Preliminary Performance Analysis of an Interplanetary Navigation System Using Asteroid Based Beacons

J. Rodney Jee,* Ahmad R. Khatib,† Ronald J. Muellerschoen,* and Bobby G. Williams*
California Institute of Technology, Pasadena, California
and
Mark A. Vincent‡
University of Colorado, Boulder, Colorado

A futuristic interplanetary navigation system using transmitters placed on selected asteroids is introduced. This network of space beacons is seen as a needed alternative to the overly burdened Deep Space Network. Covariance analyses on the potential performance of these space beacons located on a candidate constellation of eight real asteroids are initiated. Simplified analytic calculations are performed to determine limiting accuracies attainable with the network for geometric positioning. More sophisticated computer simulations are also performed to determine potential accuracies using long arcs of range and Doppler data from the beacons. The results from these computations show promise for this navigation system.

Introduction

SUPPOSE transmitters were to be placed on asteroids to serve as navigation beacons for interplanetary spacecraft. What is the potential performance of a navigation system based on the use of such space beacons? Can the asteroids' ephemerides be determined to enough accuracy to allow the transmitters to be useful signal sources? What might be an effective arrangement for such a constellation of space beacons? Can range data from the beacons be used for simple passive geometrical navigation of spacecraft? These are some of the questions we begin to answer in this study. To answer most of these questions, we perform standard covariance calculations of the space beacon based estimators of spacecraft state. Both simple analytic considerations and more sophisticated computer simulations are presented in this paper.

A major objective in placing transmitters on selected asteroids is to provide a tracking network for navigating interplanetary spacecraft. Any vision of a future where interplanetary missions are more frequent occurrences must include an alternative to the current, overloaded navigation system using the Deep Space Network (DSN). This study was further motivated by positive results from a previous analysis[1] that showed the utility of lunar beacons for near-Earth navigation. The asteroid beacon system proposed in this paper will do for interplanetary spacecraft what the current Global Positioning System (GPS) will do for Earth-orbiting satellites. As with GPS, an objective of the space beacon network will be to provide the capability for accurate passive geometrical interplanetary navigation that paves the way for autonomous navigation. Similarities of the asteroid beacons system to the GPS inspire the name Universal Positioning System (UPS) for the project.

Presented as Paper 86-2217 at the AIAA/AAS Astrodynamics Conference, Williamsburg, VA, Aug. 18–20, 1986; received Aug. 28, 1986; revision received March 12, 1987.

*Member Technical Staff, Navigation Systems Section, Jet Propulsion Laboratory.

†Member Technical Staff, Mission Design Section, Jet Propulsion Laboratory. Member AIAA.

‡Postdoctoral Fellow, Joint Institute for Laboratory Astrophysics.

From a broader point of view, other major objectives of the UPS implementation fall under the category of scientific and technological goals. The science objectives include exploration of the asteroids, measurement of the solar plasma, experiments involving solar coronal occultation, calibration of the interplanetary and terrestrial media, and monitoring for gravitational waves predicted by some gravitational theories. The technological goals in UPS implementation will be the application of various mature advanced products such as 1) low-thrust propulsion spacecraft enabling a multiload space vehicle to make soft deliveries of beacons to various asteriods; 2) transmitters with band selection, reliability, and power sources developed to give the UPS beacons useful signal strength and longevity; and 3) artificial intelligence expert systems that will make practical the operation and utilization (by means of autonomous navigation) of the remote beacons. From a fiscal viewpoint, the UPS project can be accomplished by sending the beacon package as a piggyback on outer planet missions that have sufficient surplus performance—thereby providing an economical implementation.

Because this is a pilot study on the use of asteroids as space beacon platforms, the analysis in this paper is rather preliminary. Instead of attempting to answer the introductory questions in detail and with precision, we set a more modest objective of determining the theoretical bounds and limitations on the proposed interplanetary navigation system. This is accomplished by making simplifying assumptions and including a minimal number of parameters in the problem. The navigation system is then analyzed with a best likely set of values assigned to the parameters to determine its best likely performance. The remainder of this paper is organized as follows. An initial section on notation defines the terminology we use by means of a specific example. With that done, we state more precisely the limitations of this study. The next section is devoted to presenting some rough arguments on the choice of asteroids for the futuristic navigation system. This is followed by some estimates of the performance of the beacons in geometric navigation. Then, some results of computer simulations are presented to illustrate the performance potential of the system for typical planetary encounters. A brief discussion of results precedes the concluding remarks.

