Mission Applications of the Dual Spacecraft Tracking Technique

C. C. Chao and J. P. McDanell
Navigation Systems Section

This article discusses the potential application of the dual spacecraft tracking technique to the Voyager mission. First, the concept and technology status is reviewed briefly. Then results pertaining to the JSX-Uranus option Saturn encounter, where potential navigation benefits are greatest, are presented. Results for a Jupiter encounter demonstration also are given and, finally, software modifications and tracking requirements are discussed.

I. The Concept

When two interplanetary spacecraft lie along similar geocentric lines-of-sight, significant navigation advantages may sometimes be achieved by differencing data acquired simultaneously from the two spacecraft and, in effect, determining the orbit of the second encountering spacecraft relative to the first rather than treating them independently. The potential benefits result from reduced sensitivity to at least three of the major error sources affecting orbit determination with radiometric data. First, and probably most important, is reduced sensitivity to target ephemeris errors. After encounter, the trajectory of the first spacecraft is known precisely relative to the planet. Thus, the second spacecraft may be accurately tied to the planet through the first. Second, the effect of platform parameter errors is reduced. When the two spacecraft are tracked simultaneously from nearby ground stations, errors common to both stations cancel when the data are differenced. The reduced sensitivity to station location errors that results should also make the low declination problem of orbit determination somewhat less severe. Finally, when the angular separation between the two lines-of-sight is very small, most of the transmission media effects should also cancel. The geocentric information that is lost by differencing the data may be

easily restored by including a suitable amount of conventional range and/or doppler, deweighted to avoid reintroducing the error sensitivities.

II. Technology Status

Extensive studies of dual spacecraft tracking have been performed (Refs. 1-3) including analytic investigation of the information content of dual spacecraft data types and two flight demonstrations with the Viking spacecraft, one during early cruise and the other during the approach phase of Viking 2. Results indicate that dual spacecraft data types may improve navigation accuracy by a factor of 2 to 10 under the conditions of small angular separation of the two spacecraft and well determined trajectory of the reference spacecraft.

The most recent demonstration conducted with the two Viking spacecraft during the approach phase is worth special attention. With only 8 days of dual spacecraft tracking, the actual B-plane error of the trailing spacecraft was determined to better than 200 km compared with 1000 km for the same data arc using conventional radiometric data. The 1000 km error using conventional data is believed to be due to large

plasma noise (SEP ≅ 17 deg), low declination (δ < 5 deg) and station location errors. Reduced sensitivity to planet ephemeris errors was also verified in this demonstration by introducing an intentional 2000 km error in the Mars ephemeris. Dual spacecraft tracking gave a factor of 10 improvement over conventional data in the presence of this large ephemeris error. Although the Viking orbiter/approach configuration differs substantially from the Voyager dual flyby, the Viking demo has verified feasibility of the concept and gives confidence that the potential benefits for Voyager can, in fact, be realized.

III. Application to the Uranus Option Saturn Encounter

The Uranus option mission is well suited for a dual spacecraft strategy for the following reasons:

(1) The Uranus option for the second spacecraft will not be exercised unless a successful Saturn encounter is achieved by the lead spacecraft. Thus, the assumption that the first spacecraft will be available as a reference for the Uranus-targeted spacecraft is valid.

(2) The Uranus option trajectory design on certain launch days stretches propellant reserves nearly to the limit (Ref. 4). A precise Saturn encounter by the second spacecraft will reduce the magnitude of the post-Saturn maneuver and increase the probability of having sufficient propellant for a successful Uranus encounter. In fact, if a large injection error or other propellant-wasting event should occur, the dual spacecraft strategy might be a means of preserving the Uranus option without relying entirely upon optical navigation.

A series of simulated analyses of dual spacecraft tracking for the JSX-Uranus option at Saturn have been carefully performed. The data distribution and arc length of the conventional data types for the second spacecraft are the same as used for the baseline analysis reported in Section 2 of Ref. 5. (Note that "conventional" data in this context include dual station doppler and near-simultaneous range.) For the dual spacecraft tracking simulation, the approach tracking pattern for the second spacecraft was duplicated during the same time interval for the first spacecraft, which at this point has already flown by Saturn and is nine months ahead of the second. The encounter analysis was done using both two-station and four-station dual spacecraft data types. The data types will be described as the results for each are presented.

