degradation may occur whenever the rate of change of bias acceleration is so high as to make the absolute value of bias acceleration change by a large factor between consecutive thruster operations. This occurs when the bias torque disturbance passes through zero while reversing direction.

The adaptive capability of the system control law is precise in following the actual plant gain, even when performance is degraded due to a rapidly changing environment. The advantage of having this adaptive capability would be realized on an extended satellite mission as substantial fuel savings and increased system reliability due to the reduced number of thruster operations.

References

[1] "Adaptive Attitude Control System for Spacecraft Stabilization," Final Rept. ACD-8773, May 1968, General Electric Co., Binghamton, N. Y.

[2] Nicklas, J. C. and Vivian, H. C., "Derived Rate Increment Stabilization: Its Application to the Attitude-Control Problem," Technical Rept 32-69, 1961, Jet Propulsion Lab., California Institute of Technology, Pasadena, Calif.

AUGUST 1970 J. SPACECRAFT VOL. 7, NO. 8

A Spacecraft-Based Navigation Instrument for Outer Planet Missions

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This article presents the results of an analytical study of various spacecraft-based data that could be used to improve solely Earth-based navigational accuracies when approaching or orbiting outer planets. Measuring the celestial directions to outer planet natural satellites can supply the needed navigation data. The satellite motion can define the celestial direction to the center-of-mass of the outer planet-satellite system more accurately than can be determined from viewing the planet itself. An instrument similar to science television cameras used on the Mariner Mars missions would be suited to produce this spacecraft-based data by viewing satellites and reference stars simultaneously. A description of an instrument producing these measurements (accurate to better than 5 arc-sec) and the applicability of these spacecraft-based data to a Grand Tour mission are also presented.

Introduction

The positions of the outer planets during the 1970's and 1980's make various multiple-outer planet missions possible within the expected launch vehicle capabilities.[1,2] Of particular interest among possible future missions is the rare opportunity (once every 171 years) to launch spacecraft which would encounter Jupiter, Saturn, Uranus, and Neptune during a 9–13 year mission lifetime. Such outer planet missions require multiple trajectory correction maneuvers to insure the desired planet encounters. Limitations of Earth-based radio navigation capabilities at the great distances involved have led to an emphasis on developing a spacecraft-based navigation data source.[3,4] Spacecraft-based data in conjunction with Earth-based radio tracking allow more accurate control of the planet approach trajectory which significantly decreases the amount of spacecraft weight needed for trajectory correction purposes, increases mission performance, and increases the probability of mission success over that obtainable using Earth-based radio navigation only.

Radio tracking data combined with Earth ephemeris data would be used to determine the heliocentric state (position and velocity) of a spacecraft. Earth ephemeris uncertainties, tracking station location uncertainties, uncalibrated charged particle effects, and other data noise would be the major sources of error degrading the determination of the heliocentric spacecraft state when using only the Earth-based data. The determination of the target-centered spacecraft state would be degraded by this heliocentric state uncertainty and the target ephemeris uncertainty when outside the target sphere-of-influence. It is expected that Earth-based radio navigation in the mid-1970's would have the capability of determining the target-centered spacecraft state during planet approach to 0.1 arc-sec (3σ) in geocentric right ascension and declination. These uncertainties map to a spacecraft position uncertainty of 500 km at Jupiter and 3000 km at Neptune. Augmenting the Earth-based navigation data with spacecraft-based data could reduce the target-centered, spacecraft position uncertainty to $\sim$400–1000 km (3σ) during the approach to these same planets.

This article discusses the desired information content of the spacecraft-based data and the difficulties associated with obtaining the data. Spacecraft-centered measurements of the direction to the planet center-of-mass supplies the needed trajectory information lacking from the Earth-based radio tracking data. The gaseousness of the outer planets, and the rings of Saturn makes the accuracy of planet center determination from planet limb measurements questionable. Fortunately, these gaseous planets have many natural satellites whose orbital motion can be related directly to the center-of-mass of the planet-satellite system. A television type instrument which would image these natural satellites and reference stars simultaneously to produce the desired navigation data is discussed together with the application of this data to the Grand Tour mission. The instrument re-

Presented as Paper 69-902 at the AIAA/AAS Astrodynamics Conference, Princeton, N.J., August 20–22, 1969; submitted September 8, 1969; revision received April 9, 1970. This article presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract NAS 7-100, sponsored by NASA.

