A Combined Open-Loop and Autonomous Search and Rendezvous Navigation System For the CNES/NASA Mars Premier Orbiter Mission

J. E. Riedel, J. Guinn,
Jet Propulsion Laboratory, California Institute of Technology, Pasadena California, USA
M. Delpech, J.B. Dubois,
Centre National d'Etudes Spatiales (CNES), Toulouse, France
D. Geller, P. Katchmar,
Charles Stark Draper Laboratory, Cambridge, Massachusetts, USA

Abstract

The CNES/NASA Mars Premier Orbiter Mission, at the time of this writing scheduled for launch in 2007, will carry a technology demonstration package that will validate methods of searching for and rendezvousing with a carried target representative of a possible future Mars Sample Return (MSR) Mission. The target will carry a radio beacon and be optically reflective, enabling a suite of radio and optical sensors to locate, track and subsequently autonomously rendezvous with the released target. The low fidelity battery-powered oscillator on the target will provide the capability for an initial crude detection of the small target with an unknown orbit, and through subsequent multi-spacecraft links through the Electra radio transceiver instruments aboard Premiere, and MRO or GMO, provide a high quality navigation capability. Long-range optical observations with the narrow-angle (1.5degree FOV) Navigation Camera provide a completely redundant and robust search capability, and subsequently tighter navigation performance. Though the search processes are open-loop Earth-based navigation operations, when the target is within 10km of the orbiter, the ground-based orbit determination fix will be transferred to the onboard autonomous rendezvous navigation system. Here, with limited onboard compute power available, and a very restricted budget, a completely autonomous onboard rendezvous system is being built to use the narrow-angle MRO-based Opnav Camera supplemented with a MER-based wide-angle camera. Though autonomous, the onboard algorithms have been greatly simplified, and make extensive and maximum use of ground-based computations in order to limit the scope of onboard software. Nevertheless, highly robust autonomous navigation performance is achieved. The key to the simplifications are a complete separation of the attitude-control and navigation problems, made possible by highly capable momentum wheels aboard Premiere, and the very high navigation performance of the Opnav Camera. This paper will describe the search methods to be used using the radio and optical observations, and will provide a description of the methods and performance of the autonomous onboard rendezvous navigation system.

Introduction

The CNES Premier Mars '07 Mission (Ref. 1) mission-design has multiple objectives. First and foremost is the objective to deliver four Netlander science stations to the surface of Mars, and provide at least a year of science-telemetry relay for them (Ref 2). The second principal objective is to demonstrate rendezvous technologies applicable to a future International Mars-Sample-Return (MSR) mission. The third main objective is to perform orbital Mars science. Focusing on the second prime objective, the rendezvous technology demonstration objective is to experimentally validate certain hardware, rendezvous algorithm, and mission design and operations technologies. The rendezvous system uses one-way radiometric and optical observables for distant (greater than a few kilometers) measurements and optical exclusively for close observations. The radio observables are processed on the ground, whereas the optical observables are processed on the ground and autonomously onboard during critical periods of the demonstration. The mission phases of MSR and the Premier Rendezvous Demonstration are divided into five parts: Intermediate, Terminal Parking, Terminal Rendezvous, Capture and Search; additionally, the Premier technology demonstration has the obvious required phase of Target Release. Fig. 1 describes these phases (except for Target Release), and contrasts them with how they might be implemented in an actual MSR mission.

The hardware configuration of the Rendezvous system consists of two cameras, a narrow angle camera, essentially a duplicate of the Mars Reconnaissance Orbiter (MRO) Optical Navigation camera (Ref 3), and a wide-angle camera, perhaps a version of the Mars Exploration Rover (MER) lander camera. The system also makes use of the Electra UHF-band radio navigation and communication subsystem on Premier (Ref 4), and at least one other spacecraft. All computations involved in the autonomous onboard rendezvous navigation system are handled by the spacecraft main processor, as the computational load of the system is intentionally minimized to obviate the need for an additional computer.