A. Results Using Dual Spacecraft Two-Station Data

Dual spacecraft two-station differenced doppler is formed by differencing conventional two-way doppler received simultaneously from the two spacecraft by two stations within the same station complex. Dual spacecraft two-station differenced range is constructed in the same manner, but can be obtained only at the Goldstone complex where two range machines are available. In this analysis two-station differenced doppler is weighted at 15 mHz (1 mm/s) at 60-s integration time, and the conventional doppler, if included, is loosely weighted at 150 mHz to retain the geocentric range rate information without degrading the planet relative information. The two-station differenced range is weighted at 20 m, and the conventional range (near-simultaneous) is loosely weighted at 1 km. Based on various combinations of these data types and different strategies of estimation, a series of B-plane solutions were obtained. These solutions may be grouped into two kinds: (1) estimating the state of the second spacecraft and considering the state of the first one, (2) estimating the state of both spacecraft. Both (1) and (2) are considering station locations and range biases as error sources that are not estimated. The results are given in Fig. 1.

The improvements in navigation accuracy of the second spacecraft using two spacecraft tracking depend heavily on how well the first spacecraft is tied to the planet during the approach of the second one. A post flyby long arc solution (radio only) of the first spacecraft was tried, and it yielded a position error of about 250 km relative to Saturn at the epoch of the trajectory of the trailing spacecraft. Later this is used as the a priori covariance for the state of the first spacecraft whether it is considered or estimated.

B-plane solutions of the first kind, where the first spacecraft state is considered, show significant improvements from the results of conventional radiometric data types beginning about 11 days before encounter. These solutions, which give a time history of Saturn B-plane statistics as shown by the uppermost broken line in Fig. 1, are based on dual spacecraft two-station doppler combined with loosely weighted conventional range (no conventional doppler) with nongravitational accelerations of both spacecraft estimated stochastically. The rapid increase in B-plane accuracy during the last 10 days of Saturn approach would offer substantial benefit to the mission if the final approach maneuver could be delayed to, say, E-7 days. Delivery and knowledge accuracy would be improved by 35% and 60%, respectively, in this case. The local maximum at E-18 days is believed to be due to the fact that the sensitivity to the reference spacecraft is magnified by the zero declination of the second spacecraft which occurs at E-22 days. This sensitivity becomes even greater when the dual spacecraft two-station range is included. These large sensitivities suggest that the state of the first spacecraft should be estimated as well.

When the states of both spacecraft are estimated, improvements in B-plane accuracy occur much earlier as may be seen

from the appropriate curves in Fig. 1. The data set used in generating these orbit determination (OD) solutions is the same as for the first cases except that dual spacecraft two-station range is also included. The upper curve of the two where both spacecraft states are estimated represents the case where stochastic nongravitational accelerations from both spacecraft are estimated sequentially with a two-day batch size and a one-day correlation time. The B-plane accuracy improvement after E-8 days is fairly consistent with the first case, where the state of the first spacecraft is not estimated, but the performance prior to E-8 days is dramatically improved. Because the improvement occurs earlier in this case, it would not be necessary to delay the final approach maneuver from its nominal time at E-10 days in order to realize the potential benefits of this strategy.

If the stochastic unmodelled accelerations from both spacecraft are assumed to be negligible during the Saturn approach, sequential estimation of these parameters becomes unnecessary, and further improvement in B-plane accuracy may be expected as shown by the lower curve in Fig. 1. A factor of 4 improvement in both delivery and knowledge may be possible provided that the above optimistic assumption is valid.

B. Results Using Dual Spacecraft Four-Station Doppler

The sensitivity to nongravitational accelerations indicated by the difference between the two lower curves in Fig. 1 and the sensitivity to the state of the reference spacecraft indicated by the upper curve provide the motivation for considering the use of dual spacecraft four-station doppler data. If the same spacecraft is simultaneously tracked from two widely separated tracking stations such as Goldstone and Australia, differencing of the corresponding doppler data from the two stations provides differenced doppler that is unaffected by geocentric range rate changes and hence relatively uncorrupted by unmodelled spacecraft accelerations. With dual spacecraft tracking the differenced doppler data from both spacecraft will again be differenced. This twice differenced new data type requires simultaneous tracking by four stations, and thus is called dual spacecraft four-station doppler.