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quires a refinement of existing capabilities rather than an advance in the state-of-the-art.

Instrument Concept

Expected Earth-based radio tracking data would provide an accurate determination of the spacecraft heliocentric state, whereas ephemeris data would provide an accurate determination of the target planet velocity. Lacking from these two data sources are accurate data on the target-centered position of the spacecraft. Additional data that could provide the desired position information are spacecraft-based measurements of the target planet direction. Planet direction measurements contain information that defines the spacecraft motion in its trajectory plane and also the orientation of the trajectory plane.

Determination of this direction requires an instrument or instruments to measure the individual directions to the target planet and reference bodies. The individual direction measurements would then be related to each other by using measured instrument calibration characteristics, and measured alignments between the instruments when more than one instrument is used. Viewing the target planet and/or its natural satellites could yield planet direction; stars (including the sun) could be used as celestial references for the measurement of planet direction.

Measured Planet Direction

The illuminated (lit) limb (apparent edge) of a planet can be used in determining the direction to the optical center of a planet. Instruments that view the planet lit limb to yield planet direction information could process the planet image aboard the spacecraft to derive the location of planet center[5,6] or produce a planet image for transmission to Earth, e.g., a science television camera, where ground-based software could operate on the image to derive the planet center. For processing planet image data either aboard the spacecraft or on the earth, an algorithm based on image intensity would be used to define the lit limb of a planet image, and then a curve fitting technique would be used to determine the center of the image from measured points on the lit limb. The measured image center location would be converted into planet direction in an instrument coordinate system using instrument calibration data.

Major sources of error degrading the measured direction to the planet center-of-mass are 1) limb darkening, 2) marked albedo variations near the lit limb, 3) atmosphere, 4) algorithm defining lit limb, 5) uncertainties in the target planet figure and spin axis orientation with respect to the instrument coordinate system, 6) differences between the planet optical center and center-of-mass, 7) electrical and optical geometric distortion of the image, 8) photometric distortion of the image due to image plane sensitivity nonuniformities, and 9) instrument calibration errors.

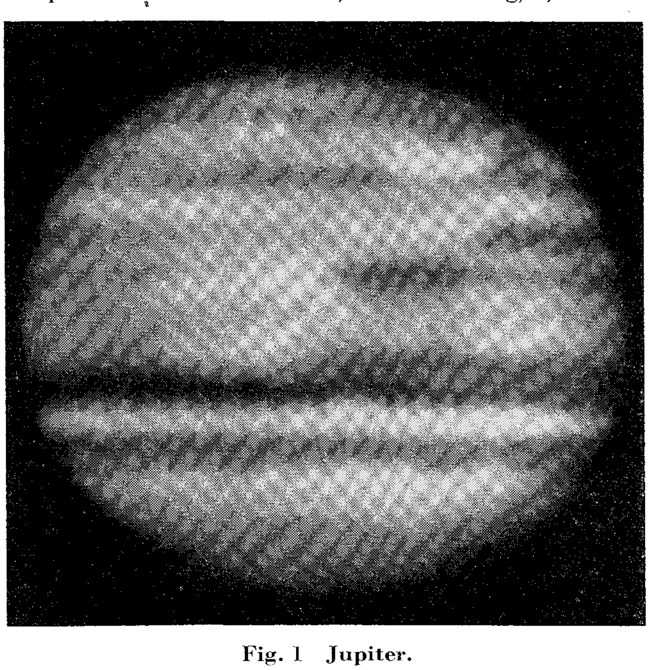

Fig. 1 Jupiter.

Figure 1 illustrates the aforementioned error sources 1, 2, 3, and 4. The darkening of the lit limb of Jupiter near its poles tends to exaggerate its oblateness. A simple limb algorithm (the type that could be used aboard the spacecraft) based on a fixed level of intensity would not be able to accurately distinguish the effects of limb darkening, dark surface features, or regions of less dense atmospheres from dark space. A more complex limb algorithm would undoubtedly require the aid of a computer. The rings of Saturn (Fig. 2) mask a significant portion of the limb and increase the complexity of a suitable limb algorithm.

