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# Navigation Accuracy Analysis for a Halley Intercept Mission

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**A ballistic intercept mission to Comet Halley was recently considered by the United States. This paper describes the navigation system and the navigation strategy which would have been employed in such a mission, assuming a launch in the summer of 1985 and an arrival in March of 1986. Spacecraft comet-relative orbit determination accuracies are presented as functions of time for the baseline navigation strategy, along with the results of a number of parametric sensitivity studies involving parameters such as data frequencies, data accuracies, stochastic acceleration levels, cometary ephemeris uncertainties, maneuver execution errors, and encounter date.**

## Introduction

THE exploration of comets by means of unmanned spacecraft has received the strong endorsement of the space science community for a number of years. Various cometary missions have been considered by NASA, including a 1980 Comet Encke Rendezvous,[1,2] a 1980 Comet Encke Slow Flyby,[1,3] a 1985 Comet Halley Rendezvous,[4-6] and a Halley Flyby/Tempel 2 Rendezvous.[7-10] While these missions would all have required the use of electric propulsion or solar sailing, this paper deals with a fast flyby of Comet Halley, using chemical propulsion. Such a mission was recently a candidate for a new program start in fiscal year 1983.

The mission would have involved a launch in the summer of 1985 and an intercept of Comet Halley (passage within 500-2000 km of the cometary nucleus) in March of 1986. A projection of the reference heliocentric trajectory onto the ecliptic plane is shown in Fig. 1. The encounter geometry is shown in Fig. 2. The flyby speed is quite high—in excess of 60 km/s at the nominal arrival date—owing to the retrograde motion of Comet Halley about the sun. Very modest launch energies are required over a considerable range of launch and arrival dates. Various mission design considerations, as well as a preliminary Halley Intercept spacecraft design, are presented in Ref. 11. The scientific objectives of the mission and a candidate set of scientific instruments are discussed in Refs. 11 and 12. Some earlier mission design work on this and other ballistic cometary intercept missions is described in Ref. 13.

This paper discusses navigation of the Halley Intercept Mission. While navigation is less complex in this mission than in some of the ion drive cometary missions, such as the Halley Flyby/Tempel 2 Rendezvous,[8,9] several features of this mission present navigational problems which have not been experienced in previous ballistic planetary flyby missions. The flyby speed is very high, so that the events associated with an encounter are compressed into a short time span (the encounter phase of the mission is presently defined to be 4 days in length, compared with a number of weeks for the Voyager encounters with Jupiter and Saturn, for example). In addition, certain errors in onboard optical imaging data, used for target-relative orbit determination, are roughly constant in angular terms, and thus are larger in rectilinear terms, at a given time from encounter, for a fast flyby than for a slow flyby. Thus a good target-relative orbit determination solution is obtained much later for a fast flyby than for a slow flyby.

Moreover, a comet is a very different sort of encounter target than a planet or a planetary satellite. A cometary nucleus is quite small (the diameter of the nucleus of Comet Halley is estimated to be roughly 5 km) and is surrounded by a diffuse atmosphere or coma. Thus imaging of the target body (the nucleus) against a star background for optical navigation purposes is potentially a good deal more complex for a comet than for a planet or satellite, especially in the very first cometary mission, given our limited knowledge of the nature of cometary nuclei and comae. In addition, ephemeris uncertainties for comets are generally larger than for planets and planetary satellites owing to the relative infrequency of

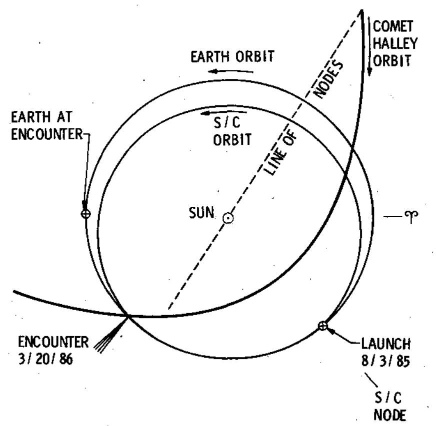


**Fig. 1 Typical heliocentric trajectory (ecliptic plane projection).**

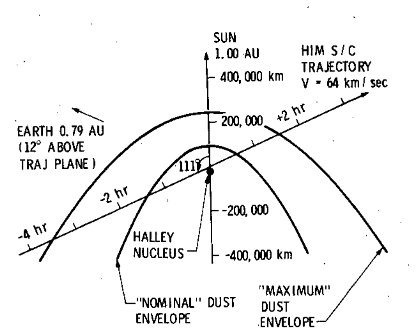


**Fig. 2 Halley encounter geometry.**

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astrometric viewing opportunities for comets and owing to the nongravitational forces to which these bodies are subject.