Phases of the Rendezvous Mission

The Search phase of the rendezvous technology demonstration is not a "search" in the sense that knowledge of the Orbital Sample (OS) is totally, or even partly, lost. Instead, the ability to perform an "MSR-like" search is demonstrated, where radio and optical observables are obtained

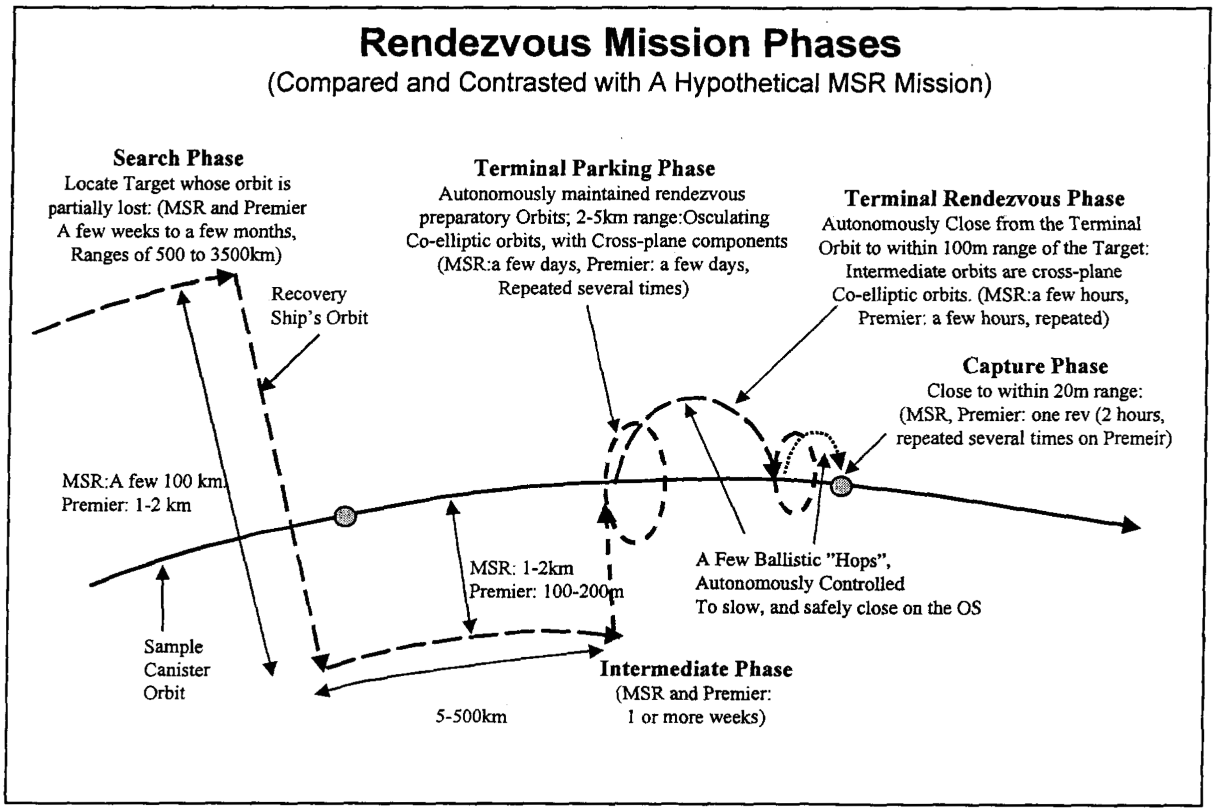


Fig. 1: Schematic of Premier Rendezvous Demonstration Mission Design Compared to an MSR