Notation

In this section, we introduce the notation and terminology used in this paper and quickly review the statistical framework of our study by considering a simple, special case of interest. Those unfamiliar with the framework should find Ref. 2 helpful. We denote the spacecraft state vector by $x = (x_1, x_2, \ldots)^T$ and do likewise for the asteroid beacon state vectors y_i (for $i = 1, \ldots,$ number of beacons). We will use the convenient abbreviation $y^T = (y_1^T, \ldots, y_n^T)$. An observation from a UPS transmitter is denoted z and its partial with respect to x is denoted

$$\frac{\partial z}{\partial x} = \left(\frac{\partial z}{\partial x_1}, \frac{\partial z}{\partial x_2}, \ldots\right)$$

and similarly for $\partial z/\partial y$. The basic navigation problem is to use the observations to improve a priori estimates of x and y (which in turn provide for estimates of z). The typical linearized least-squares approach is to write

$$\Delta z = \frac{\partial z}{\partial x}\Delta x + \frac{\partial z}{\partial y}\Delta y + \eta$$

where the measurement precision is modeled by η, which is uncorrelated Gaussian noise with mean 0 and variance σ_N^2. Solution of the system of equations provides corrections Δx to the estimated state. Since this study is concerned with measuring the accuracy of the navigation system, it is the covariance of Δx that is the appropriate item of interest.

A Special Case

We now consider the special case of geometric navigation where one set of range observables ρ_i is taken simultaneously from each of n beacons. In this case, the state vectors of the spacecraft and UPS beacons have position components only. Since the geometry of the spacecraft relative to the constellation of beacons does not change significantly over the transmission time of a signal from a UPS beacon to a spacecraft in the solar system, we assume instantaneous signal transmissions to simplify the partial derivatives. Thus, with $\rho_i = \|x - y_i\|$, it is easy to derive that

$$\frac{\partial \rho_i}{\partial x} = \hat{\rho}_i^T \text{ (a unit vector)}$$

and that

$$\frac{\partial \rho_i}{\partial y} = (0^T, \ldots, -\hat{\rho}_i^T, \ldots, 0^T)$$

where the nonzero vector appears in the ith slot. If we assume zero errors in the UPS beacon positions, then the regression matrix for the restricted problem is

$$A_x = [\hat{\rho}_1, \ldots, \hat{\rho}_n]^T$$

and the corresponding covariance matrix of Δx is

$$\Sigma_x = \sigma_N^2[A_x^T A_x]^{-1}$$

A Useful Result

Additional uncertainties in Δx due to errors in the asteroid beacon positions are considered by augmenting the restricted covariance by adding the term $S\Sigma_y S^T$ where the sensitivity matrix

$$S = \Sigma_x A_x^T(\sigma_N^{-2} I)A_y$$

Σ_y is the a priori covariance of Δy and A_y is the matrix formed by stacking the partials of ρ_i with respect to y. Making a simplifying assumption that $\Sigma_y = \sigma_a^2 I$ and finding that $A_y A_y^T = I$, the considered covariance becomes

$$\Sigma = (1 + \sigma_a^2/\sigma_N^2)\ \Sigma_x = (\sigma_N^2/\sigma_a^2)(A_x^T A_x)^{-1}$$

This last equation allows us to cleanly separate the information, or more directly the covariance, from a set of range observations into a noise component and a geometric component. We will use this equation in the sections that follow.

Study Assumptions

The example of the previous section specifically defines the nature of the covariance analysis performed in this study and serves as the basis for all analytic calculations presented here. The additional covariance calculations based on computer simulations use long arcs of data and more accurately indicate the navigation potential of the UPS tracking network. However, the parameters directly involved in the covariance calculations are the same in both the simplified case and the computer simulations. The parameters are as follows: 1) the state vector of the spacecraft (both position and velocity components), 2) the a priori uncertainties in the position and velocity of the UPS beacons, and 3) the measurement precision associated with the observation type. Additional parameters such as uncertainties in the encountered planet's ephemeris, errors in the beacons' clocks, and media effects of the interplanetary plasma are not considered as would be done in more thorough mission tradeoff studies. The major dynamical simplifications of the computer model are as follows: 1) the mutual gravitational acceleration of the asteroids and the long-term evolution of their orbital interaction are ignored; 2) the rotational motion of the asteroids (and hence of the beacon antenna) is not modeled; 3) the accelerations of the spacecraft result totally from the Newtonian accelerations of the sun and the nine planets; and 4) the transmission times of the signals from the beacons to the spacecraft are instantaneous.

The computer programs used in this study are part of the orbiter analysis and simulation software (OASIS) developed at the Jet Propulsion Laboratory.[3] The OASIS is designed to provide the tools for covariance analyses of Earth-orbiting satellites using GPS-type navigation beacons. It provides for high-precision integration of satellite trajectories and variational equations in the IAU's J2000 inertial coordinate system. The OASIS's capabilities for covariance analyses are based on a numerically stable U-D factorized formulation.[2] Although the programs were primarily developed for Earth-orbiter tracking analysis, their capability for multisatellite parameter modeling and satellite-to-satellite measurement models makes them equally suitable for the present analysis. In view of the simplifications listed above, no software modifications to OASIS are necessary to perform this study; the transition from Earth-centered GPS-type analyses to sun-centered UPS-type analyses is performed by adjusting OASIS input parameters.