A navigation system design and a navigation strategy are presented below for the current baseline Halley Intercept Mission, with an encounter around March 20, 1986, about 6 weeks after the perihelion passage of Comet Halley, which occurs February 9. Comet-relative spacecraft orbit determination accuracy estimates are presented as functions of time, for the baseline navigation system and navigation strategy. Various parameters, such as data frequencies, data accuracies, stochastic acceleration levels, cometary ephemeris uncertainties, and maneuver execution errors are then varied, in order to determine the relative importance of these parameters on the orbit determination accuracy. Finally, an earlier encounter date, March 13, is considered. This is the nominal arrival date for the ESA-sponsored Giotto mission. Encounters with Comet Halley prior to its perihelion passage are also possible,[11,13] but are not considered in this paper.

It appears that the Halley Intercept Mission will not be flown, due to budgetary limitations. However, much of the material in this paper is applicable to cometary intercept missions in general, not just to the Halley mission.

## Navigation Objectives

The principal requirement on the navigation system in this mission is that the spacecraft pass on the sunward side of the Halley nucleus, with a distance at closest approach of no less than about 750 km and no more than about 1250 km. The requirement to pass on the sunward side of the nucleus is motivated chiefly by the desire that the nucleus be well illuminated for imaging near closest approach. The requirement to stay at least 750 km from the nucleus is due to the hazard to the spacecraft posed by cometary dust particles. The dust hazard, and the mass of the shield needed to protect against it, are thought to increase substantially as the spacecraft-comet range at closest approach decreases. In addition, the peak rate of rotation of the spacecraft-comet line of sight is inversely proportional to the separation at closest approach, making it more difficult to keep the imaging system boresighted at the cometary nucleus during closest approach, the less the separation. The requirement to pass within 1250 km of the nucleus is motivated by several scientific objectives. Certain molecular species present at the surface of the nucleus may dissociate as they travel away from the nucleus. Thus mass spectrometry performed some distance from the nucleus may reveal only "daughter" products of the dissociative processes, rather than the original molecular species, which are of greater interest. It is thought that the region of "parent" molecules may extend outward from the nucleus to a range of about 1000 km. In addition, the imaging resolution (in at least a few pictures) will be better the shorter the flyby distance.

In addition to requirements on the delivery accuracy of the spacecraft relative to the cometary nucleus, requirements will exist on the accuracy with which encounter conditions can be predicted, after all trajectory correction maneuvers have been made. This will allow accurate pointing and sequencing of the science instruments. Moreover, requirements will exist on the accuracy with which the spacecraft trajectory relative to the comet can be reconstructed after the encounter has occurred. This will allow the accurate correlation of scientific data with spacecraft position relative to the cometary nucleus. Quantitative requirements of this sort have not been formulated.

## Navigation System Design

The navigation system for this mission consists of the Deep Space Network (DSN), elements of the spacecraft, ground-based astronomical obseratories, and ground-based computational facilities and software.[14] The DSN will provide various radiometric data types for orbit determination purposes. These data types include two-way doppler and range, multistation differenced doppler (two-way minus three-way), and multistation differenced range. It is planned that these radiometric data types will be packaged in the form of navigation tracking cycles. A navigation tracking cycle consists of four consecutive overlapping passes of coherent range and doppler data with simultaneous doppler and near-simultaneous range acquired during the overlapping station view periods. The tracking cycle is enhanced if it begins and ends with southern hemispheric coverage (Australia) to balance the northern hemispheric coverage. DRVID (differenced range vs integrated doppler) data may be used to calibrate the radiometric data for the effects of charged particles in the transmission media (interplanetary space plasma, Earth's ionosphere, and near-comet environment). Although not presently included in the baseline navigation system design, narrow-band or wide-band differential very long baseline interferometry (ΔVLBI) could also be used as a radiometric data type.

The portions of the spacecraft which may be considered part of the navigation system include the imaging subsystem, which provides data useful for orbit determination, and the propulsion subsystem, which provides the means of effecting trajectory changes. Both of these subsystems, of course, while important for navigation, serve other functions as well. Optical navigation data consist of images of the cometary nucleus against a background of cataloged stars. Such images are recorded using the narrow angle (1500-mm focal length) optics in the spacecraft imaging subsystem, in conjunction with a charge-coupled device photodetector (an 800 × 800 element array). An image of this sort, after suitable processing, yields an accurate estimate of the spacecraft's position relative to the nucleus in the directions perpendicular to the line of sight. The onboard optical data will be complemented by ground-based comet observations (photographic plates recorded at astronomical observatories), to be supplied by the International Halley Watch.[15] The propulsion subsystem will include several groups of monopropellant hydrazine thrusters for trajectory correction and attitude control maneuvers.

## Navigation Strategy

The collection of orbit determination data for the Halley Intercept Mission will begin before launch, with the acquisition of Comet Halley with Earth-based telescopes. Since the comet has not been observed for nearly 70 years, its ephemeris is much less accurately known than are planetary ephemerides. Comet Halley is presently (July 1981) at a distance of about 14 AU from the sun and is too faint an object to be seen from the Earth. Initial acquisition is likely during the next two years.