sufficient to validate hardware and actual MSR search procedures. This entails taking radio observations of the OS from multiple receivers (e.g. Premier and MRO or GMO) and taking optical observables at varying ranges and phase angles. In the actual MSR mission it is assumed that total orbit knowledge is not lost, but that only Mean Anomaly is unknown, reflecting the tacit assumption that observations of the OS are obtainable within a few days after it is placed into orbit. Spacecraft/OS ranges during the search phase will span 500 to 4000 km. The optimum search range is from 2000 to 3000 km; in these ranges the s/c will point the body-mounted camera toward a position along the OS uncertainty annulus (see Fig. 2). The spacecraft will also slew the camera to match the apparent motion of the OS in the field, where the apparent motion assumed is that at the center of the annulus where the search mosaic is being taken. Such motion compensation enhances the signal strength of the OS image, at the expense of star images. Optical image processing will entail identification and location of all signals from the camera field that exceed a certain threshold, and will include images of stars and, when captured, the OS. These locations will be correlated on the ground, using multiple occurrences of a bright signal showing positions and drift rates consistent with a likely OS orbit as the means of identifying the OS signals. In conjunction with the optical measurements, one-way Doppler measurements will be taken with the Electra instrument onboard the carrier spacecraft and simultaneously on at least one other spacecraft in Mars orbit. These radiometric observables will be downlinked, and processed on the ground. The search phase is expected to take only one or two weeks in the real MSR, but may occupy one or two months for the technical demonstration. The purpose for the latter apparently long duration is to achieve large range changes with minimal fuel expenditure, and to provide a maximum opportunity in the middle of intensive rendezvous operations to provide other experimenters an opportunity to have dominant use of spacecraft resources, and to provide an opportunity for the rendezvous team to apply experience learned from the first set of rendezvous events, which preceded the Search experiment, to the second set, which will follow it.

In the Intermediate phase of the mission, the spacecraft/OS range is reduced and/or increased to position the spacecraft in anticipation of the following phase. The navigation during Intermediate Phase will be performed primarily optically, although Doppler observables of the OS from the Premier orbiter will be taken and processed on the ground. The power of the radiometrics in the intermediate phase will not be as high as that of the optical. Figure 3 shows a comparison of the applicability at different ranges of various sensors that were considered for use in the demonstration, including a ranging LIDAR and a Radio-Direction-Finder (RDF). The orbit determination, using onboard processed images, is performed on the ground; although in this phase, initial trials of the autonomous closed-loop navigation system will be made. Control of the spacecraft trajectory will be via maneuvers computed

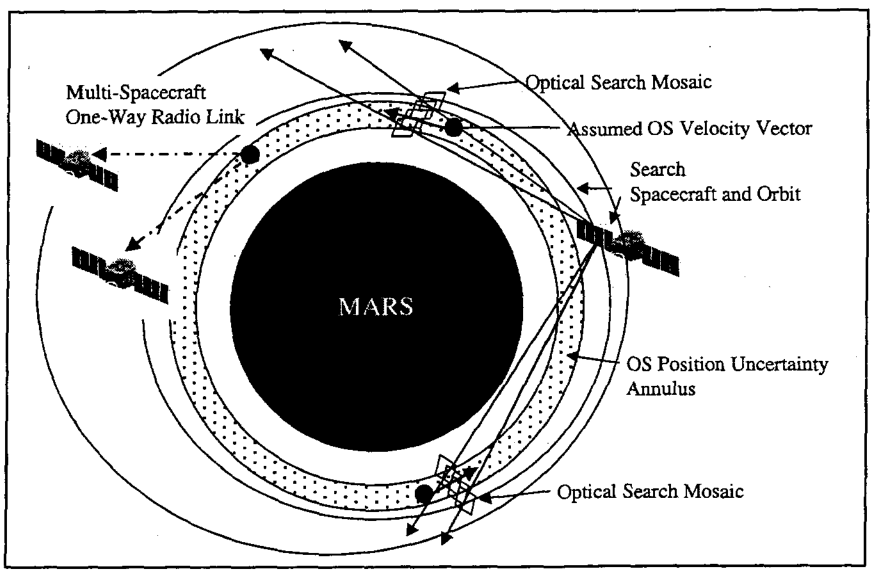


Figure 2: Search Phase Data Taking Geometries and Strategy

on the ground and uplinked. Spacecraft to OS ranges vary from 5 to 500km in this phase. The Intermediate phases of both an MSR and the rendezvous technology demonstration will likely cover a week or so in time.

