DEEP SPACE NAVIGATION SYSTEMS AND OPERATIONS*

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ABSTRACT

The paper reviews the U.S.-NASA's deep space navigation system as it has evolved from use during the past 20 years. We describe both the measurement systems and data processing systems employed and the historical mission-to-mission performance. The paper provides a description of the Voyager navigation system and reports the recent navigational achievements for the Voyager missions. We then identify the new navigational challenges implied by a near-term future mission set, which includes the 1985 Galileo mission to Jupiter and the 1988 Venus Orbiting Imaging Radar Mission.

I. INTRODUCTION

In the United States' NASA planetary mission program, navigation is defined as the process of locating the position and predicted flight path of a space vehicle and correcting that predicted flight path to achieve mission objectives. A pre-flight mission design activity provides the baseline trajectory for a space flight, then navigation provides the systems required to execute that flight. Navigation support for each deep space mission involves a planning phase, in which flight accuracies are predicted and the systems to execute the flight are developed, and an operations phase, where the actual process of navigating is carried out.

The navigation process is carried out by a sequence of actions. First measurements related to the flight path are acquired. They are then processed to determine an orbit or best estimate trajectory. Based on this trajectory and a knowledge of the required targeting or orbit maintenance objectives, trajectory correction maneuver parameters are computed. These parameters, when commanded to the spacecraft and processed by the onboard guidance and control system, result in the execution of trajectory correction thrusts to achieve the desired targeted flight path.

On deep space missions, precision navigation is usually carried out just prior to a critical event such as a planetary encounter, where the target body is to be observed scientifically, while being flown by or orbited. The trajectory correction maneuver, is, in this case, used to set the flight path on its proper course for meeting the mission goals. Often, the orbit determination process is repeated, after a trajectory correction maneuver, to facilitate accurate science instrument pointing. After the encounter, a final best orbit is computed to provide precise reconstruction of the location of the science instrument footprints on the target body.

As we near the end of the second decade of NASA deep space exploration missions, we can look back on a history rich in challenging applications for deep space navigation. In the 1960's, beginning with the Mariner 2 mission to Venus in 1962, a series of spacecraft were sent to the inner planets to perform remote science sensing during flyby encounters. In the 1970's, the range of navigation applications was expanded to include the delivery of spacecraft to orbit the inner planets; first with the Mariner 9 mission to Mars in 1971, then followed by the Viking missions to Mars in 1976 and Pioneer mission to Venus in 1979. Atmospheric probes to the Venus atmosphere were also delivered by the Pioneer Venus program. Finally, in the late 1970's we have begun exploration of the outer planets, with the early Pioneers to Jupiter and Saturn, and most recently, with the Voyager program.

The Voyager mission program, with its two spacecraft sent to both Jupiter and Saturn, including close encounters with some of their natural satellites, represents the most demanding challenge for deep space navigation seen thus far in the NASA Planetary Program.

The future holds challenges of still greater magnitude. The 1985 Galileo mission will send an atmospheric probe to the Jovian atmosphere and then orbit the Jovian system, encountering repeatedly the Galilean satellites. The 1988 Venus Orbiting Image Radar mission will place

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and maintain a surface radar mapping satellite in a low (250 km) circular orbit around Venus. Both these missions present demanding navigational challenges.

This paper discusses the Jet Propulsion Laboratory's deep space navigation system, which has evolved over the last 20 years, and is currently employed on the NASA planetary missions. Section II describes the elements of the measurement system and data processing system that comprise today's navigation system. We provide both a summary of the recorded historical performance chieved with the sytem during the past 20 years of planetary exploration, and a description of how the system is used operationally. Section III describes the Voyager mission navigation experience, including a description of the mission profile, the navigation requirements, and a report on the actual Voyager navigation performance. Section IV provides a description of the Galileo and VOIR missions, the challenges they impose on deep space navigation, and a description of some of the changes in the Voyager system being considered to meet those challenges.

II. THE JPL NAVIGATION SYSTEM

Figure 1 illustrates in schematic form the elements of measurement and computation that comprise the current JPL Navigation system, which is being employed for Voyager mission navigation. The left-hand side of the diagram shows a spacecraft acquiring optical TV images of a target body and being tracked by two ground antennas. On the right-hand side is shown the ground processing

On the right-hand side is shown the ground processing system, which models the trajectory motion, estimates the orbit, and computes the flight path corrections.

The Measurement System

The baseline navigation measurement system of the 1960's consisted of 2-way S-band (2.3GHz) radio doppler, and indeed this system was used to navigate the early Mariners missions to Venus and Mars.[2] Beginning with Mariner 9, 2-way, 1 MHz bandwidth ranging data was also employed. Ranging was used as supplementary data to doppler during the cruise to Mars, and was used as a backup for doppler during the planet orbiting phase, when the doppler data noise increased dramatically near superior conjunction. Ranging data, if taken nearly simultaneously from two widely separated station on earth, can be used to obtain a direct measurement of the geocentric direction to a spacecraft. Voyager navigation uses ranging data acquired in this near simultaneous mode.

Beginning with the Viking mission in 1975, NASA spacraft transponders have transmitted S-band and X-band(8.4 GHz) downlink to the earth, both signals being coherent with the uplink S-band. The processing of S and X band data allows a calibration of the effects of charged particle on the downlink signal. Mapping methods are employed to infer the effect on the uplink. This dual frequency technique has been used successively to calibrate both doppler and range during periods of high acitivity in the solar plasma and earth's atmosphere.

Optical measurements, acquired from the science

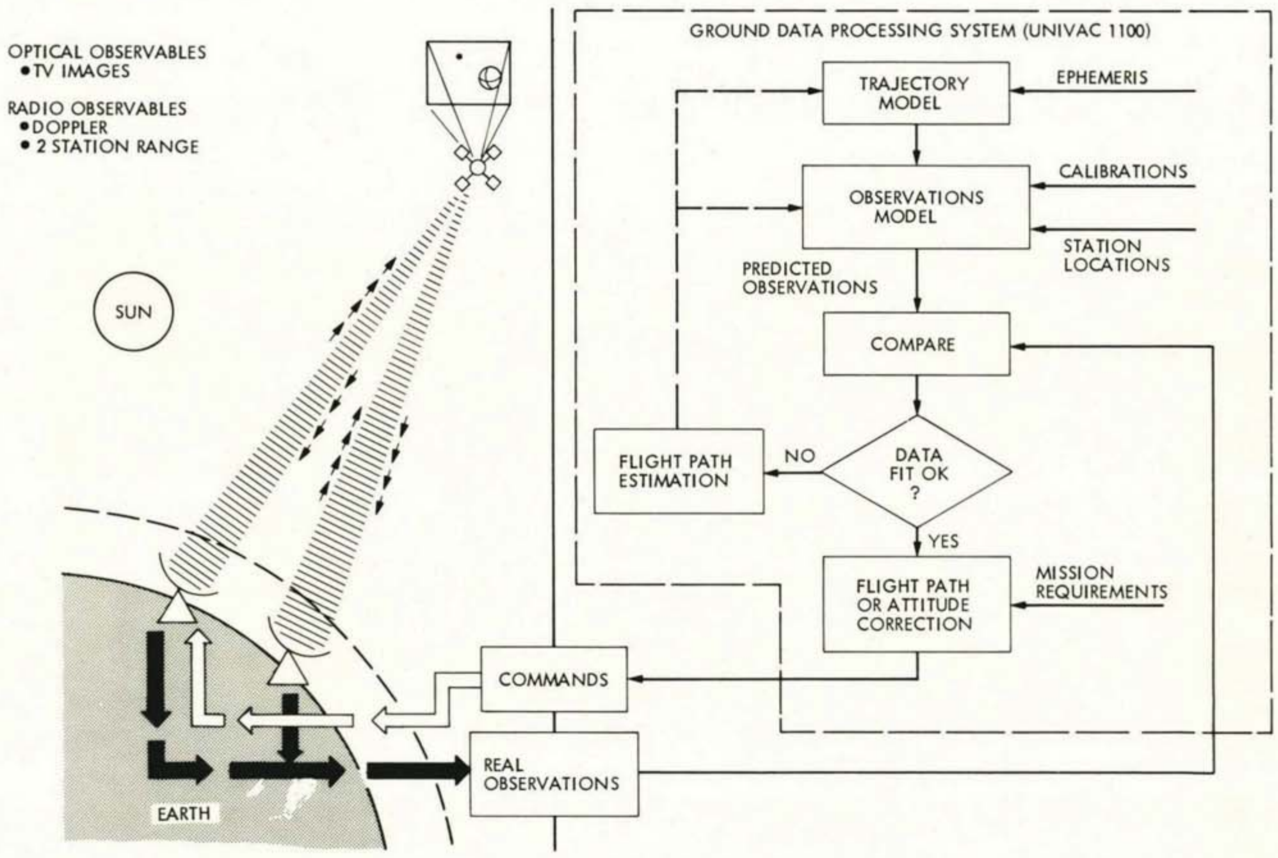

Figure 1. A Schematic Description of the Current JPL Navigation System Used for Voyager Navigation

TV instrument onboard the spacecraft, have been used on the Viking and Voyager missions to improve the target relative orbit determination accuracies in the final approach stages of their planet and satellite encounters.