One of the functions of the International Halley Watch will be the development and coordination of an astrometry network, which will support the Halley Intercept Mission, should it become an approved flight project, and perhaps other nations' Halley flyby missions as well. It is recommended in Ref. 15 that the astrometry network consist of at least six Northern and six Southern Hemispheric observatories, spaced in longitude to reduce the impact of weather problems. Each observer should supply to the Halley Intercept Mission Navigation Team a pair of observations per week between January and September of 1985, excluding a 2-month period during the summer in which the comet's angular separation from the sun will be too small for astrometric viewing. Each observer should supply a pair of observations every 3 days between October of 1985 and March of 1986, excluding part of January, all of February, and part of March, again owing to sun interference.

Radiometric tracking data will be recorded throughout the mission. Navigation tracking cycles will be scheduled twice per week between L and L + 20, every 2 weeks between L + 20 and E − 40, and every week after E − 40 (L and E denote launch and Halley encounter; numbers denote days). In addition, navigation tracking cycles will be scheduled before and after each trajectory correction maneuver. Single station passes of two-way coherent doppler data, with ranging, will be needed between navigation tracking cycles, at the rate of once per day between L and L + 20 and between E − 40 and E and at the rate of twice per week between L + 20 and E − 40.

Onboard optical data will be recorded at the rate of two frames per week between E − 160 and E − 40, two frames per day between E − 40 and E − 20, four frames per day between E − 20 and E − 10, and eight frames per day between E − 10 and E. Approach navigation relies heavily on onboard optical observations of the cometary nucleus relative to background cataloged stars. These observations directly link the spacecraft and the target body and are extremely important because of the large cometary ephemeris uncertainty. The cometary nucleus will resemble a star in all optical navigation frames taken more than a few hours from encounter, since the angular diameter of the nucleus will be smaller than that of a picture element in the charge-coupled device (CCD) photodetector array. During this 160-day time interval, the maximum distance between the spacecraft and Comet Halley is 1.6 AU. The cometary nucleus, as seen from the spacecraft, should resemble a star of eleventh magnitude or brighter and thus should be detectable, except when the sun-spacecraft-comet angle is small, which happens in late January and early February of 1986.

Five trajectory correction maneuvers have been scheduled—at L + 10, E − 100, E − 30, E − 10, and E − 2. It is assumed that these maneuvers will be executed based upon orbit determination data which are at least 24 hours old.

## Navigation Accuracy Analysis—Baseline Case

Covariance analyses have been carried out to investigate the statistical properties of the navigation strategy described above. The required computer runs were made with orbit determination software which is simpler than, but mathematically similar to, that which will be used in mission operations.[14]

The parameters which were estimated in carrying out the orbit determination solution were the spacecraft position and velocity, the cometary ephemeris, the nongravitational accelerations acting on the spacecraft, and the velocity changes achieved during the last four trajectory correction maneuvers. The solution was obtained by using a sequential filtering procedure which allows for stochastic nongravitational accelerations by modeling them as first-order Gauss-Markov processes. These accelerations were represented as independent variations in three orthogonal directions, with identical correlation times, but different standard deviations.

A priori error standard deviations for the estimated parameters and correlation times for the Gauss-Markov processes are given in Table 1. These a priori statistics correspond to the date Sept. 29, 1985, which is 180 days before encounter. The launch date for the trajectory investigated is Sept. 2, 1985. The a priori error standard deviations for estimates of spacecraft position and velocity were chosen to be very large, so as to have little impact on the orbit determination results. Actual orbit determination accuracies 27 days after launch can be expected to be much better than these numbers.

Parameters which were considered, rather than estimated, in carrying out the orbit determination solution include equivalent station location errors (crust-fixed station location errors plus residual calibration errors associated with transmission media effects, polar motion, and Earth spin rate) for stations 14, 43, and 63 (errors in station spin radius and longitude were included; errors in distance above the equatorial plane were not), differenced range biases between stations 14 and 63 and between stations 43 and 63, differenced frequency biases between the same pairs of stations, and biases in the onboard optical data.

**Table 1 Orbit determination a priori error standard deviations and random process statistics – baseline case**

| Parameter | A priori standard deviation |
|---|---|
| Estimated parameters | |
| S/C position | 1,000,000 km |
| S/C velocity | 1 km/s |
| Comet position | 5000 km |
| Comet velocity | $2.0 \times 10^{-4}$ km/s |
| Nongravitational acceleration errors (5-day correlation time): | |
| Radially away from sun | $2.0 \times 10^{-12}$ km/s$^{2}$ [a] |
| Nonradial | $1.0 \times 10^{-12}$ km/s$^{2}$ [a] |
| Maneuver execution errors: | |
| TCM2 | $4.0 \times 10^{-5}$ km/s |
| TCM3 | $4.0 \times 10^{-5}$ km/s |
| TCM4 | $2.0 \times 10^{-5}$ km/s |
| TCM5 | $1.0 \times 10^{-5}$ km/s |
| Considered parameters | |
| Station longitudes | 3 m |
| Station spin radii | 1.5 m |
| Differenced range biases | 6 m[b] |
| Differented frequency biases | $4 \times 10^{-13}$ [b] |
| Onboard optical biases | 0.5 pixels (5 μrad) |

[a] Also steady-state standard deviation of random process.
[b] Correlation coefficient = −0.5.