Relating limb measurements to the center-of-mass of the planet requires a model of the planet figure. Ideally, the planets would be homogeneous solid or fluid bodies and the limb measurements would be on the edge of the body surface. A homogeneous solid or liquid spinning body is constrained dynamically to be ellipsoidal with the center-of-mass at the ellipsoid center; therefore, fitting the limb measurements with an ellipse could yield the planet center. Unfortunately, the outer planets exist in very gaseous states or possibly completely gaseous states, particularly the planets Jupiter and Saturn. A spinning gaseous body does not have to exhibit the dynamically constrained shape or center-of-mass characteristics of a liquid or solid planet. An example of observed peculiarities for these gaseous planets is the measured differences in spin rate of Jupiter at different latitudes. Outer planet limb measurements may be in the planet atmospheres and not at the edge of a solid or liquid surface since these surfaces may not exist or are hidden by the thick atmospheres. These limb measurements would be subject, then, to composition and density variations in the atmosphere and may deviate significantly from simple limb and planet figure models.

A study has been performed to determine the effect of error source 5 on determining the optical center of a planet. Center-finding errors from 300 to 2000 km (3σ) can be expected for the planets Jupiter through Neptune if the planet center is found without improving the accuracy of Earth-based estimates of planet figure and spin axis orientation; therefore, spacecraft-based data must improve the accuracy of these parameters when used to determine the optical center. Uncorrected image distortion of $\frac{1}{2}\%$ would produce center-finding errors of similar magnitude. An uncertainty in the difference between the optical and dynamical planet centers would map directly into a center-finding error. This center-finding error together with the previously mentioned center-finding errors could not be separated from the planet direction data until the discrepancy was revealed by the gravitational effect of the planet. Unfortunately, the tra-

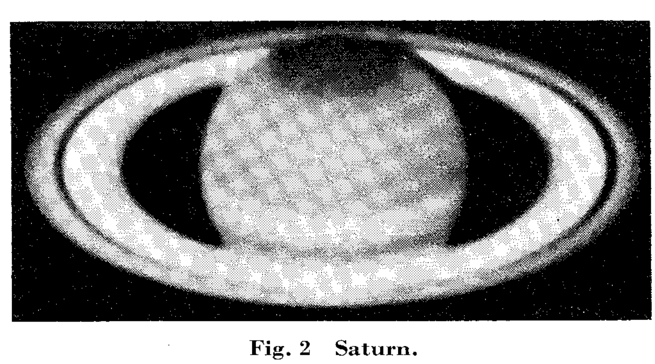

Fig. 2 Saturn.

jectory correction maneuvers to be performed on multiple outer planet missions are calculated before the pull of the planet is sufficient to enable these errors to be determined; therefore, these errors would corrupt the maneuver in addition to errors in executing the maneuver.

The problems of planet limb sensing to determine the planet center can be eliminated by viewing natural satellites of the planet. Satellite motion is related directly to the planet center-of-mass rather than the optical center. Also the rings of Saturn would not obscure from sight the natural satellites of Saturn as it would a portion of the limb of Saturn. A time history of measured directions to satellites would contain data from which orbital parameters of the satellites including the location of their common primary (planet center-of-mass) could be determined. As with the planets, satellite limb measurements would be used to determine the centers of the satellites. However, because of the small size of the satellites and the sparseness of satellite atmosphere as compared to the planets, the centers of the satellites could be determined from one to three orders of magnitude more accurately than the planet centers. The major error sources in determining the planet direction would be the accuracy of the satellite direction data and the accuracy of modeling the satellite equations of motion. Integration of the satellite equations of motion would be required at Jupiter because of the interactions of the Galilean satellites. Conic approximations of the orbits of the other outer planet natural satellites would introduce small model errors but significantly reduce the complexity of computations.

Planet Direction References

Studies[7,8] of spacecraft-based navigation measurements indicate that significant trajectory estimation errors would be incurred if multiple instruments were used to view the planet-satellite system and reference bodies. Constant misalignments of the instruments could be accurately determined in a trajectory estimation process; but slowly varying misalignments due to electrical and mechanical drifts would be difficult to separate from the slow changes in planet direction resulting from spacecraft motion along its trajectory.

Instruments viewing one body at a time would require precision electrical, optical, or mechanical gimbaling to view all of the pertinent bodies. Instruments having the capability of viewing more than one body simultaneously would require precision gimbaling or an instantaneous field-of-view (FOV) sufficient to view all pertinent bodies simultaneously. An instrument with sufficient FOV would offer more accurate relative direction information by eliminating uncalibrated, nonrepeatable gimbal errors.