The Data Processing System

Doppler and range data, which are extracted from the incoming radio signal at the tracking stations, and the optical image data, which is bit encoded at the spacecraft and telemetered to earth, are brought to the Jet Propulsion Laboratory over high speed data lines and buffered on computer tape. A large software system is operated at JPL to determine the spacecraft orbit and compute trajectory correction parameters.[3] The elements of the software system are listed in Table 1. For each program the table provides a short function description, the size of the program in terms of the approximate number of lines of FORTRAN code, and the resident computer.

PROGRAM	FUNCTION	APPROX SIZE (LINES OF FORTRAN CODE)	COMPUTER
ODP	FITS DATA TO OBTAIN ORBIT	200,000	UNIVAC 1100
DPTRAJ	INTEGRATES TRAJECTORY	150,000	UNIVAC 1100
MOPS	COMPUTES CORRECTION MANEUVER	60,000	UNIVAC 1100
IDRSPS	EDITS AND FORMATS RADIO DATA	30,000	UNIVAC 1100
MEDIA	CALIBRATES RADIO DATA	30,000	UNIVAC 1100
ONP	COMPUTES OPTICAL DATA PARTIALS	20,000	UNIVAC 1100
ONIPS	EXTRACTS OPTICAL OBSERVABLE	20,000	MODCOMP IV

Table 1. Major Software Elements of the JPL Navigation Data Processing System

Newly required radio data is first processed in the Intermediate Data Records Stripper Processing System (IDRSPS) Program, where the data blocks from different tracking stations are merged into a single time-sequenced array. Data of poor quality are edited from the array in this system, and the arrayed edited data is made ready in computer storage for the orbit estimation process.

Two major modules are used in the orbit estimation process. First is the Double Precision Trajectory (DPTRAJ) system, which computes an N-body numerical integration of the trajectory and state transition partials from initial conditions. The equations are developed in a cartesian frame referenced to the earth's mean equator and equinox of 1950.0. The numerical integration is performed using a variable order predictor, corrector method. The Orbit Determination Program (ODP) computes simulated observables corresponding to each actual observation based on the trajectory "modelled" by DPTRAJ and computes the partial derivatives of the observables with respect to to the inital conditions of the trajectory. It may also compute partial derivatives with respect to a multitude of additional trajectory and observation model parameters, such as planet gravity terms, target ephemeris coordinates, spacecraft gas leaks, and tracking station locations. An array of observation residuals is computed and a regression analysis is performed to produce a best estimate of corrections to the initial state parameters and the other desired parameters. The estimation algorithm may be batch-least squares, or sequential, with stochastic accelerations modelled if desired. The estimation process can be repeated, iteratively, until convergence is obtained. The product of the process is a numerically integrated trajectory which best fits the observations.

The best estimate trajectory serves as the basis for computation of the velocity correction parameters required to correct the flight path to meet the mission target objectives, a computation which is performed in the Maneuver Operations Program (MOPS).

Optical data is first processed in the Optical Navigation Processing System (ONIPS), where the full frame TV images are displayed on a videographics screen. There, an analyst can identify the target body and the background stars in the image. A limb fitting algorithm is employed to located the geometric center of the target body. The optical observables are then formed as the distances on the image plane between the target center and the identified stars. Dividing these distances by the camera focal length would produce the angles between the target and the star. The optical observables are passed by electrical means from the ONIPS Computer, a MODCOMP IV, to the UNIVAC 1100/81 computer, which hosts the Optical Navigation Program (ONP). The ONP computes simulated observables and partial derivatives of the optical observations with respect to the local spacecraft state and other parameters such as the target ephemeris parameters and camera biases. It produces an optical data file of the observable residuals and partials, which is merged with the radio data files within the ODP. The ODP can then compute joint orbit estimates based on both radio and optical data.

Navigation System Accuracy

Deep space navigation requires the computation of precision orbits and targeting corrections. These are made possible by the use of sub-meter accurate modelling throughout the navigation processing system, and the use of several model support systems, which furnish data and constants necessary for accurate computation. Sub-meter modelling is achieved by the use of double precision (16 decimal digits) in all trajectory and observable computations, and the use of a relativistic light time solution algorithm in the doppler and range observable computations, which takes in to account the retardation in the velocity of light by gravity and the transformation from solar system barycentric coordinate time to earth station proper time.[4] Model support systems provide the location of planets and natural satellites in the solar system, the location of the tracking stations on the earth, variations in the earth's rotation and orientation, and the effects of transmission media on the radio signal. A description of these support systems is given here.

(1) The Planetary and Satellite Ephemeris System - JPL planetary ephemerides are derived primarily from optical transit data, acquired by the U. S. Naval Observatory over the past century, radar planet surface-bounce range data, acquired by the NASA Deep Space Network over the past decade, and spacecraft ranging data, acquired from past planetary missions.[5] A large data reduction system, the Solar System Data Processing System (SSDPS) is maintained at JPL to process these many observations and produce the world-standard JPL ephemerides. With the advent of spacecraft ranging data, and with the recent refinements from lunar laser ranging data, JPL ephemerides for the inner planets, and Jupiter are accurate to within .2 geocenteric microradians. Ephemerides for the planets' natural satellites are developed almost exclusively from astrometric plate measurements, and are computed in a data reduction system similar to SSDPS.

(2) Tracking Station Locations - Position coordinates of the Deep Space Network tracking stations in California, Spain, and Australia are computed in the ODP itself from doppler data taken from the planetary encounters of the past 20 years' space mission.[6] The locations of the stations are therefore tied to the ephemeris used in the data reduction. A large data base of spacecraft-planet encounter doppler data is maintained at JPL. As a new planetary ephemeris is generated, so are the locations of the earth tracking stations recomputed. Stations are currently located relative to the current ephemeris, to a precision of 1 meter in the spin axis and longitudinal directions, and within 10 meters along the earth's spin axis.

(3) Universal Time and Polar Motion - UT1 and Polar motion data are obtained from the BIH after their reduction of meridian circle data. These earth rotation variations are stored in computer files in polynomial form and are applied as calibrations to the computed radio observables.

(4) Transmission Media Effects - Tropospheric effects on doppler and range are modelled in equation form. Charged particle effects from the earth's ionosphere are modelled as elevation dependent daily varying calibrations, whose values are computed using Faraday rotation data from an old NASA Applications Technology Satellite in geosynchronous orbit, the Japanese ETS2 satellite, and the Italian SIRIO satellite. The charge particle in the solar plasma are calibrated directly from analyzing S and X band doppler data from the spacecraft of interest.

Navigation System Operations

The navigation system is operated in support of each deep space mission both before the actual flight and during the flight. Long before the actual launch, navigation system software is exercised with simulated data. Covariances generated in these exercises enable the analyst to identify the major error sources for the mission of interest, define the total achievable mission accuracy, along with the required measurements and their acquisition schedule. One can also define performance constraints on the spacecraft systems, such as total required propellant or maximum allowable gas leakage rates.

During the flight, the navigation system is operated to support the actual guiding of the flight profile. The system produces all of the maneuvers which correct the flight path and furnishes all trajectories used to compute the spacecraft science instrument pointing sequences and tracking antenna pointing and tuning sequences. Doppler data is processed in the navigation system to investigate all spacecraft anomalies, such as abnormal gas leaks and impacts with small particles, which affect the flight path. The navigation system predicts the times of all dynamically related mission events, like occultation times. Finally, reconstructed navigation orbits are used to accurately locate the instrument viewing footprints, which aid the analysis of the science data.

Operating the navigation system to produce all the required products is a complex and often tedious endeavor. First, a large preparatory effort is required. This includes the setting up of tables and files for over 3000 initialization parameters for the system. These include parameters for the trajectory force models, start and end times, options for solution and partial derivative computation, initial state conditions, data filter options, data weighting and calibrations, and options for transforming state vectors and covariances into coordinate systems of interest.

When actual data processing begins, it is conducted as a scientific experiment, in which a hypothesized flight path is adopted and tested against the observations. This testing process usually involves:

1. Computing a Multiplicity of Flight Path Solutions, including:

- Solutions for various radio tracking data arc lengths or constant length data arcs located at different places along the orbit, to examine the distinguishing effect of changing geometry.

- Solutions for various choices of data types, such as doppler only, range only, optical only, doppler plus range, doppler plus optical, etc. to examine the degree of compatibility or conflict between data types and establish realistic data weighting policies.

- Solutions for various combinations of estimated parameters such as solutions for spacecraft state only, state plus solar pressure coefficients, state plus earth station locations, state plus planetary ephemeris, and multiple combinations of these and other parameters, to detect mismodelled phenomena and establish corrected model parameter values.

- Solutions using various data filtering algorithms and apriori statistics on estimated parameters, to detect and compensate for stochastic forces acting on the spacecraft.

plane, the geocentric declinations and right ascensions of the various encounters necessarily differ. If we attempt to compare, say, the orbit delivery error, delta X, for the encounter of Viking 1 at Mars in 1975, with other errors, we must map that error, according to the formula listed on the figure, around to some base declination, say, the maximum declination which can occur in the ecliptic plane, 23.5 degrees. We could then compare delta X′ from encounter to encounter. However, since all these encounters are at various ranges we must also map the range down to some common range like 1 AU. Better still, the comparative navigation performance index for a specific mission might be best represented by the equivalent geocentric declination error at some common declination, like 23.5 degrees.

and the doppler, this difference represents a fair approximation to the actual error in the delivery flight path. We see that the delivery error for Mariners 2 and 4 were quite high, but that missions since have experienced a remarkable consistency in navigation performance. We can note that doppler navigation systems appear to deliver spacecraft to distant targets over the past several years with an accuracy of about 1/4 geocentric microradians (at an equivalent declination of 23.5°).