The standard deviations associated with the noise in the various data types are presented in Table 2. The noise levels for the conventional range and range rate data during tracking cycles were not set to reflect actual data accuracies, but rather to give the correct relative weightings between the conventional and differenced data types. A batch size of 12 hours was used in carrying out the orbit determination solution. The data frequencies assumed in the covariance study (stated in Table 2) differ slightly from those stated in the previous section owing to certain characteristics of the analysis software and owing to certain revisions in the navigation strategy made based upon the results of the covariance analysis.

In Table 3, standard deviations of the spacecraft position uncertainty, mapped deterministically from the current time to the time of encounter, are presented. Note that the spacecraft state is referenced to that of the comet, not to that of the sun or Earth. The spacecraft state uncertainties (or orbit determination errors) are those errors associated with the spacecraft state estimate at time $t$, based upon data through time $t-1$, 1 day being the assumed time for acquiring and processing orbit determination data, calculating maneuver parameters, and generating and transmitting command sequences. The "downtrack" direction is along the spacecraft flight path, in a comet-centered coordinate frame; the "crosstrack" direction is perpendicular to the flight path and in the spacecraft comet-relative orbit plane; and the "out-of-plane" direction completes an orthogonal triad (see Fig. 3 of Ref. 9).

It can be seen in Table 3 that all three mapped position uncertainty standard deviations continually decrease from E − 160 to E. The out-of-plane position uncertainty starts out smaller than the other two components and decreases more rapidly. This is most likely due to the fact that the out-of-plane position is observed directly in the onboard and ground-based optical data, decoupled or nearly decoupled from the other position components. The downtrack and crosstrack position components, on the other hand, affect the data only in some time-varying linear combination, determined by the angle between the line-of-sight vector and the spacecraft-comet relative velocity vector. The mapped downtrack position uncertainty standard deviation does not decrease as rapidly as the crosstrack and out-of-plane components during

**Table 2 Orbit determination data frequencies and data noise standard deviations – baseline case**

| Data type | Data frequency | Data noise standard deviation |
|---|---|---|
| Range | Approximately one point every 4 hours during tracking cycles | 1000 m[a] |
| Range rate | One point per minute during tracking cycles | 100 mm/s[a] |
| Range | Approximately one point every 4 hours during station passes outside tracking cycles | 100 m |
| Range rate | One point per minute during station passes outside tracking cycles | 1 mm/s |
| Differenced multistation range | When available during tracking cycles | 2 m |
| Differenced multistation range rate | When available during tracking cycles | 1 mm/s |
| Onboard optical | Every 5 days E – 169 to E – 40<br>Every 12 hours E – 40 to E – 25<br>Every 6 hours E – 25 to E | 1 pixel (10 $\mu$rad) |
| Earth-based comet[b] | Every 5 days E – 169 to E – 40<br>Every 3.5 days after E – 40 | 3 arc-sec |

[a] Value chosen to give correct relative weighting between conventional and differenced data types.
[b] No data between Jan. 9, 1986 and March 4, 1986, owing to sun interference.

**Table 3 Position uncertainty standard deviations mapped to encounter with Halley – baseline case**

| | Mapped position uncertainty standard deviations, km | | |
|---|---|---|---|
| Time | Downtrack | Crosstrack | Out-of-plane |
| E – 160 | 11850 | 3780 | 2040 |
| E – 140 | 10540 | 3470 | 1570 |
| E – 120 | 8800 | 3360 | 1120 |
| E – 100 | 7030 | 3310 | 761 |
| E – 80 | 6360 | 3230 | 630 |
| E – 60 | 6080 | 3200 | 595 |
| E – 40 | 5630 | 3130 | 523 |
| E – 30 | 5310 | 2970 | 502 |
| E – 25 | 4650 | 2560 | 495 |
| E – 20 | 2860 | 1580 | 474 |
| E – 15 | 1730 | 908 | 438 |
| E – 10 | 1280 | 524 | 392 |
| E – 5 | 924 | 261 | 252 |
| E – 4 | 905 | 219 | 215 |
| E – 3 | 888 | 177 | 175 |
| E – 2 | 789 | 135 | 133 |
| E – 1 | 781 | 96 | 94 |
| E | 776 | 56 | 55 |

the last 10 days, since the onboard optical data have by then become much more accurate than the ground-based data, but provide little information in the downtrack direction, owing to the virtual coincidence of the line-of-sight vector and the relative velocity vector. What improvement there is in the downtrack direction during the last 10 days comes largely from Earth-based comet observations. The increasingly accurate onboard optical data and the near-rectilinear relative motion tend to circularize the position uncertainty statistics in the impact plane (perpendicular to the relative velocity vector), during the last 10 days.