The sun would be undesirable as a reference body for outer planet missions because of its brightness as compared to the other bodies of interest, and because of the large angular separation of the spacecraft-planet direction and spacecraft-sun direction during planet approach ($\sim$160.0°). The use of stars in the direction of the target planet or in the direction of selected natural satellites would be desirable to reduce the total FOV required to detect all pertinent bodies. An instrument using stars within 5° of the planet or satellites for references would need to detect 6th magnitude stars for the variety of multiplanet missions possible in the late 1970's. Detecting dim stars near the target planet direction poses a problem because stray light from the planet would tend to mask the stars.

In summarizing the major spacecraft-based instrument requirements, it is concluded that an instrument viewing the planet must produce data, based on a sophisticated limb model, that yield a solution for the planet center including a solution for the planet figure and spin axis. Instruments viewing the planet or satellites should be able to view reference stars in a single FOV, or have precision gimballing to yield relative direction accurately. It is proposed that a TV type instrument viewing natural satellites of a target planet against a star field would meet these requirements. This type of instrument would have the capability of producing the required navigation data during planet approach, planet departure, or when orbiting a planet.

Instrument Description

The spacecraft-based instrument would obtain information on outer planet satellite directions in a star field by imaging these bodies on a vidicon tube. The instrument would have a 3° × 3° FOV and would be mounted on a two-axis gimbaled platform to provide a large total FOV capability. The instrument FOV would enable the satellites and reference stars to be viewed simultaneously. The gimbaled platform would allow the instrument to view these bodies for the various planet approach directions and for the range of satellite motion.

Vidicon target raster resolution would be 1000 scan lines with 1000 picture elements (pixels) per scan line. The shutter speed of the instrument would be controllable to insure the detection of the satellites and 6th magnitude stars. To minimize stray light problems, the planet would not be within the instrument FOV during observations. An 11 × 11 grid of reseaus would be placed on the vidicon face to yield in-flight geometric distortion data. The instrument, essentially viewing dark space, would require a white reseau grid.

Since the information content of each vidicon data frame is mostly of the dark space background, the video information from the vidicon target raster could be processed selectively aboard the spacecraft to separate and store only information (pixel location and intensity) on the bright images (satellites, stars, and reseaus). Selective processing would consist of comparing the video intensity level of each picture element in the data frame with a reference video level. The reference level, brighter than the space background, would be controlled by a ground command or by information stored or calculated in a spacecraft computer to add flexibility to the selecting processing. The location and brightness of about 500 pixels out of a total of one million pixels would be stored per data frame during planet approach. At selected times, the stored data would be transmitted to earth where it would be combined with Earth-based radio tracking data. The video levels associated with the pixel locations would be used in identifying the images.

Spacecraft-Based Observables

The spacecraft-based observables would be the image coordinates of the satellites, stars and reseau, grid. A general expression for the measured image coordinates of stars and satellites with respect to the instrument principal point (intersection of optical axis with the target raster) is obtained from the colinearity equations of photogrammetry[9] and is given by

$$\begin{bmatrix} x_m \\ y_m \end{bmatrix} = -\frac{f}{w}\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}(I - E)M\hat{\imath} + \begin{bmatrix} x_0 \\ y_0 \end{bmatrix} + \begin{bmatrix} x_e \\ y_e \end{bmatrix} + \begin{bmatrix} \eta_x \\ \eta_y \end{bmatrix} \quad (1)$$

and an expression for the measured image coordinate of a reseau grid point is given by

$$\begin{bmatrix} x_m \\ y_m \end{bmatrix} = \begin{bmatrix} x_r \\ y_r \end{bmatrix} + \begin{bmatrix} x_e \\ y_e \end{bmatrix} + \begin{bmatrix} \eta_x \\ \eta_y \end{bmatrix} \quad (2)$$

where (x_m,y_m) = measured pixel and line coordinate of an object's image; (x_r,y_r) = physical location of a reseau grid

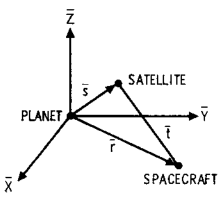

Fig. 3 Spacecraft-planet-satellite geometry.