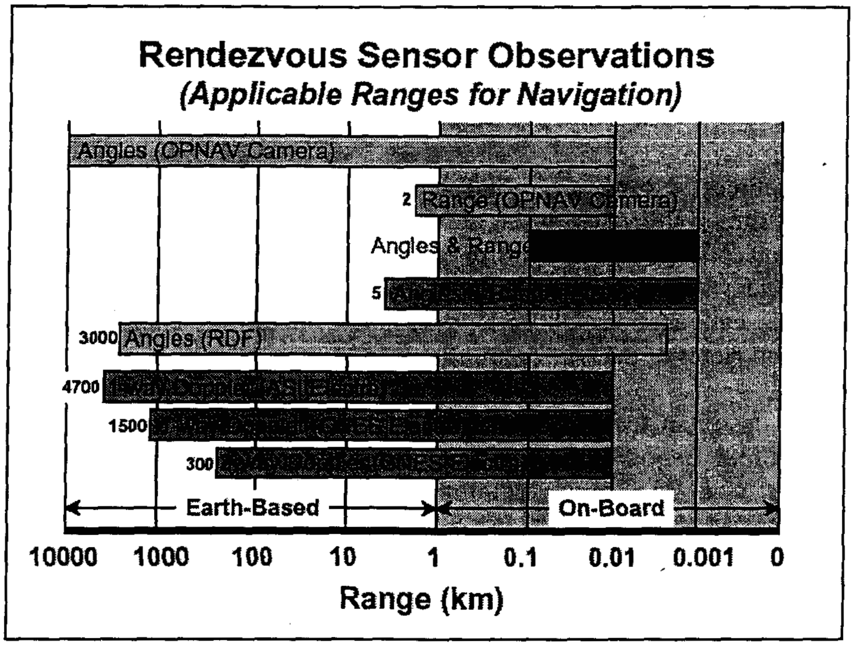


Figure 3: Comparison of Rendezvous Sensors

The Terminal Parking Phase of the mission consists of a series of "parking orbits" that the orbiter enters after executing a pair of range closing maneuvers. The characteristics of these orbits are such as to minimize the chance of OS/orbiter impacts if control of the orbiter is lost at anytime. Radial and out-of plane components of the orbiter's velocity are added to what would otherwise be an identical, except for Mean-Anomaly, orbit to create relative off-standing "football orbits." These orbits, if allowed to propagate indefinitely provide high degrees of impact safety, due to their low probability of intersecting the orbit of the OS. The Terminal Parking phase will use optical data for orbit determination, and will include large periods of time where the autonomous system is invoked. The OS/spacecraft range of this phase varies from 2 to 5km. The Terminal Parking Phase of a real MSR is likely to take less than a week, as the mission prepares for Terminal Rendezvous and Capture, but in the case of the technology demonstration, with ten or more rendezvous "sorties" planned, the mission is likely to spend many weeks in Terminal Parking Phase. With the autonomous tracking and control systems operational, this fact will likely not lead to excessive operational costs.

The Terminal Rendezvous phase is always operated autonomously, and brings the OS/spacecraft relative range to 100m from 2 to 5km. For the Premier mission, the Netlander tracking orbit where the rendezvous demonstration will take place is approximately at 550km altitude, with an approximately 2 hour period, and nearly noon/midnight nodes, local time, so, in the approximately 12 hours of activities comprising the Terminal Rendezvous phase several eclipses are experienced. In this orbital configuration, an illumination source may be necessary to keep the OS successfully tracked during the eclipses. The light would become operational within a range of about 250m.

The currently configured rendezvous experiment carries no capture mechanism, so the aspects of a rendezvous and capture having to do with mechanically contacting and "trapping" the OS will obviously not be tested. However, all aspects of the capture before that moment will be tested, including driving the OS along a slow relative orbit in very close proximity to the orbiter and slow (e.g. 2m range at 2cm/sec relative rate) with sufficient accuracy that a reasonably designed capture mechanism could capture the OS. So, even though there is not an actual physical capture of the OS, it is felt that these close proximity operations demonstrate the majority of the "capture" technologies and techniques. The Capture Phase will last less than two hours, and probably less than an hour, as the range from the orbiter to the OS is reduced from 100m to 2m.