The trajectory used in the covariance analysis is such that the spacecraft passes about 600 km from the cometary nucleus, on the sunward side. The nominal targeting geometry is essentially irrelevant to the covariance analysis, however, since all optical data processed were recorded at distances of at least 5 million kilometers from the comet (1 day from encounter).

Perhaps the most important entries in Table 3 are the crosstrack and out-of-plane position uncertainty standard deviations at time E – 2, the time of the last trajectory correction maneuver (TCM). These position uncertainty statistics include the effect of execution errors in the last TCM, and are therefore accurate representations of delivery accuracies. These statistics imply that the spacecraft will pass within 135 km of the nominal aimpoint in the crosstrack direction with probability 68% and that it will pass within 133 km of the nominal aimpoint in the out-of-plane direction with probability 68%. These miss statistics can thus be described by error ellipses in the plane perpendicular to the relative motion, centered at the nominal aimpoint. The projections of the $1\sigma$ error ellipse onto the two axes are 135 km and 133 km, respectively. The semimajor and semiminor axes of this error ellipse turn out to be 138 km and 130 km, respectively. The probability that the spacecraft will pass inside this $1\sigma$ error ellipse is 39%. The probability that the spacecraft will pass inside of an error ellipse twice (three times) as large in each dimension is 86% (99%).

In addition, the downtrack, crosstrack, and out-of-plane position uncertainties at time E are of interest. These indicate the accuracy with which the encounter conditions will be known, based upon data through E – 1. Although data taken this late cannot be used for trajectory correction purposes, given the mission time-line assumed here, the resulting orbit determination solution can be used to update instrument pointing and to update the timing of various events. Comparison of the position uncertainty statistics at times E – 2 and E indicates that the crosstrack and out-of-plane position components will be known to a substantially higher accuracy than they can be controlled. In the downtrack direction, there is relatively little difference.

Navigation accuracy analysis results for an ion drive mission to Comet Halley were presented in Ref. 9. Results for a different ballistic flyby were presented in Ref. 16. The position errors at encounter stated here are significantly smaller than those in Refs. 9 and 16. This is to be expected, though, since the three missions are quite different in nature. Orbit determination data must terminate prior to probe separation at E – 15 in the ion drive mission, if the unshielded rendezvous spacecraft is to be deflected away from the dust hazard zone so that it can safely proceed to Comet Tempel 2.

There is no corresponding requirement in the ballistic missions, so that orbit determination data much closer to encounter may be used in planning a final trajectory correction maneuver. However, the onboard imaging system assumed for the ion drive mission is better than that assumed for the Halley Intercept Mission, which is in turn much better than that assumed for the ballistic mission in Ref. 16. In addition, the ion drive mission and the ballistic mission in Ref. 16 assume preperihelion encounters with Comet Halley, while the Halley Intercept Mission, as considered here, assumes a postperihelion encounter, by which time the cometary ephemeris may be better known.

## Parametric Sensitivity Study

In addition to the navigation accuracy analysis described above for the baseline navigation strategy, a study was carried out to determine the sensitivity of the navigation accuracy to changes in the navigation strategy, in various error modeling assumptions, and in the arrival date. The results of this parametric sensitivity study will now be described. A total of 21 cases were considered, in addition to the baseline case. In each instance, nearly all assumptions were as in the baseline case, with one or more assumptions changed. The 21 cases are described in Table 4. In this table, downtrack, crosstrack, and out-of-plane position uncertainty standard deviations at E − 2 and at E are presented. Once again, these statistics represent trajectory control accuracies (after the last TCM) and trajectory knowledge accuracies at the time of the last pointing/sequencing update.

The first parameter investigated was the focal length of the onboard imaging system to be used for optical navigation. Since the same CCD photodetector would be used regardless of the imaging system focal length, a doubling of the focal length is, for the purposes of this study, equivalent to a halving of the optical data noise and a halving of the optical data biases. The crosstrack and out-of-plane position uncertainty standard deviations are seen to decrease roughly 50%, with this increase in focal length. The downtrack position uncertainty standard deviation decreases by more than 20%. Thus the crosstrack and out-of-plane position uncertainties are nearly inversely proportional to imaging system focal length (directly proportional to the angular size of a picture element), while the downtrack position uncertainties are also dependent upon focal length, though to a much lesser degree. For reference, each picture element of the 1500-mm focal length imaging system is $10 \times 10$ μrad in size. For the 3000-mm focal length system, these numbers are halved.