UPS Asteriods

For this initial study, the UPS asteroids are chosen such that their configuration relative to each other will remain fairly stable over several years time. This is most easily accomplished by picking asteroids from the asteroid belt that have similar orbital periods. A quick search came up with eight candidate asteroids that satisfy this criterion and are distributed evenly around the asteroid belt. One of the asteroids, 1976SR10, chosen for this hypothetical UPS constellation has a large inclination, while the remaining seven asteriods have inclinations below 7 deg. The eight asteroids selected and their orbit characteristics are presented in Table 1. The choice of eight asteroids is rather arbitrary. Determining an optimal number of asteroids for the UPS will be an issue for further study.

One immediate question over such a selection scheme concerns the amount of information in the z position component (the component orthogonal to the ecliptic plane) afforded by range data from a nearly planar configuration of beacons. We answer this question by employing the results on the covariance of geometric estimators presented above. In particular, we estimate the out-of-plane information content in one additional out-of-plane observation. First note that, since we are

Table 1 Asteroids selected for UPS study[a]

Name	a, a.u.	e	i, deg	Ω, deg	ω, deg	M, deg	T, years
1979XP	2.281892	0.1216595	4.61704	91.5566	285.6317	315.9503	3.447011
1974MH	2.283642	0.1527031	6.48194	346.2109	263.0668	136.2230	3.450976
ROXANE MU	2.286445	0.0849396	1.76562	150.9359	186.0711	87.6822	3.457333
1964VY	2.279888	0.1644087	1.09471	122.9319	313.2261	28.0070	3.442471
1977TO3	2.283683	0.0581467	2.75567	312.0034	105.5501	95.9585	3.451134
1982BT1	2.287560	0.1939849	3.93922	164.0444	49.7767	343.4623	3.459861
1976SR10	2.287749	0.1908836	22.39834	137.3683	303.4491	172.6867	3.460290
HEDDA C	2.284571	0.0285560	3.80267	28.8529	193.4744	76.4241	3.453083

[a]Angles references to Earth mean ecliptic, plane of 1950.0. Epoch date of 0 h Dec. 1, 1985. M = mean anomaly.

concerned only about the geometry of the problem and not the stochastic elements, we may set $\sigma_N^2 + \sigma_a^2 = 1$ and examine the resulting information matrix $(A_x^T A_x)$. Note also that we may write

$$(A_x^T A_x) = \sum_{i=1}^{n} (\hat{\rho}_i \hat{\rho}_i^T)$$

Now, suppose that n beacons are in the ecliptic plane as well as the spacecraft. Then, there is no out-of-plane information in the set of observations from these beacons. The 3×3 information matrix J_n, resulting from these n observations has the form

$$\begin{bmatrix} J_{xy} & \begin{pmatrix} 0 \\ 0 \end{pmatrix} \\ (0 \quad 0) & 0 \end{bmatrix}$$

Let the unit vector $\hat{\rho} = (x,y,z)^T$ be the partial of an additional observation and $\rho = (x_a,y_a,z_a)^T$, with a significant z component. Defining

$$\tilde{J}_{xy} = J_{xy} + (xy)^T(xy)$$

the augmented information matrix is

$$\begin{bmatrix} \tilde{J}_{xy} & \begin{pmatrix} xz \\ yz \end{pmatrix} \\ (xz \quad yz) & z^2 \end{bmatrix}$$

from which we obtain

$$\sigma_z^2 = \frac{1}{z^2\left[1 - (x\ y)\tilde{J}_{xy}^{-1}\begin{pmatrix} x \\ y \end{pmatrix}\right]}$$

With $\sigma_M^2 \equiv \|\tilde{J}_{xy}^{-1}\|$, we get the bound

$$\sigma_z \leq \frac{1}{|z|\sqrt{1-\sigma_M^2}} = \frac{\rho}{|z_a|\sqrt{1-\sigma_M^2}}$$

where the last equality is obtained by simple trigonometry. From this, we see that if enough beacons are uniformly distributed in the asteroid belt so as to provide good coverage in the ecliptic plane (thereby yielding low σ_M), the accuracy of the z component of the position estimator is essentially a function only of

$$\theta \equiv \sin^{-1}(|z_a|/\rho)$$

For example, if $\sigma_M \approx \frac{1}{2}$ (as can be achieved by a set of eight beacons for inner planets navigation) and $\theta \approx 5$ deg, then $\sigma_z \approx 11$. In such a case corresponding to asteroids with inclinations around 5 deg, the accuracy in the z component is about $\frac{1}{20}$th as good as the planar components. The situation improves if an asteroid with an inclination of 15 deg is included. With θ in the range of 10–20 deg the out-of-plane accuracy increases from $\frac{1}{7}$th to $\frac{1}{3}$rd of that in the plane. From these simple calculations, the value of having an asteroid with high inclination is clear.