point measured before launch; f = instrument focal length; (x_0,y_0) = optical distortion function; (x_e,y_e) = electrical distortion function; (η_x,η_y) = measurement noise due to vidicon tube resolution; M = transformation from an inertial reference system to a nominal instrument reference system; $\hat{t}$ = spacecraft-centered inertial direction to object; w = third component of the unit vector $\hat{p}$ with $\hat{p} = M\hat{t}$. The functions representing electrical and optical geometric distortion could be modeled as a power series with the distance between the principal point and image location as the independent variable, and the coefficients of the series as parameters to be estimated from in-flight star and reseau grid data. A detailed discussion of modeling geometric distortion is given in Ref. 10. The term $(I - E)$ is a small angle rotation matrix that defines the deviation of the actual instrument orientation from a nominal reference system. For small angles, the rotation matrix is approximated by

$$(I - E) = \begin{bmatrix} 1 & \epsilon_3 & -\epsilon_2 \\ -\epsilon_3 & 1 & \epsilon_1 \\ \epsilon_2 & -\epsilon_1 & 1 \end{bmatrix} \tag{3}$$

The spacecraft-centered inertial direction to a satellite is expressed as

$$\hat{t} = (\bar{s} - \bar{r})/|\bar{s} - \bar{r}| \tag{4}$$

where $\bar{s}$ is the planet-satellite vector, $\bar{r}$ is the planet-spacecraft vector, and $(\bar{X}\bar{Y}\bar{Z})$ is an inertial reference system (Fig. 3). The directions to stars are accurately known from Earth observations and are not a function of spacecraft trajectory or satellite orbits for the outer planet missions. The reseau locations on the vidicon target, accurately known from prelaunch calibration, do not change during flight.

During a measurement time period when the gimbaled platform is not commanded to move, the errors between the actual and nominal instrument inertial orientation would be of the form

$$\bar{\epsilon} = \begin{bmatrix} \epsilon_1 \\ \epsilon_2 \\ \epsilon_3 \end{bmatrix} = \begin{bmatrix} l_1 + m_1 + n_1 \\ l_2 + m_2 + n_2 \\ l_3 + m_3 + n_3 \end{bmatrix} \tag{5}$$

where l = constant biases that are perfectly correlated between data frames, m = slow random variations that are neither constant nor uncorrelated between data frames, n = random biases that are uncorrelated between data frames. The constant biases (l) would be associated with fixed mounting offsets between the instrument and the spacecraft structure (~3.0 mr); the slow random variations (m) would be associated with sensor electrical null drift and structural bending (~0.1 mr); and the random biases (n) would be associated with the telemetry resolution of the measured platform pointing direction and spacecraft attitude (~0.3 mr). When the gimballed platform is moved, the uncertainty of the constant biases would be degraded due to the uncertainty of the platform movement.

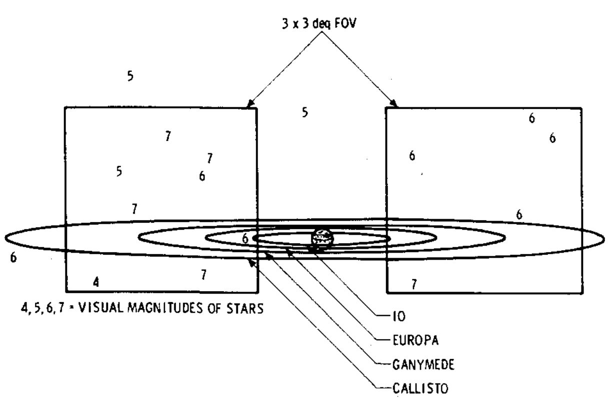

Fig. 4 10 days from Jupiter encounter.

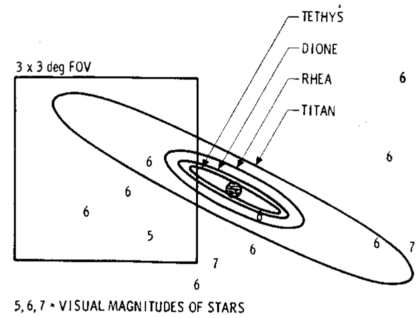

Fig. 5 10 days from Saturn encounter.