Note that a few mission encounters are missing from the figure. These are: Mariner 7 at Mars, which experienced a large velocity anomaly due to impact or a large gas leak, just before encounter, Pioneer multi-probe mission to Venus,

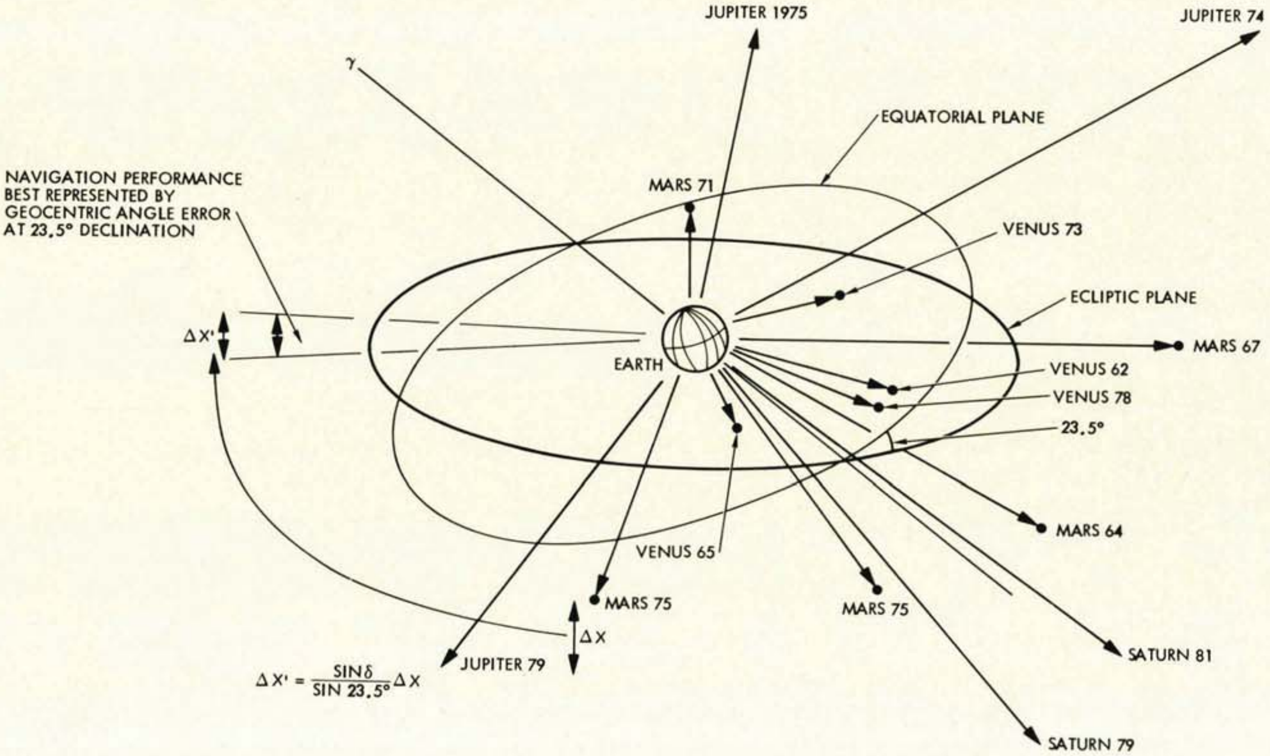

Figure 3. Geocentric Locations of the Planetary Encounters in NASA Planetary Exploration Program (1962-1981)

Figure 4 provides the flight record of achievement of deep space radio navigation in terms of the actual delivery error, mapped and adjusted for the differences in declination and range, into an equivalent geocentric declination error at 23.5°.

The error values were derived by selecting from the flight records the best or most credible flight path solution based on data obtained before the spacecraft experienced appreciable effects from the gravity field of the encountered planet and substracting the best, post-flight orbit solution from data taken during planetary encounter. Since approach trajectory estimates based on data obtained during encounter are extremely accurate due to the effect of gravity on the spacecraft

which released several probes to Venus then impacted the planet itself, making it difficult to reconstruct an accurate orbit estimate, and Voyager 2 at Jupiter, which experienced a failed capacitor in the transponder which adversely affected the doppler.

We should also note here that although declination errors nearly always dominate right ascension errors, in two cases a large right ascension error (not shown) dominated the declination error. Both Pioneer 11 and Voyager 1 experienced large, 2000 km (1 radian) errors when encountering Saturn, which is probably due to a large Saturn ephemeris error in the right ascension direction.

- Solutions using different sets of charged particle data calibration coefficients, to examine the quality and reliability of the different calibration techniques.

- Solutions with and without the non-gravitational force models derived from attitude limit-cycle data telemetered to earth, to examine the effectiveness of such models.

2. Computing the expected error covariances of all solutions and their sensitivities to errors in other model parameters which may be extremely difficult to estimate from available data.

3. Selecting an adopted "best estimate" flight path solution strategy from an in-depth analysis of the following characteristics of all solutions:

- The noise and signatures in the data residuals,
- The comparison of the flight path estimates with previous results,
- The compatibility of model parameter estimated values with estimated values from other sources, and the
- Comparison of computed error covariances and error sensitivities to unestimated model parameter errors and stochastic phenomena.

4. Exercising the adopted stratey to produce the final "best estimate" flight path.

The computation of maneuvers is also a complex process. It requires the placing of maneuvers at times which are conducive to both minimizing propellant use and achieving high accuracy, and the actual precise computation of the velocity corrections necessary to reach the desired target. It also requires a strong interaction with the mission management and the often evolving mission goals and policies. An example of this interaction for the Voyager mission is provided in Section III.

Auxillary functions also contribute to the complexity of navigation operations. These can include logging of results in a mission log book and visual charts, storage of data and other records in a computer based data management system, preparation and presentation of product material to the mission operations management, and the coordinating functions with other elements of the mission operations team.

Doppler Navigation Performance

Navigation system performance can be defined in several ways, but let us define it here by the error with which navigation delivers a flight path to its target. It should be pointed out that the delivery error to a planet or distant satellite is usually comprised almost totally of the target relative orbit determination error. Generally, maneuvers are performed shortly before target encounters, and maneuver execution errors normally don't have time to build up appreciably before the encounter is achieved. It is thus appropriate, if we are going to look at the record of planetary encounter errors, that we look briefly at the information derived from doppler data received from a station on the Earth tracking a spacecraft in distant space.

We show on the left half of Figure 2 a station on the earth doppler tracking a spacecraft at range ρ, with the earth rotating at rate ω. The doppler signal is proportional to the spacecraft-station range rate, which follows in time a pattern which resembles closely a sine wave. In the equation within the figure we see that the topocentric range rate is approximately equal to the geocentric range rate plus the sinusoidally varying term. The average signal is thus proportional to the geocentric range rate. The phase of the sinusoidal term is proportional to the cosine of the geocentric declination.

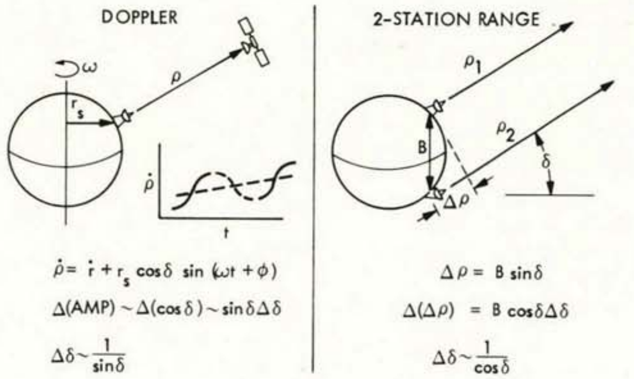

Figure 2. Properties of Doppler and Range Data as Navigation Measurements

There are three important points to note as far as the information content of doppler data is concerned: First, the ability of the doppler data based system to determine the position of a distance spacecraft is directly related to the spacecraft range, i.e. basically, the doppler measures geocentric angles. Second, the ability of this system to determine declination is inversely related to the sine of the geocentric declination. Therefore an error in declination is magnified by a factor of the reciprocal of the sine of the declination. This explains the traditional low declination problem often referred to in space navigation literature.[7] Third, the determination of right ascension is not particularly sensitive to variations in geometry. In practice, right ascension is nearly always determined more accurately than is declination.