Geometric Positioning

With a candidate constellation of UPS beacons selected, we now proceed to calculate the covariances of geometric estimators of position. For the calculations, the approximation derived earlier,

$$\Sigma = (\sigma_a^2 + \sigma_N^2)\left(\sum_{i=1}^{8} \hat{\rho}_i \hat{\rho}_i^T\right)^{-1}$$

is used. The numerical results in the discussion of this section are normalized by setting $\sigma_a^2 + \sigma_N^2 = 1$; thus, the stated values for the σ are dimensionless quantities. In addition, all of the calculations in this section are based on the configuration of the beacons on June 21, 1987. The results for three types of cases are presented graphically in Figs. 1–3. In these figures, the asteroids are represented by various symbols—the dark circles representing 1976SR10 with an inclination of 22 deg. Two plots are used to illustrate each case. A pair of plots shows complementary two-dimensional 1σ marginal ellipses in the plane of the respective components. The error ellipses in Figs. 1–3 are on the same scale to allow visual determination of relative sizes for the normalized error ellipses. Position scales on the figures are not applicable to the error ellipses except in locating the centers of the ellipses.

Figure 1 represents the shapes of the error ellipsoids for estimates of the spacecraft position at various points in the ecliptic plane within the asteroid belt. Figure 1b is a view up the z axis of the ecliptic plane. The values of both σ_x and σ_y fall between 0.5 and 0.6 for these points. Figure 1a provides a view complementary to Fig. 1b along the x axis. For these points, σ_z is 1.1–5.0. The value of having an asteroid with a large out-of-plane component is illustrated very clearly in Fig. 1a as the uncertainty in the z component is seen to grow linearly as a function of distance from the asteroid 1976SR10.

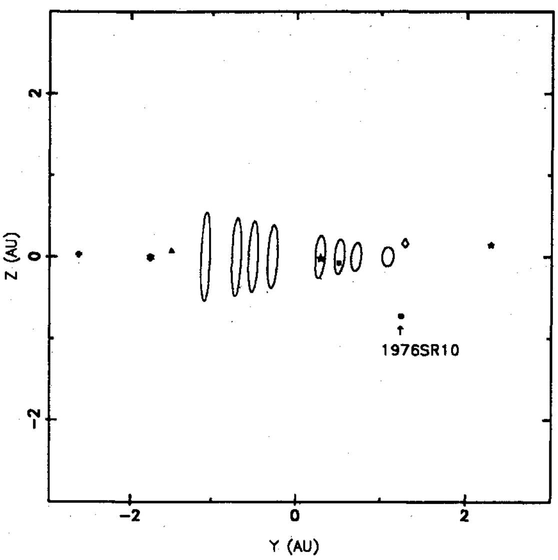
Figure 2 plots similar error ellipses for points in the ecliptic plane, but outside the asteroid belt. As before, the two figures show orthogonal views of the same error ellipsoids. The centers of the ellipses are located at positions with magnitudes about equal to the distances of the outer planets from the sun. For each ellipse in these plots $\sigma_x \approx \sigma_y$, while their value range is 0.9–6.1. The range of σ_z starts at 5.0 at a Jovian distance and increases to 51.8 at a Plutonian range.

Figure 3 depicts the error ellipsoids of geometric position estimators at points along a circular arc of radius 9 a.u. coming out of the ecliptic plane. As seen in Fig. 3a, the arc lies in the yz plane. At these points, $\sigma_z = 12.1$, 3.2, 1.2, and 0.4. The $\sigma_x,\sigma_y \approx 2$ except for the point in the ecliptic plane. For that point, $\sigma_y = 0.4$ and $\sigma_x = 2.2$.

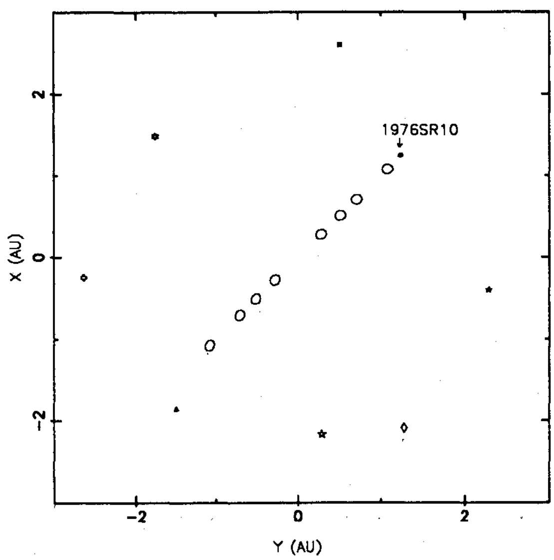
At this point, we draw some tentative conclusions on what these calculations show. First, the measurement precision of the observation σ_N and the uncertainty in the position components of the UPS beacons σ_a contribute equally to the considered covariance. Currently, the asteroids' ephemerides are known to 6000 km in position and 1 km/s in velocity. Since measurement precisions on the order of 1 m are achievable by today's technology, it is the accuracy of the UPS asteroid ephemerides that will be the limiting factor in navigation accuracy. If tracking of the UPS beacons can reduce the asteroids' location to an effective uncertainty of 1–10 km in position, then the asteroid beacons can be useful for geometric positioning for a wide range of interplanetary missions. For example, with $\sigma_a = 1$ km, the unit kilometer can be attached to all of the dimensionless results given in the preceding paragraphs of this section. The geometric positioning for spacecraft bound for the inner planets might have errors of less than 5 km in each position component. Because the only uncertainties included in these analytic calculations are measurement precision and UPS beacons positions, we cannot conclude that this is the type of accuracy to be expected with the UPS network. Instead, these numbers indicate a best possible limit achievable with the system.