Data Content of Images

The reseau grid image data [Eq. (2)] would contain information from which the coefficients of the electrical distortion function could be estimated for each data frame. The 11 × 11 reseau grid data would be sufficient to allow electrical distortion to be removed from the star and satellite data to within 2 arc-sec (1σ). Star image data [Eq. (1)] would contain information from which the optical system parameters and the inertial pointing direction of the instrument could be estimated. Selected star clusters could be viewed for the specific purpose of calibrating the optical system before viewing the satellites and reference stars. Proper design and environmental control of the instrument optical system to insure its stability over the entire measurement interval could allow the errors due to the optical system to be removed from the satellite data to within 4 arc-sec (1σ). With the measurement errors essentially removed by the reseau grid and star data, the distortion corrected satellite data (accurate to better than 5 arc-sec) would be used primarily for estimating the spacecraft trajectory $\bar{r}$ (time) and satellite orbits $\bar{s}$ (time).

Table 1 Natural satellites

Planet and satellite	Semimajor axis, 10^3 km	Eccentricity	Period, days
Jupiter			
I Io	423.	0	1.769
II Europa	673.5	0.0003	3.551
III Ganymede	1074.	0.0015	7.154
IV Callisto	1888.5	0.0075	16.689
V	181.5	0.0030	0.498
Saturn			
I Mimas	186.	0.0201	0.942
II Enceladus	238.5	0.0044	1.370
III Tethys	295.	0	1.887
IV Dione	378.	0.0022	2.737
V Rhea	528.	0.0010	4.517
VI Titan	1225.5	0.0291	15.950
Uranus			
I Ariel	192	0	2.520
II Umbriel	268.5	0	4.144
III Titania	439.5	0	8.706
IV Oberon	588.	0	13.460
V Miranda	127.5	0	1.414
Neptune			
I Triton	353.	0	5.877

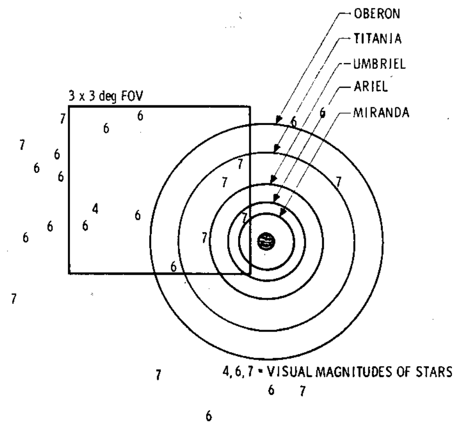

Fig. 6 10 days from Uranus encounter.

Grand Tour Navigation

The applicability of this instrument to a Grand Tour mission with an inner ring passage at Saturn has been investigated. This mission has the most demanding navigation requirements of any of the proposed outer planet missions; therefore, meeting the navigation requirements for this mission would guarantee that the navigation requirements of any of the proposed outer planet missions could be met.

Table 1 lists the satellites that could be viewed during the approaches to the outer planets.[11] Figures 4–6 illustrate the celestial geometry during the approach to Jupiter, Saturn, and Uranus for this Grand Tour mission. Measurements could be timed to obtain one or more satellite images with the star images. Measurements would begin about 20 days before encountering each planet and would be used to determine a pre-encounter maneuver for correcting the estimated trajectory deviation from the nominal approach trajectory. These trajectory deviations could be kept small by performing small trajectory correction maneuvers during the interplanetary cruise portions of the trajectory. Long arcs of Earth-based radio tracking data should be capable of reducing these trajectory deviations to within the limiting uncertainty of the target planet ephemeris at the time the spacecraft begins to approach the target planet. Figure 7 shows the rms pre-encounter velocity magnitudes required to correct these expected approach trajectory deviations.

Errors in a pre-encounter maneuver would have to be corrected by performing a postencounter maneuver to insure an accurate arrival at the next planet. These errors would result primarily from pre-encounter trajectory estimation errors which corrupt the calculation of the maneuver. Execution errors in pre-encounter maneuvers would be small relative to the maneuver-calculation errors. The spacecraft-based measurements would control the accuracy of the pre-encounter maneuver because the Earth-based tracking would have reached its limiting accuracy before the spacecraft-based measurements were taken. Sufficient measurements of satellite, star, and reseau grid positions would be taken to reduce errors in estimating the trajectory to a level commensurate with the instrument accuracy of approximately 5 arc-sec, and to have the trajectory accuracy essentially independent of the a priori satellite orbit uncertainties. The satellites would be viewed over major portions of their orbits (except near the planet) allowing this level of trajectory accuracy to be reached. A study[8] of a Mars mission using the natural satellites Phobos and Deimos and a similar type of instrument showed that the instrument error limited the accuracy of the spacecraft trajectory estimate, even with large a priori satellite orbit uncertainties.