An examination of the delivery error record of deep space navigation over the past 20 years can lead to a confusing set of statistics unless the parameters by which performance is judged are not carefully chosen. This is because the planetary encounters in the program have occurred at many different geocentric ranges and declinations. Figure 3 provides an illustration of the Earth relative directions and distances of planetary encounters in the past deep space exploration program. Note that Venus encounters generally occurred at geocentric ranges less than one AU, Mars encounters occur outside of one AU, and Jupiter and Saturn encounters occur very far from the Earth indeed. Also note that since all of these encounters have occurred near the ecliptic

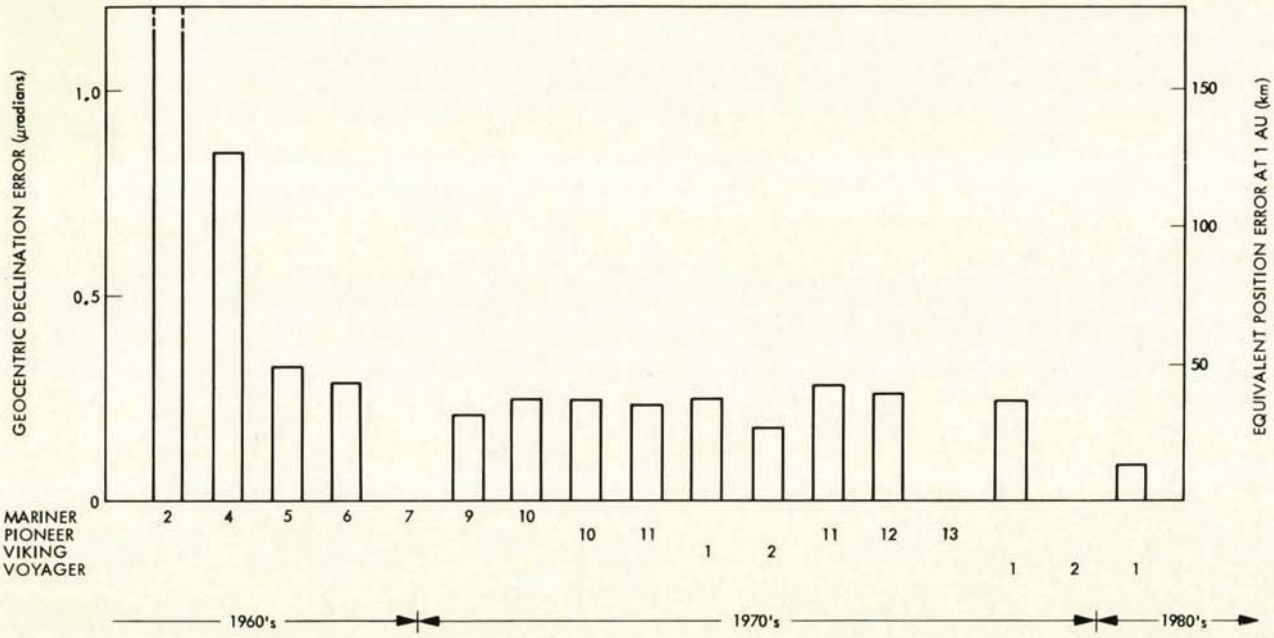

Figure 4. Mission-to-Mission Doppler Navigation Performance History ~ Equivalent Geocentric Declination Error at δ=23.5°

Two Station Range

An obvious concern develops with the accuracy of doppler navigation if the target planet is near zero declination when encountered by the spacecraft. Conceptually, a singularity occurs and doppler orbit determination accuracies in declination fall off sharply. Saturn is at near zero declination when both Voyager spacecraft encounter the planet. Hence, a new radio metric observation, near simultaneous two station two-way range, was developed for that mission. If two tracking stations with a long north-south baseline, as shown on the right half on Figure 3, measure the range at almost the same time, errors in the measured range are proportional to the reciprocal of the cosine of the declination, not the reciprocal of the sine. Hence, no singularity occurs at zero declination. The current planetary ranging system produces deep space range measurements accurate to 5 meters, hence two station range from stations at California and Australia, with a north-south baseline of 5000 km, can provide a direct measurement of a spacecraft declination accurate to about 1 microradian.

Figure 5 illustrates in schematic form the approximate navigation accuracy which is inherent in the current JPL deep space radio navigation system. The performance possible with doppler is illustrated by the curved line which approaches and error of .25 μrad for high declinations but falls off to high errors for low declinations. The near-simultaneous range measurement provides a 1 μrad "safety valve" at low declinations.

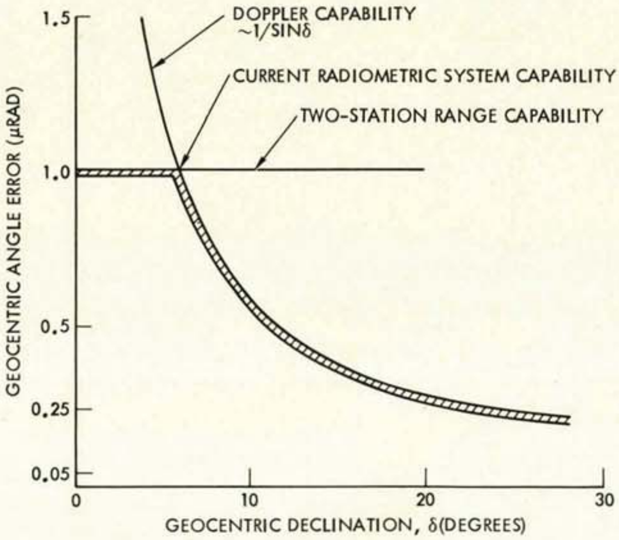

Figure 5. The Geocentric Performance of the Current JPL Radio Navigation System

Optical Navigation Performance

The navigation accuracies achievable with optical data must be characterized differently from those associated with radio data. First, the optical observation is target relative rather than earth based, a considerable advantage since the effect of the target ephemeris errors are minimized and the spacecraft is much closer to the target than it is to the earth when the final flight path delivery maneuvers are performed. Since the optical observable is directly angular and two dimensional in nature, the power of the observable is relatively insensitive to changes in trajectory/target geometry. A limiting error is, of course, the resolution of the camera. Line and pixel spacing on the Voyager spacecraft vidicons is 0.15 mm, and the camera's narrow angle telescope carried 1.5m focal length optics. Therefore 1/2 pixel resolution produces an angular resolution of 5 μrad. The ultimate position accuracy obtainable with optical data is also limited by one's ability to determine the gravitational center of the target body from the limh and terminator measurements in the optical images. Currently our centerfinding capability is within 1% of target body radii.

The accuracy of the current JPL navigation system can be summarized in a very simplified way as described in Figure 6. The accuracy of radio navigation is characterized by the uncertainty in the direction to the spacecraft as viewed from the earth. As we have stated, the ability of doppler to determine a spacecraft's declination is inversely related to the sine of the declination. Today's doppler system enables a spacecraft in cruise at high absolute declination, say 23°, to be located within a total angular uncertainty of 1/4 microradian or about 250m position error for every million kilometers distance from earth. The two station range measurement provides a 1 μrad backup at low declination.

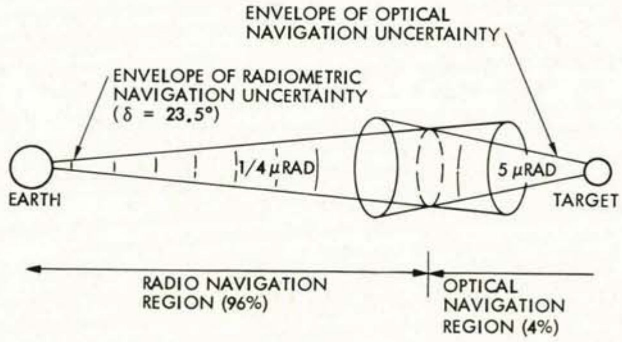

Figure 6. A Schematic Comparison of the Characteristics and Performance of Radio and Optical Navigation

Optical data locates the spacecraft relative to the target to an angular accuracy of 5 μrad, or 5 km/per million kilometers distance from the target.

Earth based radio navigation and its less accurate but target relative counterpart, optical navigation, thus form complimentary measurement sources, which provide for navigation a powerful sensory system to produce high precision orbit estimates. Radio navigation is somewhat analogous to traditional nautical dead-reckoning, since it relies on measurements relative to the origin of travel. Optical navigation is essentially a piloting system, since it relies on destination relative measurements.

III. VOYAGER NAVIGATION

The Voyager Mission Profile

The two Voyager spacecraft were launched from earth in late summer 1977. Both encountered the Jupiter system in 1979. Voyager 1 arrived at Jupiter in March 1979 and passed within 350,000 km of the planet, while being targeted to a close 20,000 km flyby of the satellite Io. Voyager 2 encountered Jupiter in July 1979, passing within 730,000 km of the planet and encountering the satellite Ganymede at a distance of 62,000 km.

Voyager 1 flew by the Saturn system last November 12 (1980). A general view of the Voyager 1 flight through the Saturn system is provided in Figure 7. The flight path was targeted such that the spacecraft flew within 7000 km of Titan, the solar system's largest natural satellite, 18 hours before the close approach of Saturn itself. After the close encounter with Titan the flight path extended directly behind the satellite, as viewed from the earth, which allowed the Titan atmosphere to affect the radio signal to earth and provide data for atmospheric studies. The spacecraft then passed close by (185,000 km) and then behind Saturn and its rings, such that similar radio signal effects from the planet atmosphere and ring system could result. The spacecraft then continued on out of the Saturn system, passing through the E ring and making TV viewing passes by several Saturnian satellites, the closest being Rhea at 73,000 km.