Computer Simulations

The results of computer simulations using OASIS are presented in this section. The first cases are simulations of UPS beacon tracking by Earth stations. We use these results to estimate the accuracy to which the space beacons may be tracked. Three cases of interplanetary spacecraft tracking by the UPS are then presented. The three spacecraft tracking cases use the asteroid positions as considered parameters rather than additional estimated parameters. Concurrent estimation of the spacecraft and UPS beacons states will lead to higher predicted tracking accuracies than those resulting from the adopted scheme. The three spacecraft tracking cases are a Mars flyby, a



a) 1σ error ellipses for geometric positioning at points inside asteroid belt.



b) Complementary view of Fig. 1a from an orthogonal direction.

Fig. 1 Error ellipses in Figs. 1–3 are on the same scale to allow visual determination of relative sizes of all error ellipses. Position scales are not applicable to the error ellipses except in locating the centers of the ellipses.

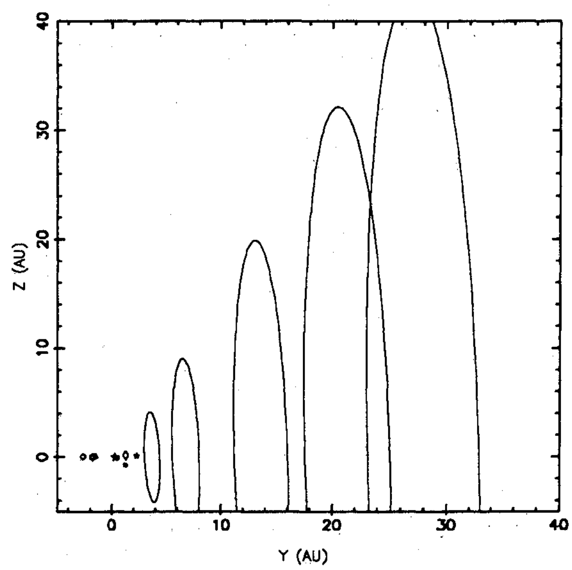


Fig. 2a 1σ error ellipses at points outside asteroid belt.

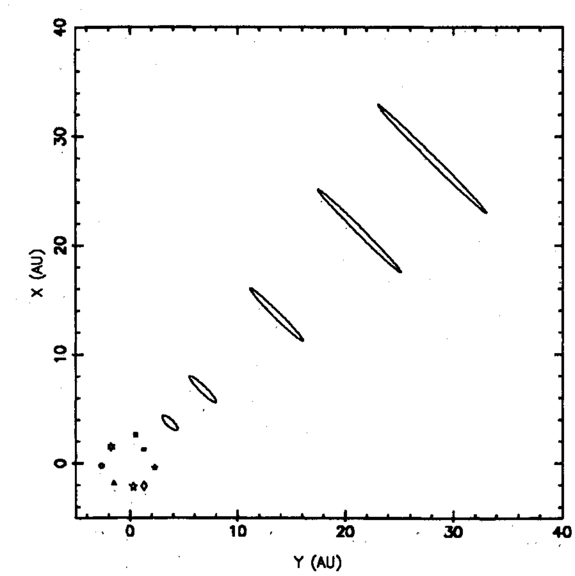


Fig. 2b Complementary view of Fig. 2a from an orthogonal direction.

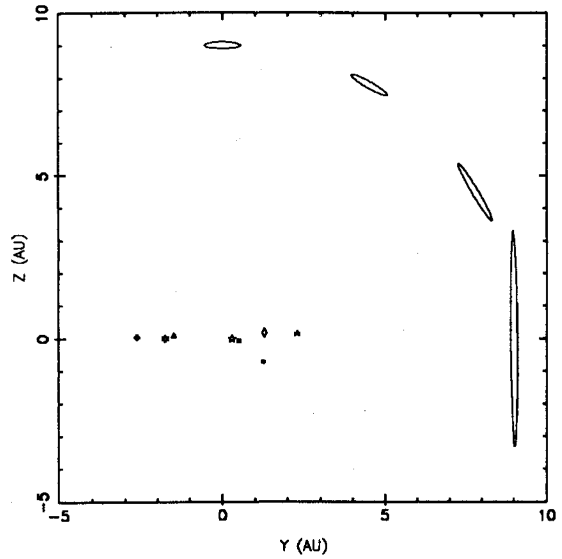


Fig. 3a 1σ error ellipses at points along a circular arc.