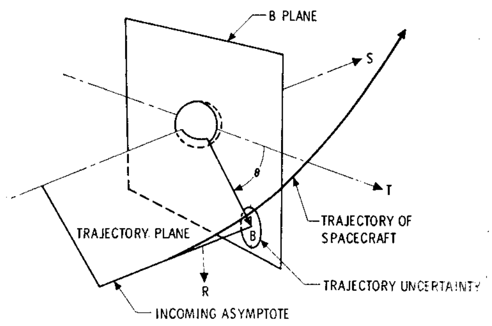

Fig. 8 $\overline{RST}$ coordinate system.

A convenient coordinate system for describing a fly-by trajectory and errors in that trajectory is the $\overline{RST}$ system (Fig. 8), where $\bar{S}$ is parallel to the approach asymptote of the trajectory, $\bar{T}$ is parallel to the ecliptic plane, and $\bar{R}$, completing the orthogonal system, is in the southern hemisphere. Trajectory errors can be expressed in terms of uncertainties of the approach asymptote direction $\bar{S}$, approach velocity V_∞, time of flight, and the impact parameter $\bar{B}$.

Earth-based data could determine the approach direction and approach velocity with sufficient accuracy so that the uncertainty in these parameters would map to negligible errors in the departure trajectory, as would time-of-flight errors. The major sources of error affecting the departure trajectory are uncertainties in $\bar{B}$. The rms magnitude of the expected postencounter maneuver as a function of errors in $\bar{B}$ is given by[3]

$$\delta V_{\text{rms}} = V_\infty \sin\psi[\delta B^2 + B^2\delta\theta^2]^{1/2}/B \tag{6}$$

where $B = |\bar{B}|$, $\theta = \tan^{-1}(\bar{B}\cdot\bar{R}/\bar{B}\cdot\bar{T})$, and ψ is the angle between the incoming and outgoing asymptotes.

The $\bar{B}$-plane trajectory uncertainty during planet approach can be approximated by the following function of instrument

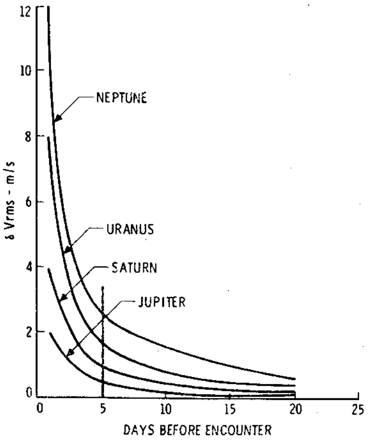

Fig. 7 Pre-encounter maneuver magnitude.

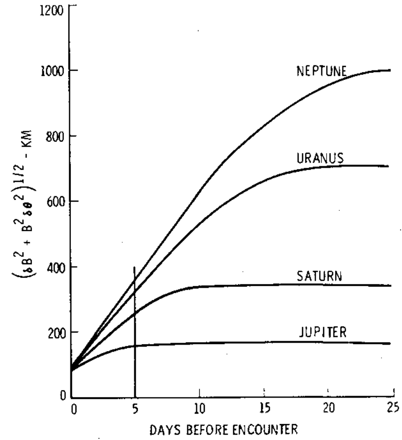

Fig. 9 $\bar{B}$-plane uncertainty using Earth-based and spacecraft-based data.

Table 2 Grand Tour maneuver magnitudes

Maneuver	δV_{rms}, m/sec	$V_\infty \sin \psi / B$, m/sec-km
Post-Earth[a]	18.00	...
Pre-Jupiter	0.40	...
Post-Jupiter	2.56	0.016
Pre-Saturn	0.80	...
Post-Saturn	29.38	0.113
Pre-Uranus	1.60	...
Post-Uranus	50.53	0.163
Pre-Neptune	2.40	...
Total velocity, m/sec	178.82	...