The next five cases investigated involve changes in the quantity of onboard optical data processed. Doubling the frequency of onboard optical data along the entire trajectory reduces the crosstrack and out-of-plane position uncertainties near the time of encounter by more than 10%. Paradoxically, the downtrack position uncertainty at E − 2 seems to increase by about 10%. This change is illusory, however, and is due to the fact that the timing of Earth-based comet observations is modified by the doubling of the frequency of the onboard optical data—a characteristic of the analysis software. Thus a set of Earth-based observations which occur prior to E − 3 in the baseline case occur after E − 3 in the doubled onboard optical data frequency case, resulting in a difference in the statistics at E − 2 (which include a 24-hour time lag). Comparison of the downtrack position uncertainties at E indicates a slight improvement with the increased quantity of onboard optical data, as would be expected. Doubling the frequency of

**Table 4 Parametric sensitivity study results**

| Deviation from baseline assumptions | Mapped position uncertainty standard deviations, km: At E − 2, Downtrack | At E − 2, Crosstrack | At E − 2, Out-of-plane | At E, Downtrack | At E, Crosstrack | At E, Out-of-plane |
|---|---|---|---|---|---|---|
| Baseline case | 789 | 135 | 133 | 776 | 56 | 55 |
| 3000-mm focal length spacecraft imaging system | 606 | 67 | 62 | 598 | 28 | 26 |
| Onboard optical data frequency doubled | 861 | 118 | 116 | 766 | 45 | 44 |
| Onboard optical data frequency doubled (last 40 days) | 865 | 118 | 116 | 769 | 45 | 44 |
| Onboard optical data last 40 days only | 835 | 133 | 131 | 827 | 55 | 54 |
| Onboard optical data eliminated owing to sun interference (E − 80 to E − 38) | 800 | 136 | 133 | 788 | 56 | 55 |
| No onboard optical data | 1763 | 1494 | 585 | 1763 | 1494 | 585 |
| Frequency of Earth-based comet observations doubled; onboard optical data last 40 days only | 655 | 136 | 138 | 598 | 56 | 56 |
| Frequency of Earth-based comet observations doubled; no onboard optical data | 1402 | 1238 | 464 | 1264 | 1137 | 462 |
| Earth-based comet observation data noise doubled | 1139 | 133 | 125 | 1123 | 55 | 53 |
| No Earth-based comet observations | 1421 | 131 | 119 | 1397 | 54 | 51 |
| A priori comet ephemeris uncertainty doubled | 816 | 136 | 133 | 804 | 56 | 55 |
| Correlated a priori comet ephemeris uncertainty | 438 | 118 | 117 | 409 | 55 | 55 |
| Correlated a priori comet ephemeris uncertainty; no onboard optical data | 531 | 183 | 175 | 531 | 183 | 175 |
| Correlated a priori comet ephemeris uncertainty; frequency of Earth-based comet observations doubled; no onboard optical data | 424 | 161 | 150 | 407 | 160 | 148 |
| No differenced multistation radiometric data | 789 | 135 | 133 | 776 | 56 | 55 |
| Nongravitational stochastic accelerations quintupled—baseline values assumed in filter error model | 796 | 135 | 133 | 783 | 56 | 55 |
| Maneuver execution errors doubled | 789 | 135 | 133 | 776 | 56 | 55 |
| Frequency of Earth-based comet observations doubled; onboard optical data eliminated owing to sun interference, E − 80 to E − 38, and doubled in frequency between E − 160 and E − 80 and after E − 10 (revised baseline) | 640 | 119 | 120 | 585 | 46 | 45 |
| March 13, 1986 arrival; frequency of Earth-based comet observations doubled; onboard optical data frequency doubled, E − 160 to E − 40 | 983 | 164 | 131 | 792 | 67 | 61 |
| March 13, 1986 arrival; frequency of Earth-based comet observations doubled; no onboard optical data (Giotto) | 2747 | 1734 | 355 | 2438 | 1627 | 349 |
| March 13, 1986 arrival; correlated a priori comet ephemeris uncertainty; frequency of Earth-based comet observations doubled; no onboard optical data (Giotto) | 607 | 159 | 141 | 590 | 157 | 138 |

onboard optical data during the last 40 days and leaving it unchanged along the remainder of the trajectory is seen to have nearly the same effect as doubling the frequency along the entire trajectory.

The elimination of onboard optical data prior to $E-40$ produces essentially no change in the crosstrack and out-of-plane position uncertainties near encounter, relative to the baseline case, and only a 5% degradation in the downtrack position uncertainty. Regardless of their contribution to the orbit determination results near encounter, though, onboard optical data prior to $E-40$ are very useful for calibration purposes and for verifying the cometary ephemeris determined from Earth-based comet observations.