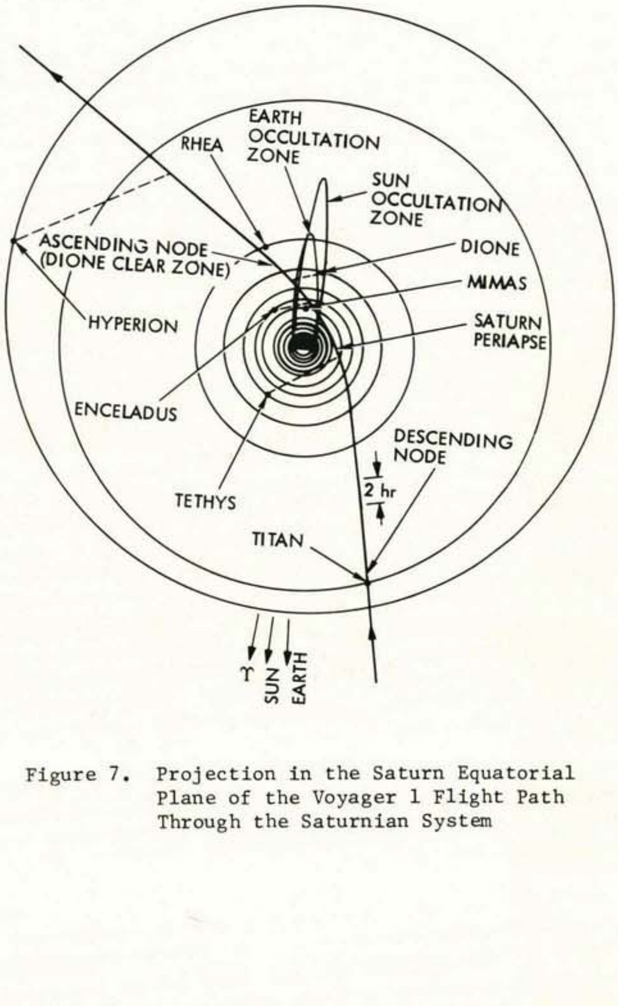

Figure 7. Projection in the Saturn Equatorial Plane of the Voyager 1 Flight Path Through the Saturnian System

Voyager 2 will encounter the Saturn system this summer on July 25 (1981). The spacecraft will pass by Saturn at a distance of 161,000 km and then pass within 100,000 km of two of the Saturn satellites, Enceladus and Tethys. The Voyager 2 flight path was designed so that the natural swingbys at Jupiter and Saturn would direct the flight path to an encounter with Uranus. The targeting of the flight path of Voyager 2 at Saturn can now enable a swingby leading to a continued trajectory to Uranus in January 1986 and to Neptune in 1989.

Voyager Navigation Challenges

The Voyager mission has provided the most demanding navigational challenges in the NASA planetary program to this time.

Voyager 1 has been navigated with the primary concern being to secure high quality TV images of Jupiter and Saturn and their satellites. The spacecraft was required to fly closest to Io at Jupiter and Titan at Saturn and point its cameras accurately to acquire the images. Additional navigational challenges were presented at both Jupiter and Saturn.

At Jupiter, Voyager 1 was required to fly directly beneath the Io and pass through its 2000 km wide flux tube, a cylindrical shaped corridor created by Io's interruption of charged particles motion along the Jovian magnetic field lines. The time of the spacraft's passing behind Jupiter had to be controlled to within 30 sec, so that a critical preprogrammed antenna slew to enable a strong signal to pass through the Jupiter atmosphere could be properly timed with the atmosphere's refractive effects.

At Saturn, Voyager 1 was required to perform a diametric earth occultation with Titan to within a tolerance of 265 km, and then, after closest approach to Saturn, pass through a 5000 km wide corridor in the E ring, where it was believed that particles would have been swept away by the natural satellite Dione, and the chances of a disastrous impact would be minimized. The close encounter with Titan itself created a difficult navigational challenge for controlling the instrument pointing for observations of the Saturn satellites on the out-bound leg of the system encounter. Uncertainties in the dispersed flight path after the Titan and Saturn flybys made it mandatory to quickly and accurately redetermine the trajectory after the Titan closest approach. The new trajectory could be used to repoint the instruments for the science imaging sequence, which took place just hours after Saturn closest approach.

Voyager 2 has been navigated both to Jupiter and to Saturn with the primary concern being the retention of adequate propellant to reach Uranus. During a planetary swingby an error in either the approach trajectory or the mass of the planet leads to an error in the outbound direction of travel, which must be corrected with a propulsive maneuver. This maneuver reduces the remaining propellant available for both attitude control and subsequent flight path corrections. Thus, for Voyager 2, as with Voyager 1, a premium has been placed on the accuracy of delivery of the spacecraft on its incoming trajectory at both Jupiter and Saturn.

Voyager Navigation Strategy

Voyager navigation was carried out using the navigation system described in Section II. A special emphasis was placed on optical navigation, which was required for the first time on Voyager to meet a deep space mission's objectives. The radio doppler system was used as the baseline cruise system, but optical measurements were employed over the final few months before each encounter and served as the most accurate and hence the controlling navigation measurements for the planetary encounters. The doppler system served as an initilization and backup to optical navigation during the Jupiter approaches. The doppler system, augmented with the two station range measurement system, was adopted as a backup at Saturn.

Optical navigation has been performed on Voyager from TV images of the satellites of Jupiter and Saturn, not the planets themselves. The smaller size of the satellites and their sharp (rather than diffuse) surface makes them more attractive as optical navigation targets than the central planets. In addition, many of the encounter target conditions were relative to the satellites themselves as well as to the central planet, so that the flight path of the satellite was required known to the same precision as the spacecraft flight path.

Special satellite ephemeris propagation systems for the Galilean and Saturn satellite systems were developed, and an extensive pre-encounter ephemeris generation activity, including the acquisition of many new astrometric plate observations from the University of Virginia, the University of Texas and the U. S. Naval Observatory, was undertaken. The ephemeris propagation software used in the generation of the ephemerides was also used in the flight navigation system. The satellite ephemerides were then corrected as the spacecraft orbit was determined from the optical navigation measurements.

Jupiter Navigation Results

The optical navigation processes at Jupiter for both Voyagers 1 and 2, and at Saturn for Voyager 1 were extremely successful. At Jupiter more than 100 TV pictures of the Galilean satellites were acquired during the last 60 days before encounter. Orbits determined from these images were used to maneuver the spacecraft to its target flight path with a 4 m/sec velocity correction performed 34 days before Jupiter encounter and a "clean-up" .6 m/sec correction 12 days out. The spacecraft then flew through its Io relative corridor with an Io relative error of just 100 km.[8] All scientific close range TV images of Io were successfully acquired-images which later were recognized to show volcanism on Io. The Jupiter occultation time was controlled to within 1.5 seconds, and the radio signal was successfully transmitted and acquired through the Jovian atmosphere.

On Voyager 2, a similar optical navigation approach process was followed, with a 1.5 m/sec correction, performed 45 days before Jupiter encounter, and a 1.6 m/sec correction 12 days out, providing the spacecraft delivery. Although there were no exceptional science related navigation requirements for Voyager 2 at Jupiter, the experience there serves to illustrate the interaction required between the navigation function and the mission planning activity.

Along with the concern about the total Voyager 2 fuel expenditure, there was also a mission policy to keep open an option for timing the Voyager 2 Saturn encounter so that a Titan encounter could be achieved, in case Voyager 1 failed before reaching Titan. It was recognized that a Voyager 2 velocity correction as large as 44 m/sec, if performed 14 days after Jupiter encounter, was required to prolong this option. This maneuver would correct the timing of the Saturn encounter to achieve a Titan flyby. Performing the maneuver 14 days after the Jupiter encounter would avoid conflict with the Jupiter science data acquisition sequences. It was also determined, just before the Jupiter encounter, that a partial Titan timing maneuver could be performed with a propellant expenditure of only 13 m/sec if the maneuver were performed very near the close Jupiter approach time.[9] A partial Titan timing maneuver would allow both the options to encounter Titan and the option to reach Uranus to remain open. If the decision to encounter Titan was made later in the flight, there would be sufficient fuel to achieve the encounter.

But the spacecraft computer was overly burdened with sicence sequence processing during the time of Jupiter closest approach, and it was impossible to find onboard computer word storage for a maneuver direction. However, the onboard computer resource problem was solved by recognizing that the optimum near-closest approach maneuver was directed almost along the earth-spacecraft line, the direction in which the spacecraft thrusters are nominally pointed, being lined up by design parallel to the axis of the earth antenna. Figure 8 depicts the geometry. A decision was made to perform the maneuver at closest approach. This was accomplished with a word limited command, involving only the turn time and duration, and not the turns, at little expense to science acquisition, with which the maneuver was competing. The net fuel savings made possible by this ingenious maneuver strategy amounted to some 30 m/sec, which improved considerably the chances of the Voyager 2 spacecraft reaching Uranus. Since Voyager 1 did indeed encounter Titan, the Voyager 2 will not be targeted to a Titan encounter.