[a] See Ref. 4.

accuracy (α) per axis:

$$(\delta B^2 + B^2 \delta\theta^2)^{1/2} \approx (2)^{1/2} r\alpha \tag{7}$$

where r is the spacecraft range from the planet at the time of the pre-encounter maneuver. This $\bar{B}$-plane uncertainty (Fig. 9), using Earth-based and spacecraft-based data, would have an upper limit corresponding to the target ephemeris uncertainty and a lower limit corresponding to the satellite center finding accuracy (tens of km).

Minimizing the sum of the pre- and postencounter maneuvers at each planet would require pre-encounter maneuvers to be performed within a few days from encounter. Performing the detailed data processing, maneuver computations, and command sequencing at these times would be undesirable because of high activity and complexity of mission operations in support of the near-encounter science sequence. Therefore, it is assumed that the pre-encounter maneuvers would be performed at 5 days before encounter to ease mission operations at the expense of an off-optimum maneuver policy.

Table 2 lists the expected rms maneuver sizes at each planet and the total velocity magnitude (99 percentile) based on a Rayleigh distribution. The small trajectory correction maneuvers performed during interplanetary cruise were neglected. Even with the nonoptimum maneuver policy, only 180 m/sec velocity correction capability is required to meet (99% probability) the Grand Tour navigation requirements.

Conclusions

Viewing the natural satellites of an outer planet could yield more accurate spacecraft navigation data than could be obtained from viewing the target planet itself. Satellite data would not be degraded by the large planet center-finding errors associated with viewing the gaseous outer planets. Viewing the satellites against a star background could be performed while approaching, orbiting, or departing a target planet. The satellite data would not be degraded by the rings of Saturn.

The instrumentation required to produce the satellite data essentially exists in the form of science television cameras being used on interplanetary missions to Mars. Simple data compression algorithms could be used to reduce the amount of navigation data transmitted to Earth to a low level when compared with the expected science data to be transmitted to earth. This navigation data, when combined with Earth-based data, would allow any of the possible multi-planet missions to be flown with less than 180-m/sec velocity correction capability.

References

[1] Long, J. E., "To the Outer Planets," *Astronautics and Aeronautics*, Vol. 7, No. 6, June 1969, pp. 32–47.

[2] Flanders, J. H., Fraser, D. C., and Lawson, J. R., "Technology for Guidance and Navigation of Unmanned Deep Space Missions in the 1970's," AIAA Paper 68-1104, Philadelphia, Pa., 1968.

[3] Friedlander, A. L., "Guidance Analysis of the Multiple Outer Planet (Grand Tour) Mission," Paper 68-109, Sept. 1968, American Astronautical Society.

[4] Kingsland, L., "Trajectory Analysis of a Grand Tour Mission to the outer Planets," AIAA Paper 68-1055, Philadelphia, Pa., 1968.

[5] Fraser, D. C. et al., "Final Report on Guidance and Navigation Requirements to the Outer Planets—Vol. II, Impulsive High Thrust Missions," NASA Contract NAS 2-5043, 1970, Massachusetts Institute of Technology Instrumentation Lab.

[6] Chamberlain, F. R., "Development of an Approach Guidance Optical Planet Tracker," *Space Program Summary 37-52*, Vol. III, Jet Propulsion Lab., Pasadena, Calif., Aug. 31, 1968, pp. 49–52.

[7] Breckenridge, W. G. and Duxbury, T. C., "Investigation of Planetary Navigation Using Spacecraft-Based Measurements," *Proceedings of the Institute of Navigation National Space Meeting on Space Navigation—Present and Future*, Institute of Navigation, 1969, pp. 18–30.

[8] Duxbury, T. C., "Spacecraft Navigation Using Science Television Data," Paper G60, April 1969, American Institute of Astronautics and Aeronautics/American Geophysical Union.

[9] Thompson, M. M., ed., *Manual of Photogrammetry*, 3rd ed., Vol. 1, American Society of Photogrammetry, Falls Church, Va., 1966, pp. 461–490.

[10] Wong, K. W., "Geometric Calibration of Television Systems for Photogrammetric Applications," paper presented at the 11th International Congress of Photogrammetry, International Society for Photogrammetry, Lusanne, Switzerland, July 1968.

[11] Melbourne, W. G. et al., "Constants and Related Information for Astrodynamic Calculations, 1968," TR 32-1306, July 15, 1968, Jet Propulsion Lab., Pasadena, Calif.