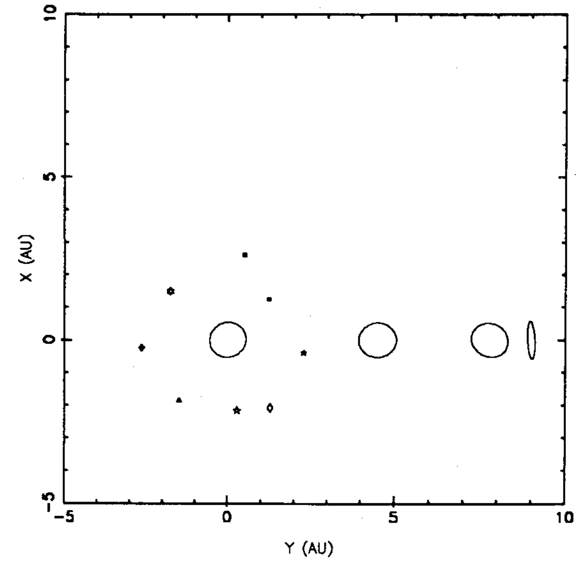


Fig. 3b Complementary view of Fig. 3a from an orthogonal direction.

Jupiter encounter, and a cruise phase heading out of the ecliptic plane. For each of the three cases, range and Doppler data from the UPS beacons are processed in different simulations to allow a comparison between the potential performance of each data type. Furthermore, two cases using different a priori uncertainties for the UPS asteroids are simulated for each data type. Based on the results of the previous analytic calculations and on the UPS beacon tracking simulations to be described, the two sets of asteroid 1σ uncertainties are as follows: case 1) 10 km uncertainty in each position component, 1 mm/s uncertainty in each velocity component; and case 2) 1 km uncertainty in each position component, 0.1 mm/s uncertainty in each velocity component. Because of the simplifications in the dynamical models and the choice of including a minimal number of considered parameters, the results can provide only a beginning for determining fundamental limitations of UPS tracking performance.

UPS Asteroids

To determine the potential accuracies to which the UPS asteroids may be tracked, we ran two simulations in which the UPS beacons were tracked by three Earth stations. No error sources (such as station locations) were considered and the asteroids were treated as point masses. These are among the factors that must be included in a more thorough assessment of UPS beacon tracking accuracies. The only parameters involved in these covariance analyses were the position and velocities of the eight UPS beacons.

In the first simulation, the Earth stations processed range data from the space beacons at a rate of 1/month for a period of two years beginning June 21, 1987. With a range measurement precision of 1 m, all but one of the beacons were determined to have a standard error of better than 10 km in each position component at epoch. One beacon had a position component with a standard error of 16 km. The velocity components of each beacon were determined to have standard errors of at most 3 mm/s; in most cases, the errors were at least an order of magnitude less.

In a second simulation, three Earth stations processed both range and Doppler data from the UPS beacons at a rate of twice a week for a period of six months, also beginning June 21, 1987. For this case, a range measurement precision of 1 m and a range rate measurement precision of 1 cm/s were used. This stronger data combination yielded standard errors of under 0.1 km per position component and 0.01 mm/s per velocity component.

Mars Flyby

The first covariance analysis of the UPS tracking network is for a Mars flyby.[4] The closest approach of the spacecraft to Mars is 11×10^3 km (or 3.3 Mars radii) on July 21, 1987. The performance analyses were done as follows: 1) the data from all eight UPS beacons were received by the spacecraft at an hourly rate beginning June 21, 1987; 2) at each time in the spacecraft's trajectory, the accumulated data were used to determine the projected covariance matrix of the spacecraft state estimate at closest approach; and 3) the covariance of the position estimate was examined by plotting the square root of the trace of the projected 3×3 matrix [or equivalently the projected encounter square root sum of square (rss) position uncertainties] as a function of time.

For the first simulation, only range data from the UPS beacons were processed. A range measurement precision of $\sigma_N = 1$ m was used. As described at the beginning of this section, the resulting covariances for two sets of a priori beacon uncertainties were calculated. For case 1, with 10 km beacon position uncertainty, the projected encounter rss position uncertainty remained almost constant at 34 km. Even additional data from two days past the closest approach do not improve the total variance of the position estimate. Using the smaller beacon uncertainties of case 2, the projected rss decreases to 3.5 km, but also remains essentially constant throughout the span of data arc. We note that this value is the same as that obtained by analytic calculations for geometric positioning.