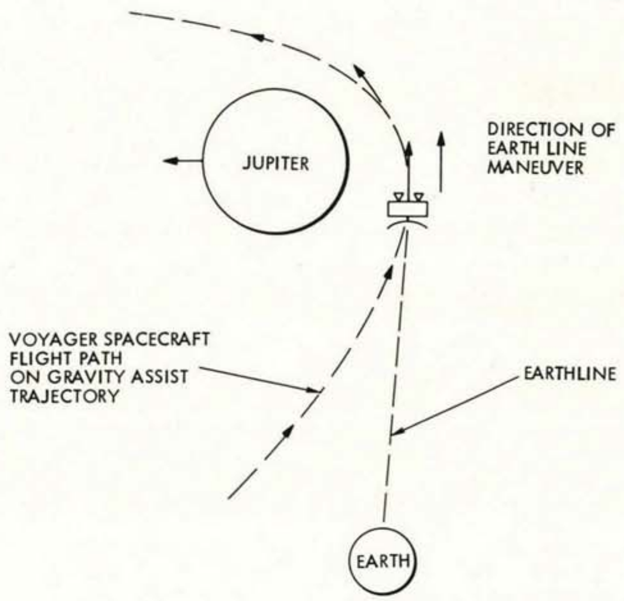

Figure 8. Voyager 2 Jupiter Encounter Geometry

Saturn Navigation Results

The Voyager 1 encounter with Saturn was the most complex navigational planetary encounter yet experienced. First, the Saturn satellite ephemeris propagator, used for the pre-flight ephemeris generation, was not accurate enough for the reduction of optical measurements for Titan. Therefore the pre-flight Titan ephemeris theory parameters had to be transformed to a cartesian state vector and the subsequent path of Titan numerically integrated. The conversion of both the ephemeris parameters and their uncertainties to cartesian coordinates caused difficulties in the orbit determination process. Navigating Voyager 1 to its 7000 km close approach and occultation of Titan was tedious, with many orbit solution being processed and reviewed before a final, successful one was chosen. Voyager 1 did achieve its flyby of Titan by a 1.9 m/sec maneuver performed 33 days before encounter and a 1.5 m/sec cleanup 5 days out. The flight path was accurate to 330 km. There was a great science interest in the occultation being as nearly diametrical as possible. The error in the flight path was only 37 km in this key direction, thus a nearly perfect diametrical occultation with Titan was achieved.[10]

During the Titan encounter, doppler data, which was then greatly influenced by Titan and hence very sensitive to the flyby distance and Titan's mass, was processed to quickly determine the flyby trajectory to high precision. This action led to quickly constructed instrument pointing adjustments for the outbound imaging of the satellites Mimas, Enceladus, Dione, and Rhea. These science image acquisitions were entirely successful, an engineering feat not possible without the fast, accurate trajectory reconstruction made possible by the close Titan doppler. Titan, in this case, after creating the post-Saturn instrument pointing problem by adding dispersion to the Saturn approach trajectory, also contained the solution to the problem, since its gravity bending effects on the doppler data provided the sensitivity to redefine the trajectory well enough to correct the instrument pointing.

The delivery to Titan was also accurate enough so that as the spacecraft passed through the E ring on its escape from the Saturn system it did so through a gap of space thought to be more nearly devoid of particles than other regions. This relatively particle free section of the E ring might have been swept free by Dione. Whether the region is actually safer than other regions is, of course, still open to speculation. However, the spacecraft did survive the E ring passage and continued its science data acquisition sequences.

The Voyager 2 navigation requirements at Saturn are neither as stringent or as complex as those of Voyager 1. The closest satellite encounter is with Enceladus at 87,000 km, and, if the optical navigation process is successful, the imaging of all targets will be achieved. There is however, a high premium placed on navigating the incoming trajectory as accurately as possible so that the post-Saturn correction maneuvers are small and propellant use is minimized. If all goes well and Voyager 2 is delivered to Saturn with an accuracy of 100 km or better, there will be a better than 90% probability of reaching both Uranus and its inner satellite Miranda and Neptune and its major satellite Triton.

To summarize the Voyager navigation experience to this time, we must say that although Voyager has presented the toughest deep space navigation challenge yet faced, our successes in meeting the challenges have made it the most satisfying mission to navigate. Voyager 1, at Saturn, provided the opportunity to produce, with fast and accurate data processing, a trajectory accurate enough that subsequent TV images of several Saturn satellites, otherwise unattainable, were in fact acquired. Voyager 1, at both Jupiter and Saturn, has primarily been a challenge to the orbit determination process to deliver accurately precision remote sensing instrument fields-of-view. Voyager 2 at Jupiter, on the other hand, was primarily a challenge for the maneuver analyst, where an innovative, propellant saving earth-line maneuver at Jupiter closest approach has, in fact, opened up the realistic prospects of extending this mission past Saturn and Uranus to Neptune and its primary satellite, Triton.

The Voyager navigation experience has brought to reliable maturity the optical navigation process. The two station range backup system, although a wise investment in overall mission reliability, never had to be actually used. Optical navigation can now take its place alonside radio navigation as a baseline system which can be totally relied upon for future missions.

IV. Future Challenges for Deep Space Navigation

Table 2 provides a list of continuing and possible, missions which will present challenging navigation problems to be addressed in the 1980's. The Voyager 2 mission will of course continue to Uranus and Neptune, where optical measurements will be used just as they were at Jupiter and Saturn to deliver the spacecraft precisely to its target conditions. Both the International Solar Polar Mission and the Halley Intercept Mission are possible missions for the 1980's, however both are under severe scrutiny in NASA due to funding limitations. The U. S. participation in the ISPM program may be curtailed sharply, however, JPL Navigation is prepared to navigate the European spacecraft and will employ its doppler system, which will meet the mission objectives. The HIM mission, if finally approved, will be navigated in cruise with radio data and during the comet approach with optical data, as was Voyager.

• VOYAGER	CONTINUING	SATURN, URANUS, AND NEPTUNE ENCOUNTERS
• PIONEER	CONTINUING	CRUISES AND VENUS ORBITER
• GALILEO	LAUNCH 1985	JUPITER ORBITER/SATELLITE TOUR, JUPITER PROBE
• HIM	LAUNCH 1985	FLYBY OF COMET HALLEY
• ISPM	LAUNCH 1986	JUPITER SWINGBY, OUT OF ECLIPTIC
• VOIR	LAUNCH 1988	VENUS CIRCULAR ORBITER

Table 2. Some NASA Candidate Missions for the 1980's

Galileo Mission Profile

The approved Galileo mission represents perhaps an even greater navigation challenge than has Voyager. In 1985 a single shuttle launch will send the dual-spin Galileo spacecraft to Jupiter. On the spin-stabilized part will be carried an atmospheric entry probe, and on the attitude stabilized part will be carried an articulated platform with science instruments, including a charge-coupled device television camera.

Figure 9 depicts some of the major segments of the Galileo flight profile. The heliocentric cruise orbital plane will be broken in mid-flight by a 170 m/sec velocity correction. The spacecraft will then be targeted to meet the flight path entry requirement for a descent into the Jovian atmosphere. Then, 150 days before encounter with Jupiter, the entry probe will be released. The remaining spacecraft will be deflected a few days later by a 55 m/sec burn to fly over the probe as it descends into the Jovian atmosphere, and act as a relay link for data being transmitted by the probe. The current mission design calls for the spacecraft to fly close by (1000 km) Io for purposes of gravity retardation on its way to a 280,000 km altitude (4 R_J) close approach to Jupiter, where it will perform its 675 m/sec orbit insertion maneuver.

The spacecraft then becomes a long period (200-day) orbiter of Jupiter, and at its first apoapsis passage will perform a 380 m/sec burn to raise the periapsis radius to 850,000 km (12 R_J), where the spacecraft is less susceptible to radiation damage. Having reached its baseline 12 R_J periapsis Jovian orbit, the spacecraft will then be targeted to a dozen or more close encounters with the Galilean satellites: Ganymede, Callisto and Europa.