This new data type is insensitive to nearly all the error sources usually associated with radiometric data, and therefore the OD capabilities depend heavily on the quality and quantity of such data within a given arc of the trajectory. In this analysis, during the three station overlaps of each tracking cycle (as defined in Section 2.1.2 of Ref. 5) a total of 8 to 10 hours of dual spacecraft four-station doppler was generated. Four different OD solutions were tried using this data, and the resulting B-plane histories are shown in Fig. 2. The two curves shown with nonuniform dashed lines are the results of the

same estimation strategy (estimating the state of the second spacecraft and the constant part of nongravitational accelerations and considering the state of the first spacecraft and station locations) with different data weights. The upper curve has the four-station doppler weighted at the standard 1 mm/s with conventional range loosely weighted; the lower one has the weight of the four-station doppler reduced to 0.5 mm/s to account for the expected improvement in data quality after double differencing. It is clear that the improvement in navigation depends strongly on the quality of this new data type which has not yet been demonstrated.

Although a 40% improvement in delivery may be possible with the four-station doppler and conventional range, the improvement at the knowledge point is not as good as that of dual spacecraft two-station data. This is because the information contained in the four-station doppler observables consists only of the differential angles between the two spacecraft, which are less effective in determining the bending of the trajectory caused by the planet than the differential range and range rate information in the two-station data types. The range rate information may be provided by including loosely weighted conventional doppler. The results for this case are given by the remaining two dashed curves in Fig. 2, which show substantial improvement after E-5 days, where planetary bending begins to occur.

The two-station and four-station dual spacecraft data types were analyzed separately to determine the characteristics and accuracy potential of each. The four-station doppler is "cleaner" and less vulnerable to unmodelled accelerations, but its information content is less, and it can only be obtained during view period overlaps between stations. It may be possible to gain the advantages of both by combining them in a single solution. However, the strategy for doing this (relative data weights, choice of estimated parameters, etc.) must be carefully investigated as new error sensitivities may be introduced by the combined data set which will offset the potential advantages.

IV. Demonstration Opportunity at Jupiter

Although the Viking demonstrations were successful, further verification of dual spacecraft tracking for the Voyager application is needed for the following reasons:

(1) Four-station dual spacecraft data was not available during the Viking demonstrations; therefore, its quality is uncertain and its utility has not been verified.

(2) Angular separation of the Viking spacecraft at encounter was extremely small (0.15 deg). Voyager separation will be 5 to 6 deg at Jupiter, 9 deg at Saturn.

(3) In the Viking encounter demonstration the reference spacecraft was an orbiter. Voyager is a dual flyby with relatively large time separation between encounters.

(4) The information content of the differenced data is a function of local accelerations, which will be quite different for the massive outer planets than for Mars.

The Voyager dual flyby at Jupiter provides a good opportunity to demonstrate this technique for application at Saturn. Furthermore, if the test can be conducted in near-real time, the results may be of direct benefit for navigation of the trailing spacecraft at Jupiter. To determine the potential navigation enhancement at Jupiter, analysis was performed using the JSX-CB10 encounter. This trajectory was selected because it is the more difficult of the two JSX Jupiter encounters considered in the baseline analysis. The Jupiter relative and Callisto relative B-plane time histories for dual spacecraft tracking are compared with the corresponaing baseline results in Figs. 3 and 4, respectively.

Figure 4 shows that dual spacecraft two-station data are capable of reducing Callisto relative errors to the level of the satellite ephemeris error (300 km) at the delivery epoch (E-13.5 days) and gives a factor of 3 improvement over conventional data at the knowledge epoch (E-3.5 days). The Jupiter relative improvement shown in Fig. 3 is more dramatic, since it results from the combination of a direct effect (reducing Jupiter relative errors which exist prior to the Callisto flyby) and an indirect effect (reducing the magnitude of the Callisto perturbation uncertainty by reducing Callisto relative errors).

The relative performance of the two-station and four-station dual spacecraft data types at Jupiter is similar to that observed in the Saturn encounter analysis. However, since the conventional data performance is better at Jupiter, the four-station· doppler (with its limited information content) does not show substantial improvement over the baseline results until fairly close to encounter, near the knowledge epoch. This is true even though the four-station doppler was assumed to be of high quality in this analysis (0.5 mm/s).