The baseline case assumes that onboard optical data are available even when the angular separation between the comet and the sun, as seen from the spacecraft, is quite small (the minimum angular separation turns out to be 6 deg). If onboard optical data are eliminated when the sun-spacecraft-comet angle is less than 30 deg (which occurs between $E-80$ and $E-38$), the orbit determination accuracies around encounter change by only about 1%. The complete elimination of onboard optical data causes a gross degradation in all three components of the position uncertainty near encounter, demonstrating the importance of onboard optical data in successfully navigating the Halley Intercept Mission (see the comments below about a similar case run with a strongly correlated a priori error covariance matrix for the cometary ephemeris, however).

The next cases investigated involve a doubling of the frequency of Earth-based comet observations relative to the scheduling stated in Table 2. These results should be compared not with the baseline case, but rather with two other cases discussed above. When onboard optical data are recorded only during the last 40 days prior to encounter, this doubling of the frequency of the Earth-based comet data has a minor impact on crosstrack and out-of-plane uncertainties, but improves the downtrack position uncertainty near encounter by about 20%. When onboard optical data are eliminated entirely, doubling the frequency of the Earth-based data reduces all components of the position uncertainty near encounter by 20% or more.

A doubling of the noise in the Earth-based comet observations (to 6 arc-sec) causes the downtrack position uncertainty near encounter to increase by roughly 40% relative to the baseline case. The crosstrack and out-of-plane position uncertainties near encounter decrease slightly, which is surprising, though not unprecedented.[9] The complete elimination of Earth-based comet observations within 180 days of encounter (the a priori cometary ephemeris uncertainty is left unchanged, implying an unchanged number of Earth-based comet observations prior to this time) produces a similar, though more exaggerated, effect on all three components of position uncertainty near encounter. It should be kept in mind that each triplet of entries in Table 4 is a highly condensed representation of a $27\times27$ covariance matrix. Changes in data accuracies often produce large changes in some variances and covariances and small changes in others. The large changes in variances are certainly significant. The accompanying small changes in other variances may not be, as in these two cases.

The next four cases investigated involve changes in the a priori cometary ephemeris uncertainty. In the baseline case, and in all other cases discussed to this point, a diagonal, isotropic covariance matrix was used for the a priori cometary ephemeris uncertainty. A simple doubling of the standard deviations was found to degrade the downtrack position uncertainty near encounter by about 3% and to degrade the crosstrack and out-of-plane components by 1% or less. The use of a fully correlated $6\times6$ covariance matrix, furnished by Yeomans,[17] was found to have a very substantial effect, however. (Ten of the 15 correlation coefficients are larger in magnitude than 0.75; three are larger than 0.98. The correlations are due principally to the inclusion of 1909-1911 observational data, which aid in determining the mean motion, in particular.) The downtrack position uncertainties near encounter decrease by more than 40%, while the crosstrack and out-of-plane uncertainties decrease by more than 10%, relative to the baseline case. More striking is the fact that when onboard optical data are excluded entirely, the use of the correlated a priori covariance reduces the position uncertainties near encounter by 70-90% relative to the case with the uncorrelated covariance, making the navigation accuracy seem at least marginally acceptable with no onboard optical data whatsoever. Several cautionary remarks are in order, however. Both the software used by Yeomans and the software used in this study assume that the Earth-based comet observations are noisy, but are otherwise free from defect. No systematic data errors (due to cometary center-of-mass/center-of-brightness offsets, for example) are explicitly taken into account. Moreover, stochastic nongravitational accelerations acting on the cometary nucleus (due to the expulsion of material near the sun) are not taken into account. To partially compensate for these simplifications in the observational and dynamical models of the comet, the Earth-based data noise has been inflated above its expected level by Yeomans, and in this study also. Still, the cometary ephemeris accuracy results, based upon observations from the Earth, may be somewhat optimistic. Note that systematic biases are accounted for in the onboard optical data model in this study. The principal conclusion to be drawn here is not that the Halley Intercept Mission may be marginally navigable without onboard optical data, but rather that the navigation accuracy analysis results, in the absence of onboard optical data, are quite sensitive to the assumptions one makes regarding the a priori cometary ephemeris uncertainty. More sophisticated software for the determination of cometary ephemerides and ephemeris uncertainties is currently under development, to allow a more realistic treatment of observational errors and nongravitational accelerations.[17]

It is also worth noting that in the November 1980 encounter of Voyager 1 with the Saturnian satellite Titan, the use of a diagonal covariance matrix for the ephemeris uncertainty of Titan provided more realistic results than the use of a strongly correlated covariance matrix, the correlations being due to accurate measurements of the mean motion of Titan over a period of years.[18]

Three relatively simple cases were examined next. One involved the complete elimination of multistation differenced radiometric data (no changes were made in the scheduling of single station data). Another involved a quintupling of the standard deviations of the stochastic nongravitational acceleration components, relative to the levels assumed in the orbit determination error model. The third involved a doubling of the maneuver execution errors. In the second case, the effect on the position uncertainties near encounter was small. In the first and third cases, the effect was almost imperceptible.