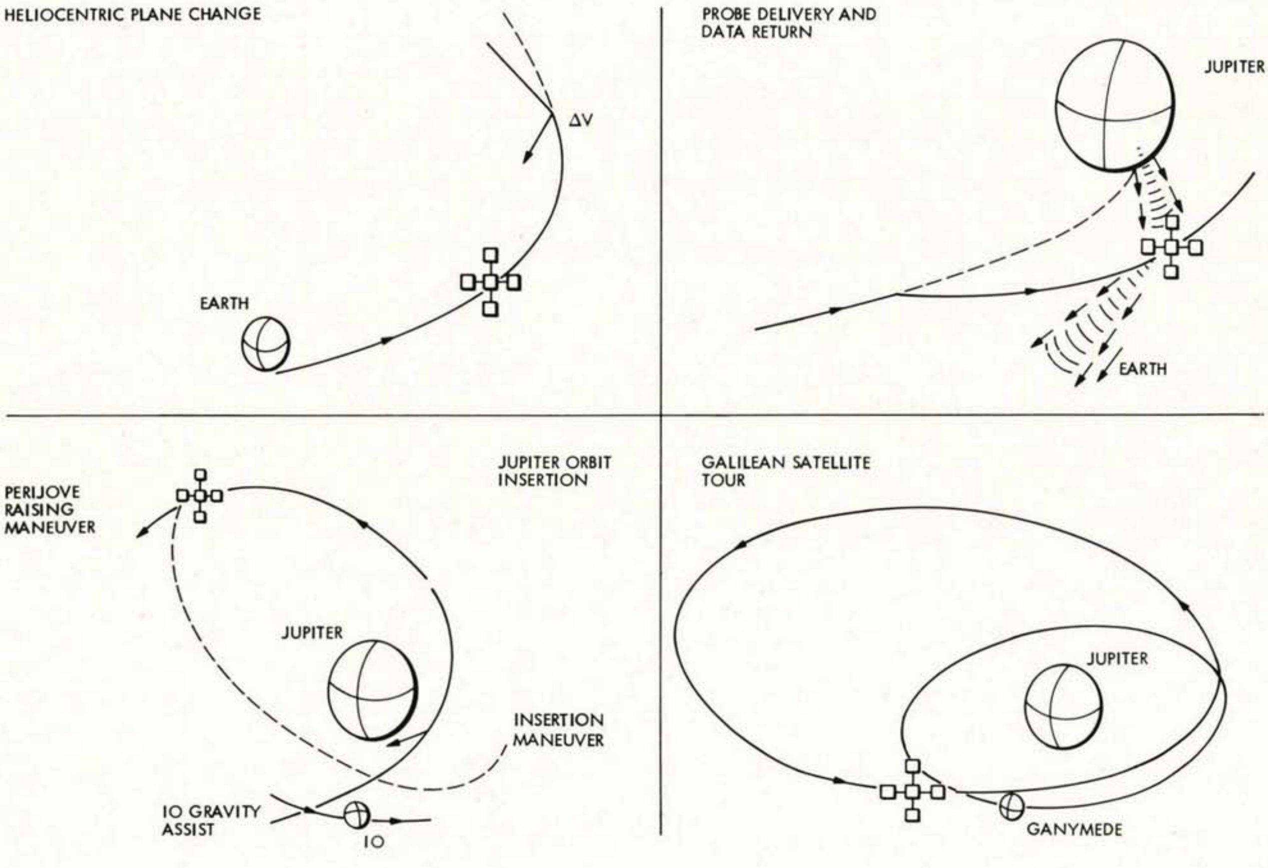

Figure 9. Major Elements of the Galileo Flight Profile

Galileo Navigation Challenges

The primary challenging navigation functions for the Galileo mission are to (1) deliver the atmospheric probe to the atmosphere of Jupiter and deliver the orbiter to a flight path which will enable it to relay the probe data to earth and (2) deliver the orbiter to a Jupiter centered orbit and guide it through its tour of the Galilean satellites.

The probe must be released 150 days away from Jupiter so that the orbiter deflection maneuver is small; yet the probes' atmospheric entry angle must be controlled to 1.6°. The orbiter must then be maneuvered over the probe so that data can be transmitted and relayed to earth for at least one hour after the probe reaches the .1 bar atmospheric pressure level. This requires that the probe-orbiter relative geometry be delivered to within a Jupiter centered angular uncertainty of 2°. The probe trajectory in the Jovian atmosphere must be reconstructed to a very great accuracy to enable the precise correlation of the probe-acquired temperature, pressure, and acceleration data with the descent altitude. The atmosphere entry angle must be determined to .05° to make this possible.

The Galilean satellite tour must be navigated with extreme precision. For each close satellite encounter, the science instrument fields-of-view must be delivered accurately enough that the desired images are obtained. Most important however is the requirement that the entire tour, a dozen encounters in 20 months, be navigated within a 205 m/sec ΔV propellant allocation. These stringent requirements imply that delivered flight paths must be accurate to 20 to 30 km at the Galilean satellites.

Galileo Navigation System

Two developments at JPL will permit changes in the Voyager navigation system, which will enable it to meet the stringent Galileo requirements. The first development is the use of Very Long Baseline Interferometry (VLBI) as a new navigation radio measurement to improve earth based navigation accuracy. The second is the ground automation of the optical navigation processing system to decrease the processing time during satellite approaches and therefore allow more accurate optical navigation during the Galilean tour.

Very Long Baseline Interferometry

VLBI, as a navigation measurement technique, involves the simultaneous tracking of first a spacecraft , then a nearby extragalactic natural radio source, from two widely separated ground based stations. Through the ground correlation processing of the spacecraft data, the difference between the times the two stations receive the same signal can be computed to extreme precision, about 1 nanosecond. If the same correlation process is applied to quasar data, a similar time delay difference is obtained. Both computed time delays differences are sensitive to station location relative errors, transmission media errors and station timekeeping errors, but they are sensitive in the same way. If the respective time delays differences are differenced again, the resulting doubly differenced delay is relatively insensitive to the major error sources. Whereas the individual time delays provide information which can yield an angular fix to about .25 μradians, the double difference technique provides a spacecraft direction angle fix accurate to .05 μradians or better, relative to the observed quasar. If the spacecraft signal is only narrow-band, or doppler, the VLBI technique can only measure the differenced time delay rate of change, which is poportional to the rate of change of the spacecraft direction.

Figure 10 illustrates how the wideband VLBI system produces time delays. The Galileo spacecraft transponder is being outfitted with 19 Mhz side tones at X-band and 4 MHz side tones at S-band to allow the correlation process to extract the time delays.

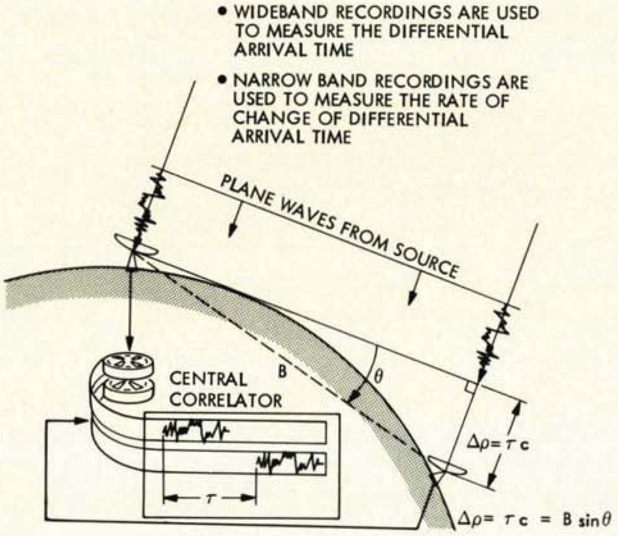

Figure 10. Illustration of VLBI as a Navigation Measurement

Wideband VLBI is thus a downlink doubly differenced range system, which requires only short, 10 minute passes of data, and is accurate to .05 μrad. Its accuracy characteristics are similar to the Voyager system's differenced 2-station, 2-way range in that there is no appreciable degradation at low geocentric declinations, but it is of course some 20 times more accurate. Narrowband VLBI is a downlink doubly differenced doppler system, which requires long data arcs of several hours, as does two-way doppler, but is 5 times more accurate, at .05 radians. Narrowband VLBI does also experiences accuracy degradation at low declinations.

Automated Optical Navigation

For the Galileo mission the processing of optical measurements during target approaches, which has been performed in the ODP system along with the processing of radio data for the Voyager mission, will be performed in a dedicated minicomputer. The Automated Optical Navigation System (AON) will provide a ground-based automated navigation data processor for Galileo, which will produce approach navigation products faster than the traditional system. The AON will also serve as ground prototype for onboard navigation systems needed in the planetary exploration program in future years.

As an initial condition for target approach, AON requires a radio data-determined orbit, to be computed in the ODP and transferred to the AON software. Then as TV pictures of the target against the star background are received on Earth during the approach, the AON system will automatically extract angular information from the pictures, compute a sequentially updated estimated flight path with each newly received and validated picture, and compute the trajectory correction parameters for command to the spacecraft.[11] Figure 11 depicts the sequence.

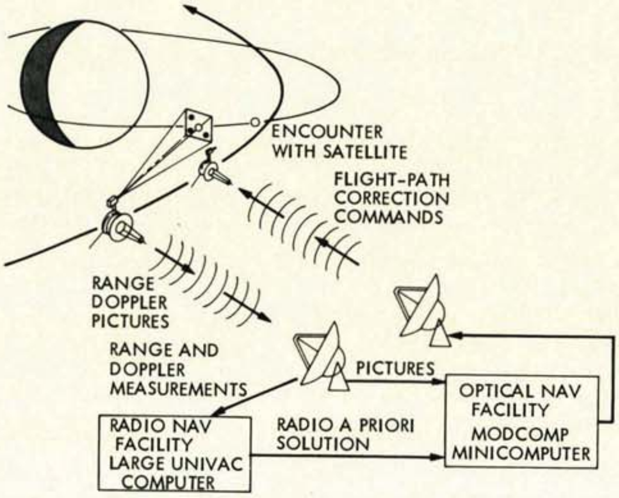

Figure 11. Schematic Diagram of the Ground-Automated Optical Navigation System

The automated extraction of precise angular information from the raw TV pictures will be a special AON challenge. Vidicon TV cameras, like Voyager's now, experience deflections in the scanning beam due to electric and magnetic disturbances. If left uncalibrated, beam bending destroys the metric accuracy in the angular measurements by tens of microradians. The calibration process requires analysis on a picture-by- picture basis, which prohibits automation. However, Galileo will carry charge-couples devices (CCDs) as camera sensor-elements. CCDs should produce TV images of high metric quality, and should allow automation of the angular measurement extraction process.

Galileo Navigation Strategy

The cruise and atmospheric probe delivery and trajectory reconstruction will be based on doppler and wideband VLBI measurements. VLBI data will provide a delivery well within the requirements and a reconstructed probe descent trajectory which just meets requirements.

The Io flyby during the final approach to Jupiter will be navigated optically in much the same manner as Voyager was navigated in 1979. The spacecraft will be delivered to Io with an uncertainty less than 100 km. The Jupiter orbit insertion maneuver can be planned from the Io delivery trajectory, and the perijove raising maneuver can be planned using a doppler determined orbit.