V. Tracking and Data Processing Requirements

Dual spacecraft tracking, by definition, requires the acquisition of radiometric data simultaneously from two spacecraft. This means, of course, that the first spacecraft must be given relatively dense tracking coverage during the approach phase of the second, which would normally be a quiescent period for the first. However, the Viking demonstrations and covariance analyses have shown that relatively short arcs of dual spacecraft data are effective (a characteristic that is shared with differential VLBI, which is very similar to dual spacecraft tracking in principle). Therefore, tracking requirements are not excessive. In fact, one of the potential benefits of dual spacecraft tracking is an overall reduction of tracking time.

Dual spacecraft tracking requires no hardware changes and only minor modifications to navigation software. For the Viking demonstrations a special version of the program ODE was created to maintain simultaneity of dual spacecraft doppler after editing and compression. Another special program was developed to difference the two-station and four-station data types. The differenced data can be processed by the Voyager ODP with no additional modifications. The demonstration software is available and can serve as a prototype software.

References

1. Preston, R. A., "Dual Spacecraft Radio Metric Tracking," *The Deep Space Network Progress Report 42-22*, JPL May to June 1974.

2. Chao, C. C., Siegel, H. L., and Ondrasik, V. J., "Improvements in Navigation Resulting from the Use of Dual Spacecraft Radiometric Data," *The Deep Space Network Progress Report 42-38*, April 15, 1977.

3. Chao, C. C., "A Demonstration of Dual Spacecraft Tracking Conducted with the Viking Spacecraft During the Approach Phase," Paper presented at the AAS/AIAA Astrodynamics Conference, Jackson, Wyoming, Sept. 7-9, 1977, and published in this issue of DSN Progress Report pp.