The second simulation using only Doppler data from the UPS beacons used a range rate measurement precision of 1 mm/s. The projected position rss at closest approach using this data type is not as good as that using range data. However, it does show greater sensitivity to the planetary encounter, as illustrated in Fig. 4. At 25 days before encounter, the Doppler data accumulated from June 21, 1987 yields position estimates with rss under 140 km for the case 1 beacon uncertainties. Near encounter, the position rss falls to under 80 km and, after encounter, the rate of decrease in projected encounter rss is larger. For the case 2 beacon uncertainties, we see similar behavior in the projected position rss with approximately an order of magnitude improvement.

Jupiter Encounter

The second covariance analysis of the UPS based navigation system is for a Ulysses-type Jupiter encounter.[5] The closest approach of the spacecraft to Jupiter is 8.5×10^5 km (or 11.9 Jupiter radii) on July 28, 1987. As in the Mars flyby case, data

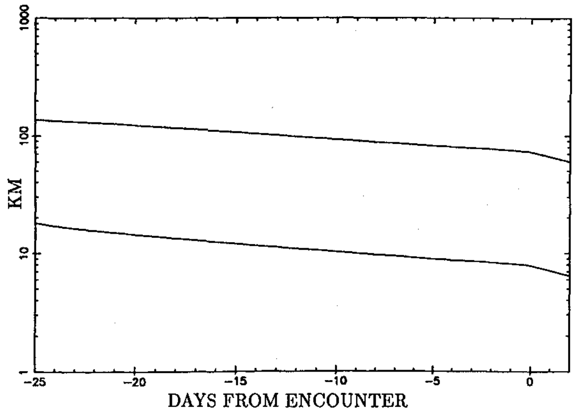


Fig. 4 Two levels of projected position error of projected Mars encounter based on Doppler data.

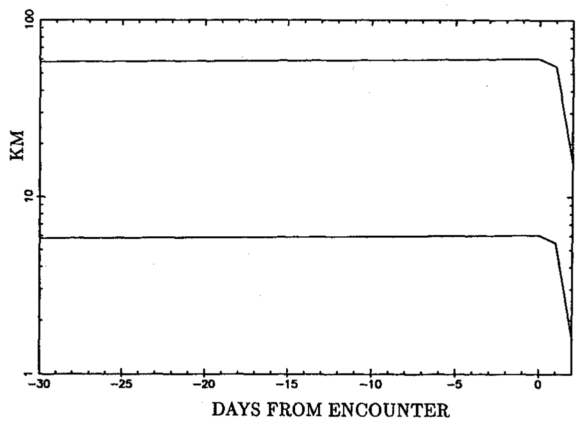


Fig. 5 Two levels of projected position error at Jupiter encounter based on range data.

are acquired hourly beginning June 21, 1987 from all eight UPS beacons and the measure of performance is the projected encounter position rss.

A range measurement precision of 10 m was used for the range data simulation. For the case 1 UPS beacon uncertainties, the projected rss increases from about 58 km at 30 days until encounter to 60 km at near encounter. The additional range data after encounter, however, greatly improve knowledge of the position at encounter. This is illustrated in Fig. 5 where we see similar behavior for the case 2 beacon uncertainties. We note that the case 2 position rss of about 5.9 km before encounter is close to the value of 5.5 km predicted for geometric positioning.

A range rate precision of 1 cm/s was used for the Doppler data simulation. As in the Mars flyby case, Fig. 6 shows the sensitivity of Doppler data to the gravity focusing of an encounter. For both the case 1 and 2 UPS beacon uncertainties, the rss position errors fall from hundreds of kilometers at 30 days from encounter to under 20 km at encounter.

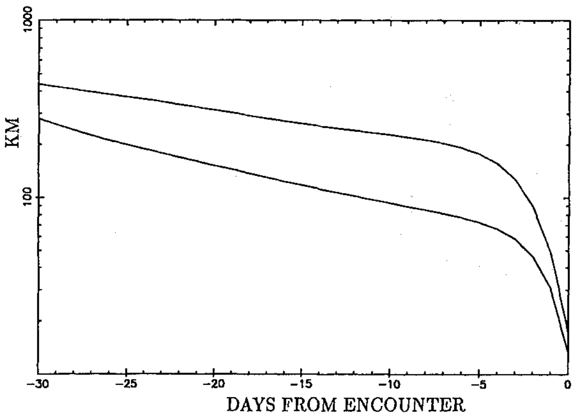


Fig. 6 Two levels of projected position error at Jupiter encounter based on Doppler data.