The Rendezvous and Sample Capture System

The Premier Rendezvous and Sample Capture System (RSCS) is a combined ground and flight software system that, when combined with the optical sensing instruments onboard, provides a means of manual "ground-in-the-loop" tracking and maneuvering relative to the OS. It also provides automatic "closed-loop" tracking and maneuvering relative to the OS, and in the latter case, can accomplish close-proximity operations including a simulation of a "capture." Components of the system are shown in Fig.4.

The design of the RSCS is such as to maximize use of ground computation ability and therefore minimize onboard computation. This unequal division of responsibility between ground and flight systems is made possible by making maximum use of knowledge about the expected geometry of any rendezvous operations. By predicting position and timing of the rendezvous trajectory, and always constraining the Orbiter/OS relative position to be near this nominal trajectory, virtually all-numerical components of a closed-loop rendezvous navigation system can be pre-computed before the fact, uplinked to the spacecraft, and the rendezvous set into motion at the pre-determined time. Though there is substantial loss of generality in such a design, a Mars Sample Return (MSR) mission, for which the RSCS is intended to demonstrate certain technologies, is not a general problem; the recovery events will be very few, and each such event can be very carefully tailored, and be operationally intensive if need be. Such a limited and restricted system also minimizes costs of flight software development, and reduces testing costs due to the very simplified onboard algorithms, and greatly simplified operational scenarios.

The RSCS is a very limited closed-loop system, because it can take no action without a

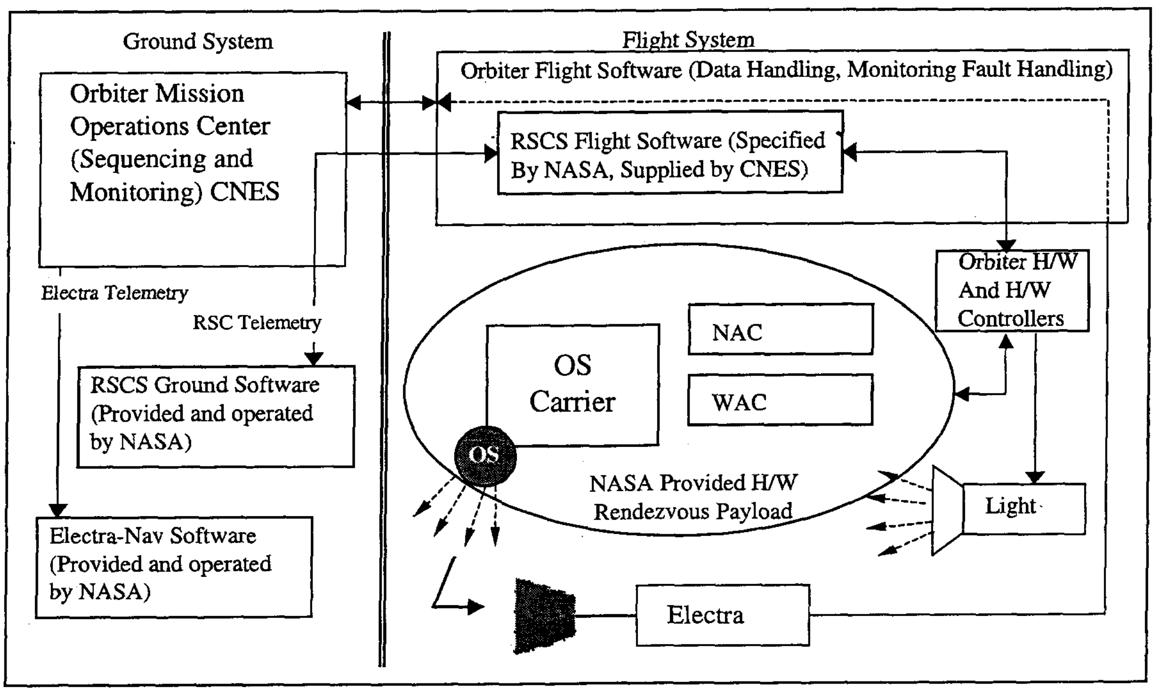


Figure 4: Rendezvous and Sample Capture System Components

command, either directly, or indirectly from the Command Sequence. The operation proceeds in the following steps, that are sequentially repeated, A) Target Tracking B) Picture Processing, C) Orbit Determination and Ephemeris Update, D) Maneuver Calculation, E) Maneuver Execution.