4. PD 618-115, Rev. A, Voyager Navigation Plan, 20 April 1977 (JPL internal document).

5. McDanell, J. P., et al., "Voyager Orbit Determination Strategy and Accuracy," PD 618-118, 1 August 1977.
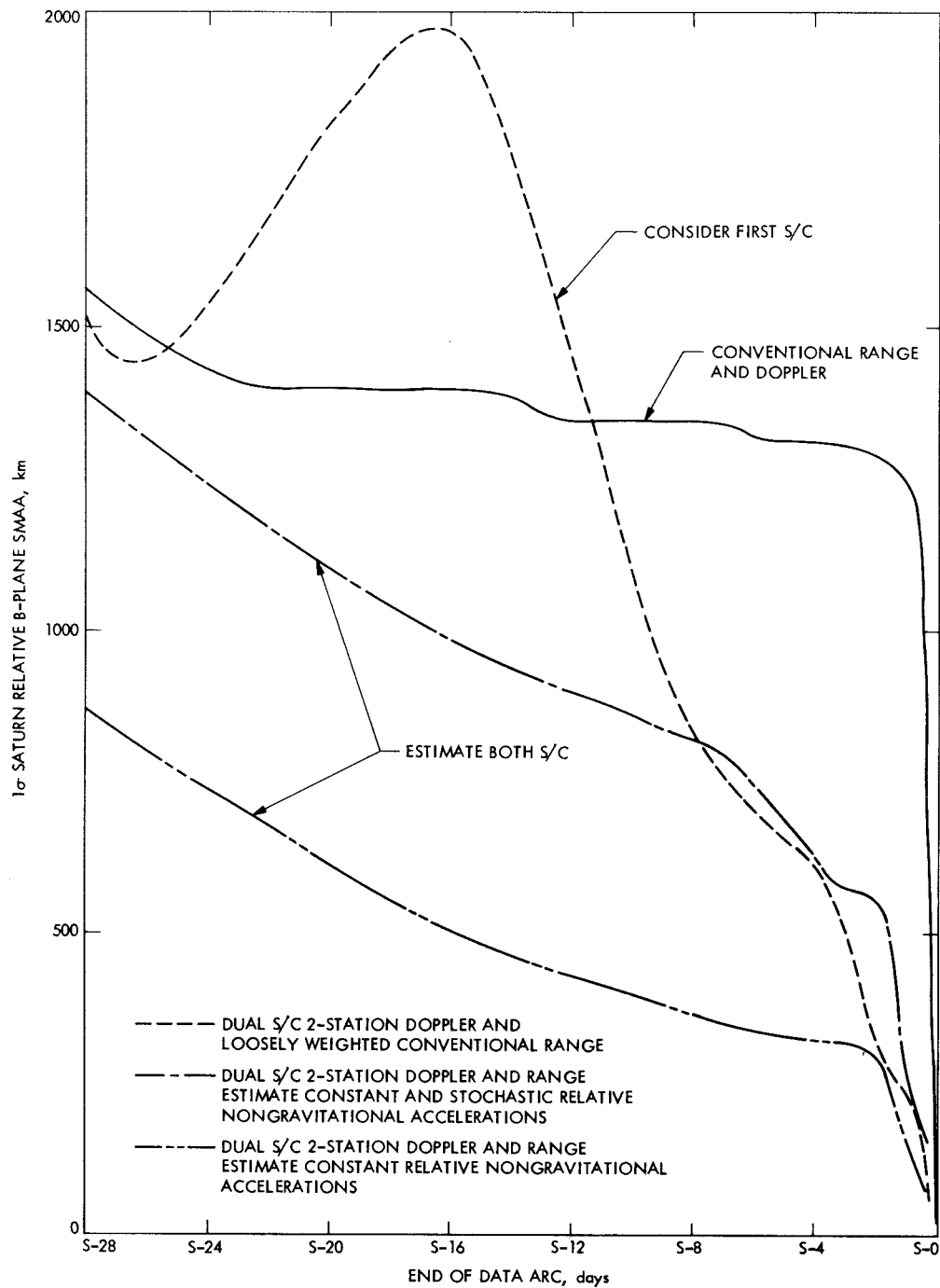
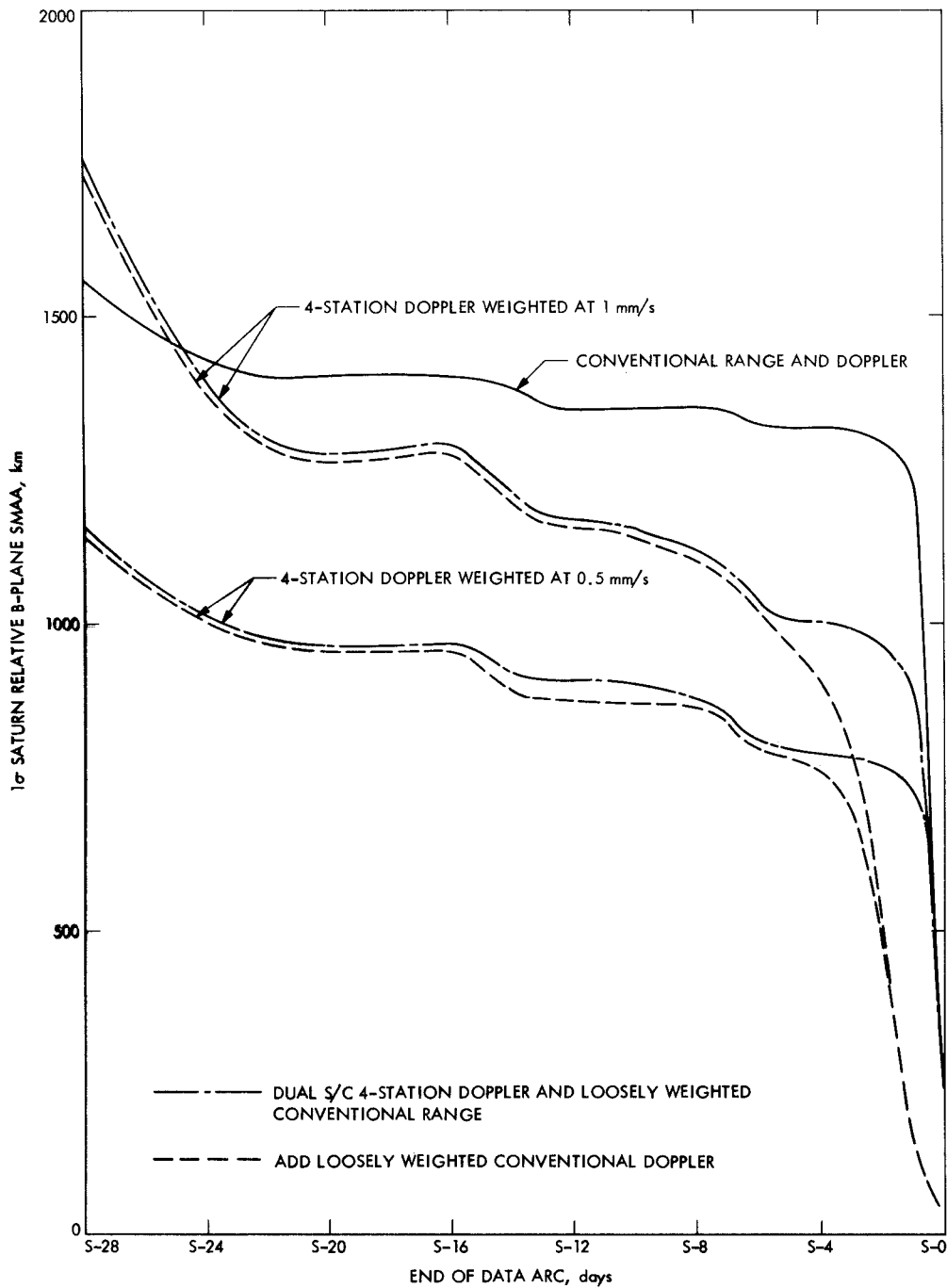Fig. 1. JSX-Uranus option Saturn relative B-plane errors using dual spacecraft
two-station data