Out-of-Plane Cruise

The Jupiter encounter trajectory of the previous case was continued through Oct. 1, 1987, to provide a cruise phase study with a significant departure out of the ecliptic plane. For this case, the spacecraft received data from each UPS beacon once per day from Sept. 1 to Oct. 1, 1987. The data accumulated over this period were used to determine the covariance of the state estimate for Sept. 1. This epoch covariance was then mapped throughout the time of the data span. The performance of the UPS tracking system was then examined by plotting the rss position error of the mapped covariance.

Using a range measurement precision of 1 m and the case 2 UPS beacon uncertainties, the rss grew linearly from 9.3 to 11.2 km over the span of the data arc. Use of the case 1 uncertainties gave an rss graph that was larger by an order of magnitude. Geometric positioning did not agree as well in this case as in previous cases. Using a 1 km position uncertainty in the beacons yielded a predicted rss of 5.7 km for the spacecraft estimate.

Using a range rate of measurement precision of 1 mm/s and case 2 UPS beacon uncertainties, the rss grew linearly from 29 to 31 km. Use of case 1 errors yielded an rss of 200–210 km over the period of the data arc.

Discussion

In the previous sections, we showed that in a UPS navigation network Doppler and range data types have the potential for producing position estimates with accuracies in the range of 4–80 km (1σ) for encounters with Mars and Jupiter. Because of the minimal number of parameters considered in the analysis, these values represent theoretical limiting accuracies as were sought in this initial study. The possibility of using a combination of data types in the UPS network to obtain better accuracy was not pursued in this study. The stated accuracies are on the order of the needs for current interplanetary missions[6] and anticipated missions.[7,8] Currently, Doppler is the primary data type received by the DSN for use in spacecraft navigation. Supplemented by optical navigation, differential very-long-baseline interferometry, and other developing techniques, the DSN can meet the required accuracies for anticipated missions.

While the near-term expected navigation needs can be met by present or soon to be matured technologies, a principal motivation for this alternative system is to relieve the burden on the DSN. A major difference between the DSN and the UPS is in the manner of utilization. The tracking capability of the DSN can be overwhelmed as the number of spacecraft increases. A UPS-type system will not suffer from such a problem; increasing the number of spacecraft adds no additional burden to the system. Thus, a vision of a strong future interplanetary space program forces one to consider alternatives to the present system.

Conclusions

The main objectives in this paper were to introduce the concept of an interplanetary navigation system based on a network of transmitters placed on asteroids and to initiate a study into the performance potential of the system. We chose eight real asteroids distributed fairly uniformly throughout the asteroid belt for the study. Some calculations of the accuracies achievable with this asteroid-based navigation system for geometric positioning indicated that if the space beacons' positions could be tracked to 1–10 km in position, then it could provide accuracies comparable with today's system using the Deep Space Network. Computer simulations showed that tracking of the asteroid beacons to kilometer level accuracy is a reasonable expectation.

With asteroid position uncertainties in hand, spacecraft tracking covariance analyses were performed using asteroid uncertainties of both 1 and 10 km to bracket the potential accuracies of the navigation system. The separate performances of range and Doppler data from the asteroid beacons for encounter and cruise phases over the range of asteroid uncertainties were comparable to or exceeded those achievable currently; however, due to the limitations of the analyses, the results are more indicative of best possible performance of the proposed system. More detailed and sophisticated studies are required before the true realizable potential of this futuristic navigation system can be determined. What we can conclude from this pilot study is that the concept does hold a promise as an advanced navigation system suitable and desirable for a future interplanetary space program.

Acknowledgments

This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

References

[1]Khatib, A. R., "Autonomous Navigation Using Lunar Beacons," AIAA Paper 83-0351, Jan. 1983.

[2]Bierman, G. J., *Factorization Methods for Discrete Sequential Estimation*, Academic Press, New York, 1977.

[3]Wu, S. C. and Thornton, C. L., "OASIS—A New GPS Covariance and Simulation Analysis Software System," *Proceedings of the First International Symposium on Precise Positioning with the Global Positioning System*, Vol. 1, National Oceanic and Atmospheric Administration, April 1985, pp. 337–345.

[4]Gordon, H. J. et al., *The Mariner VI and VII Flight Paths and Their Determination from Tracking Data*, NASA TM 33-469, Dec. 1970.

[5]Thorpe, T. E., *Science Requirements Document for the NASA Spacecraft*, ISPM 628-50, Rev. B, Sept. 1980.

[6]Jordan, J. F. and Wood, L. J., "Interplanetary Navigation: An Overview," *Journal of the Astronautical Sciences*, Vol. 32, Jan.–March 1984, pp. 17–28.

[7]Wood, L. J. and Jordan, J. F., "Interplanetary Navigation through the Year 2005: The Inner Solar System," *Journal of the Astronautical Sciences*, Vol. 32, Oct.–Dec. 1984, pp. 357–376.

[8]Wood, L. J., "Interplanetary Navigation through the Year 2005: The Outer Solar System," *Journal of the Astronautical Sciences*, Vol. 32, April–June 1985, pp. 125–145.