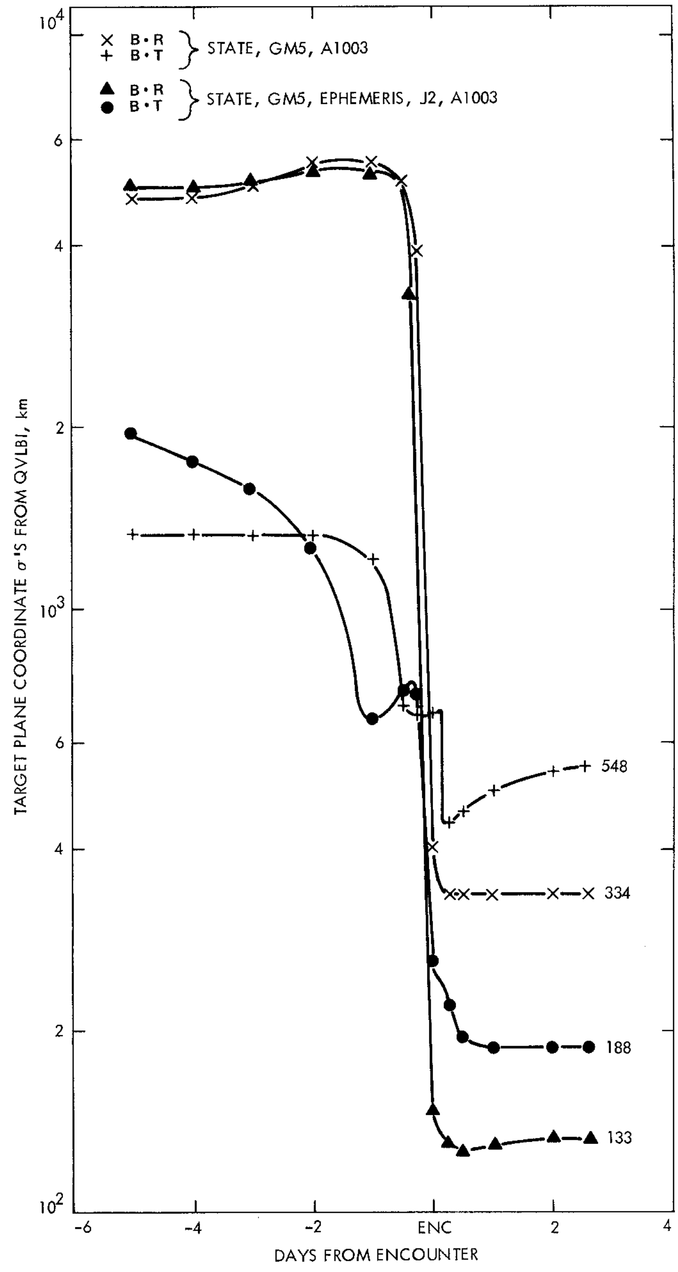

Fig. 5. Uncertainties in B · R and B · T vs time from encounter