Fig. 2. JSX-Uranus option Saturn relative B-plane error using dual spacecraft four-station doppler
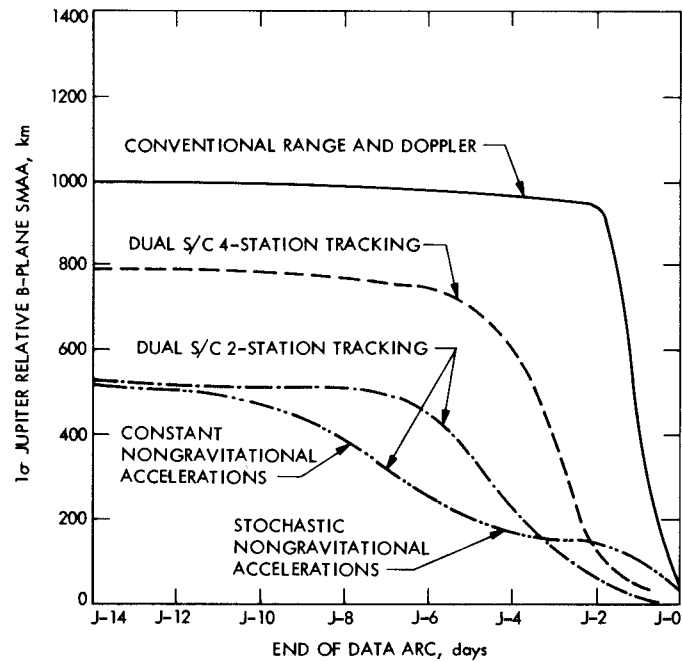
**Fig. 3. JSX-CB10 Jupiter relative B-plane errors with dual
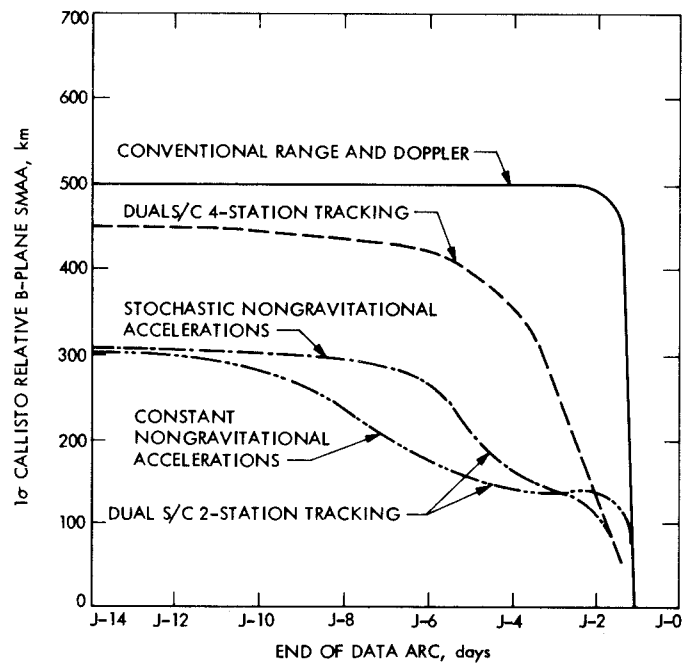spacecraft tracking**

**Fig. 4. JSX-CB10 Callisto relative B-plane errors with
dual spacecraft tracking**