Though part of the overall Rendezvous Mission Demonstration, the taking and processing (on the ground) of radiometric data through the Electra instrument is not part of the onboard autonomous rendezvous system, the RSCS.

Target Tracking

It is necessary for the Premier orbiter to track the OS, and other objects such as Phobos or Deimos, and certainly Mars (e.g. the nadir point.) The RSC will use and extend this basic AOCS (Attitude and Orbit Control System) Tracking Subsystem (AOCST) by supplying this subsystem with nominal ephemeris files and offsets from those files. This interface will allow the orbiter to put the specified target in the field of view (FOV) of the specific instrument.

Picture Processing

All picture data used by the RSCS is created by commands in the ground-generated Command-Sequence. When a "Take-Picture" command is issued by the Command Sequence the camera will shutter the picture and then (if the picture is designated as a "Nav" picture) a message is sent to the RSCS. Upon receipt of this "Picture Ready" Message, the RSCS will process the picture. The onboard RSCS picture processing is limited to simple geometric calculations of locations of objects in the field-of-view, using the (corrected) nominal ephemerides, and then searching in sub-sets of the frame for "bright" objects. If close enough to the OS, the RSCS image processor will measure the maximum width of the OS image, and from this measurement infer a range measurement.

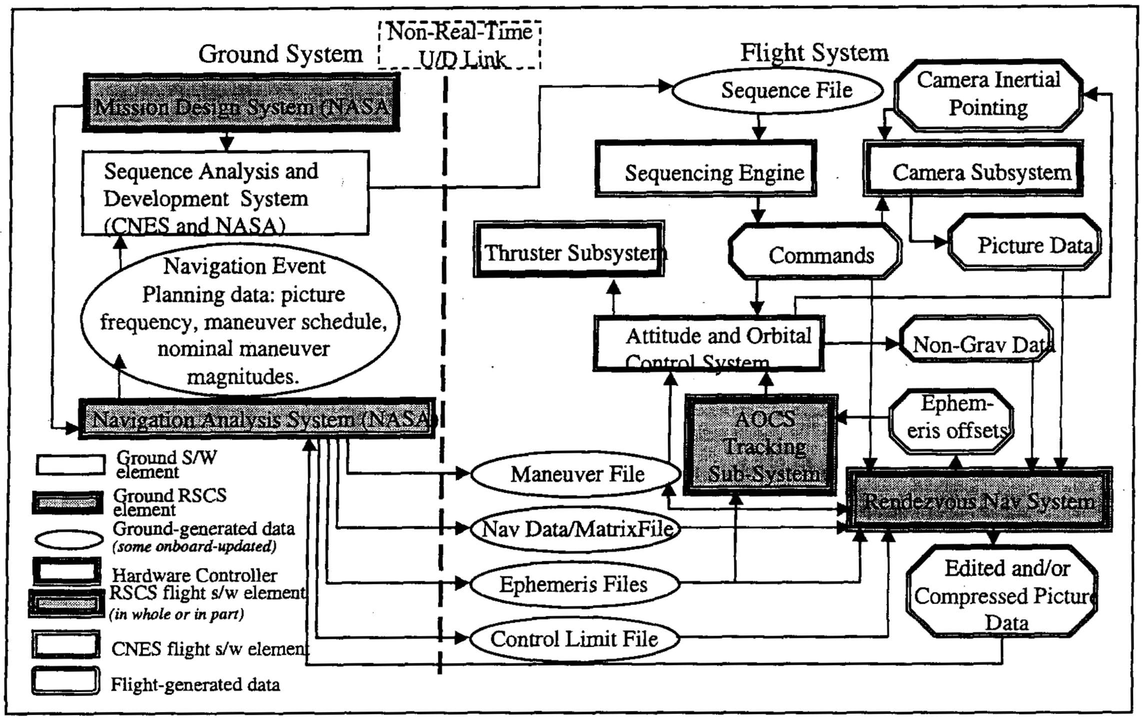


Figure 5: Rendezvous and Sample Capture Architecture and Block Diagram

Orbit Determination and Ephemeris Update

Using the extracted information from the picture-position of target image and its range - and that from previous pictures, the RSCS will compute a least-squares-estimate of the Orbiter and OS position and velocity offset vectors; making use of uplinked navigation data on the Nav-Data File. This estimate requires a small number of matrix and vector multiplications and additions with no numerical integrations or other extensive computations are required. After the ephemeris offsets are computed, they are transmitted to the AOCST, to provide current tracking information.