Based upon the information gathered to this point, a revised baseline case was formulated, with the frequency of Earth-based comet observations doubled throughout, the frequency of onboard optical data doubled between $E-160$ and $E-80$ and between $E-10$ and E, but with the onboard optical data eliminated between $E-80$ and $E-38$, owing to sun interference. This improves all position uncertainties by 10-20% relative to the baseline case, at a modest increase in data collection and processing requirements.

The final three cases studied involved a shift in the Halley encounter date from March 28, 1986, the date so far assumed in the covariance analysis, to March 13. The earlier arrival requires a lower launch energy than the later one; in fact, March 13 is very nearly the optimum arrival date from the standpoint of minimizing launch energy or maximizing delivered payload. For the Halley Intercept Mission, considerations other than minimizing launch energy originally led to the selection of an arrival date around March 28. In particular, the spacecraft-Earth range at encounter is shorter the later the encounter, an important consideration in telecommunication system design. Moreover, an arrival around March 28 allows a return to the vicinity of the Earth a year after launch, enabling an encounter with another comet or an asteroid, after an Earth gravity assist[13] (no such encounters are included in the baseline mission plan, however). This 2-week advance in arrival date produced a 30-50% degradation in downtrack position uncertainties and a 20% degradation in crosstrack position uncertainties. The principal reason for the former difference appears to be the lack of Earth-based comet data between January 9 and March 4. Velocity uncertainties on January 9 are transformed into substantial position uncertainties by March 4, in the absence of observations in the interim. The observations made between March 4 and March 13 still leave large position uncertainties at the latter date. The inclusion of another 15 days of Earth-based comet data brings the position uncertainties down somewhat. The difference in the crosstrack results is most likely due to the fact that the approach speed for a March 13 encounter is roughly 15% greater than for a March 28 encounter, making the onboard optical data about 15% less accurate at any given time relative to encounter, in the March 13 arrival case. The preferred arrival date for the Halley Intercept Mission is March 20, halfway between the two cases investigated here. This encounter date, with its associated reduced launch energy, allows a greater choice of launch vehicles than does March 28.

In the case of the ESA-sponsored Giotto mission, minimization of launch energy is quite important, leading to the selection of a March 13 arrival date. It appears doubtful that the imaging system on the Giotto spacecraft will allow optical navigation to be performed at any substantial distance from the cometary nucleus. The fact that the spacecraft is spinning (with no despun platform), rather than three-axis stabilized, as in the case of the Halley Intercept spacecraft, means that only relatively bright stars can be imaged, thus rendering undetectable the background stars needed for obtaining accurate orbit determination data from images of the comet. The navigation of this mission was investigated, assuming a navigation strategy similar to that for the Halley Intercept Mission, apart from the deletion of onboard optical data. The resulting trajectory control accuracy of 1734 km ($1\sigma$) in the crosstrack direction is quite large and is roughly 40% larger than in the case of identical assumptions applied to a March 28 arrival. The less critical downtrack position uncertainty around encounter has almost doubled.

When the diagonal a priori cometary ephemeris uncertainty covariance was replaced by the correlated covariance of Yeomans, the crosstrack position uncertainty near encounter decreased by more than 90%. The other position uncertainty components decreased by at least 60%. Thus delivery of the Giotto spacecraft within, say, 700 km of the Halley nucleus, assuming that the nucleus is the nominal aimpoint, appears to be an unlikely occurrence if the diagonal a priori ephemeris uncertainty is realistic, but appears to be a virtual certainty if the correlated a priori ephemeris uncertainty is realistic.

## Conclusions

A navigation accuracy analysis for the Halley Intercept Mission has been carried out. Using a navigation system design and a navigation strategy derived from the Voyager and Galileo flight projects, and modified where appropriate to take into account the unique features of this mission, it has been found that for a March 28, 1986 arrival, the Halley Intercept spacecraft can be delivered to within about 120 km ($1\sigma$) of the desired aimpoint relative to the comet, in each of two orthogonal directions. The encounter conditions should be predictable to an accuracy of about 45 km ($1\sigma$) in each of two directions perpendicular to the relative velocity vector and about 640 km ($1\sigma$) parallel to the relative velocity vector. The sensitivities of these results to changes in data frequencies, data accuracies, stochastic nongravitational acceleration levels, a priori cometary ephemeris uncertainties, maneuver execution errors, and encounter date have been investigated. Particularly noteworthy is the strong sensitivity of the results to the form of the a priori cometary ephemeris uncertainty covariance matrix when onboard optical data are not available (a situation more applicable to the Giotto mission than the Halley Intercept Mission), a diagonal, isotropic covariance yielding substantially poorer results than a correlated covariance derived from 1909-1911, as well as 1985, comet observations.

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