The tour of the Galilean satellite presents a special challenge for navigation. The tour will basically be navigated optically, with wideband VLBI measurements used as a backup. Maneuvering through the tour will be a complex process, as noted in Figure 12. After each close satellite encounter a maneuver to correct the spacecraft orbital period will be performed, to time the encounter with the next satellite. At the apojove a second maneuver will be performed to adjust the flight path to the correct encounter aimpoint. Then optical measurements become all important as the spacecraft approaches the satellite to be encountered. On previous orbital passes, optical measurements will have been acquired both when the satellite was at the same orbital position as the encounter position and 180° on the opposite side of its orbit. These measurements will help locate accurately the satellite for the encounter. Now a sequence of optical measurements will be aquired as the spacecraft approaches the satellite.

The final maneuver, based on the optically determined orbit, will be processed in the AON system and performed three days before the encounter. This maneuver will not target to the approaching encounter, but to the subsequent satellite encounter in the sequence, thus perpetuating the tour.[13] Of course, as optical navigation is performed on each successive encounter, the ephemerides of the satellite will be further improved to aid subsequent tour encounters. Most of the deliveries will be accurate to the limit of optical resolution, 20 to 30 km. It is expected that the tour can be completed within the allocated fuel budget.

VOIR Mission Profile

The proposed Venus Orbiting Imaging Radar Mission, (VOIR) presents a new and unique set of navigation challenges. The VOIR mission, although not fully approved, is currently planning to launch a spacecraft to Venus in 1988 which will precisely map the surface of Venus from a low circular orbit. The spacecraft will carry as its principle instrument a combined Synthetic Aperture Radar (SAR)-altimeter system, capable of both high resolution (150m) mapping of the Venus surface through the atmosphere and 50m surface altitude measurements. The SAR image swaths, when mosaicked and combined with the altimetry data and gravity, derived from doppler analysis of the orbit, will provide the measurement base for refining our knowledge of the physics of the Venus interior, including the density distribution and surface tectonics.

The current mission plan, although evolving, calls for a launch on the Space Shuttle in 1988, a three month cruise to Venus, and an insertion to a near polar long period orbit about Venus, with a periapsis altitude of 250 km. This preliminary orbit

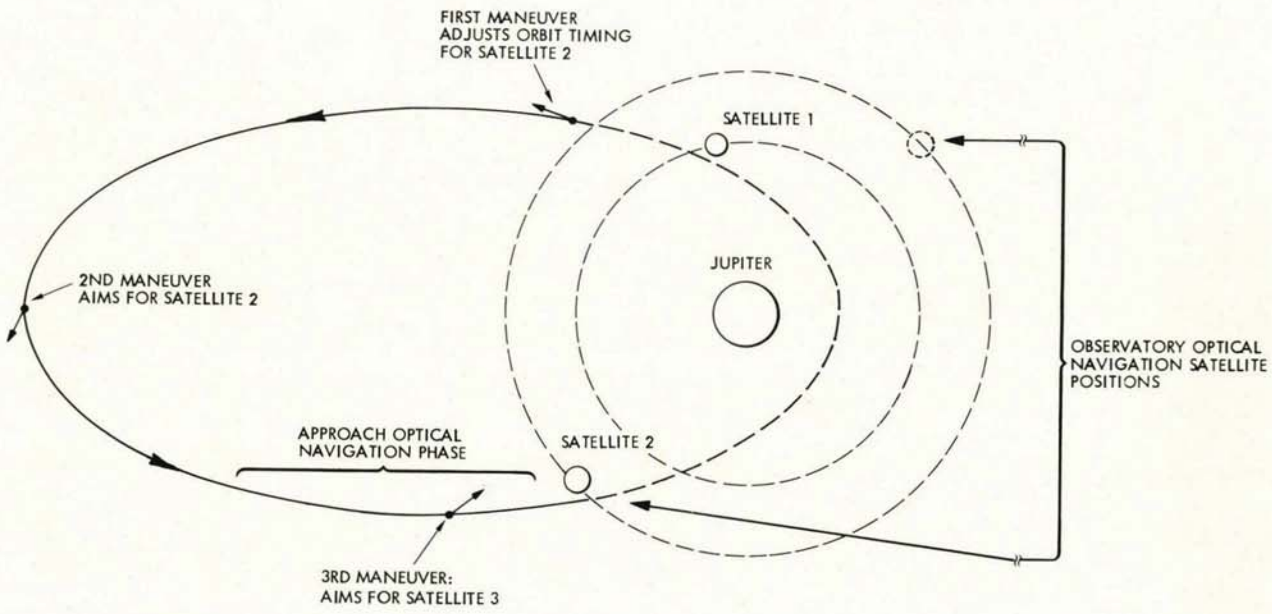

Figure 12. Typical Galilean Tour Navigation Sequence for Single Revolution

will be trimmed down to a 24 hour orbit within a few days after orbit insertion. Then the periapsis altitude will be lowered to 125 km by a series of retro maneuvers at apoapsis, which will initiate an aerobraking phase to lower the orbit period to 2 hours within a specified period of time, about 60 days. See Figure 13.[14] The periapsis altitude will then be raised back to 250 km again and the orbit will be trimmed into its circular mapping orbit, with an altitude of 250 km and an inclination 87.2° or 92.8°. In this orbit the SAR mapping will be performed for several months.

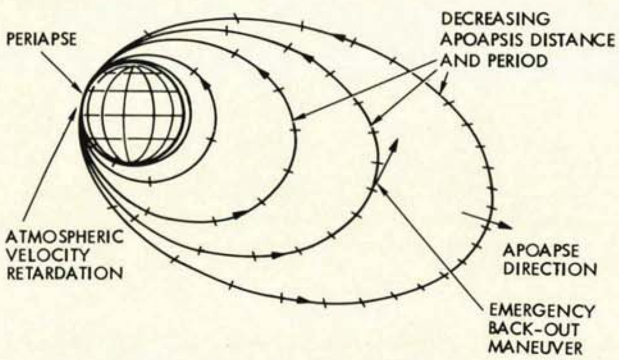

Figure 13. VOIR Aerobraking Sequence

VOIR Navigation Challenges

Most of the VOIR mission will be navigated with doppler data as was Mariner 9 in 1971. There are, however, two difficult navigation challenges: (1) the control of the spacecraft during the aerobraking phase, and (2) the determination of precise mapping phase orbits to aid the SAR image mosaic construction.

The aerobraking process represents a high risk phase in the mission profile. Maneuvers will be required to control the spacecraft periapsis altitude such that it is high enough that acceleration limits are not exceeded, but on the other hand, such that it is low enough that the aerobraking phase does not exceed its specified duration. Furthermore, the exact tolerance on the periapsis altitude will be unknown until experience is gained in the aerobraking phase itself. Great care must be exercised not to exceed maneuver propellant allocations. In summary, the aerobraking phase will be a supreme adaptive operations challenge.

Control of the mapping orbits represents a significant challenge, but one that can be met with conventional doppler measurements. The orbit eccentricity must be controlled to within .004 (25 km variation in altitude), and a series of period adjustments and recircularization maneuvers will be required. Uncertainties of determined radii should be well within 1 km.

In the horizontal direction, however, doppler orbits are accurate to only 10-100 km, due to gravity perturbations on the dynamics and hence the signature of the doppler measurements. The primary uncertainty parameter for a determined orbit is the orbital angular orientation about the earth-Venus line of sight. Precision mosaicing requires footprint locations accurate to 1 km, hence 1 km orbit determination is desired. Narrowband VLBI, as discussed earlier in this section, provides the capability to determine orbits with an accuracy of about 1 km. Therefore, VOIR provides the first mission requirement for continuous, narrowband VLBI tracking.

V. Summary and the Future

As we complete the navigation of missions of the 1970's and approach the challenges of missions in the mid and late 1980's, we can pause and note where we are in the evolution of navigation systems for deep space missions. The developmental history of deep space navigation is characterized by two major stages, (1) the development and maturation of radio doppler navigation in the 1970's, which really reached is zenith when Mariner 9 and Viking 1 and 2 were navigated to and about Mars, and (2) the development and maturation of optical navigation, which, with the Voyager successes, take its place alonside radio navigation as a proven reliable technology.

The future, at least for the next decade, appears to bring additional changes to deep space navigation. First is the development of VLBI as a navigation measurement source, and along with it the concept of high precision quasar-relative navigation. VLBI will be used primarily in the 1980's for precision reconstruction of orbits, but could eventually replace doppler as the primary radio navigation measurement, if the planetary ephemerides are improved during the next decade and computed in a quasar relative coordinate frame. Next is the increasing autonomy in ground processing, with its potential for faster, and hopefully more reliable, data processing. Another change lies in the increasing complexity of maneuver planning. The methods associated with optimal maneuver location and 2nd body targeting algorithms, first exercised for the Voyager mission, will reach critical importance as missions like Galileo become more complex and yet remain, as always, propellant-constrained.

Looking ahead to the 1990's, it is difficult to forecast the deep space mission program with much degree of certainty. We can say, however, that if the planetary exploration program continues to seek new adventures, deep space navigation systems will have to change, to enable the missions. Electric propulsion missions of any kind will require new orbit determination and maneuvering algorithms. Close solar gravity structure sensing probes will require the use of drag-free trajectory control systems. Asteroid or comet close rendezvous missions will require onboard navigation systems, with orbits determined and maneuvers computed at the spacecraft. Planetary sample return missions will require precision landing systems, based on optical landmark tracking and radar altimetry data, and systems to rendezvous and dock a sample return craft with a mother craft. Perhaps the 1980's will witness challenges for deep space navigation which will rival and even surpass those experienced over the last two decades.

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