Maneuver Calculation

After a number of pictures have been processed (via commands issued by the Command Sequence), the Command Sequence issues a "Calculate_Maneuver" command to the RSCS. This command causes the RSCS to first determine if the currently estimated state offsets are large enough to warrant a correction (by comparing against a tabular schedule of allowable errors given in the Control Limits File) and if it is, multiply its current estimated Orbiter and OS relative offset vector by a state-transition matrix read from the Nav-Data File, to compute the parameters for two maneuvers that will return the Orbiter to the nominal Orbiter-OS relative trajectory by the completion of the second of the two maneuvers. The parameters of these maneuvers are then written to the Maneuver File.

Maneuver Execution

Finally, at a time consistent with the Maneuver File, the Command Sequence issues a command to the AOCS to execute a maneuver. To do this, the AOCS will read the Maneuver File for the maneuver parameters, specifically, the inertial delta-velocity vector. This process is repeated throughout the Terminal Phase, and until Capture is achieved.

RSCS System Interfaces and Architecture

The onboard software architecture alluded to in the above discussion of the RSCS is displayed in Fig. 5 as a block diagram of the system and its interaction with other onboard systems. The software elements highlighted in color are the only elements that contain RSCS computations. Data necessary for onboard computations is transmitted to onboard RSCS elements through files. Data transfers onboard may be by file or other means. Only one of the RSCS data files is modified during rendezvous operations and that is the Maneuver File. All activity of the RSCS is triggered either by a direct sequence command (e.g. "Plan-Maneuver") or is an indirect result of a command to take a picture. The latter command causes a signal to be sent to the RSCS when the picture file has been transferred into the CPU, and image processing commences.

RSCS Onboard Computation Description

As noted earlier, the computations in the RSCS maximally depend upon precomputed quantities. These are largely matrices that have reference epochs, and refer to some particular precomputed spacecraft and OS ephemerides. In the discussion that follows, reference is made to five of these quantities, and their meaning is summarized in Table 1.

ID	Name	Size	Occurrence/Frequency
M1	Covariance	6x6	Associated with every Nav picture time
M2	Observable DataPartials	3x6	Associated with every Nav picture time
M3	Maneuver K-Matrix	6x6	Associated with every maneuver time
M4	State-Transition-Matrix	6x6	Frequency ≤ 1/10mins, may be rev-cyclic
M5	STM-Time-Derivative	6x6	Frequency ≤ 1/10mins, may be rev-cyclic

Table 1: Definition and Description of Precomputed Navigation Quantities

Target Tracking

The RSCS must communicate information to the AOCST about the location of targets, in particular, the OS. Before any orbit determination (OD) functions have been performed, the means of data transfer is simply through the nominal Ephemeris Files. These files are in the form of Chebyshev polynomials describing position, with the velocity to be computed from position differences. The order of the polynomials to be used and the period of time over which the polynomial applies are adjustable parameters.

After OD functions begin, the nominal ephemerides need to be updated by the state corrections (offsets). The OD function will produce both Orbiter and OS state corrections. These state corrections are referenced to a specific time epoch. In order for the AOCST to have current geometry, RSCS will supply through the Ephemeris Offset Data, the state corrections ΔX as well as state-transition matrices (M4), and their time-derivatives (M5), allowing AOCST to correct the nominal ephemeredes to the current time. If t is the time of the desired position, and t_m is the epoch of M4 and M5, then the updated state $X_{corrected}$ is given by:

$$X_{corrected} = X_{nominal} + M4 \cdot \Delta X + (M5 \cdot \Delta X) \cdot (t - t_m)$$

Having computed the corrected Orbiter and OS states, the relative inertial vector is computed by differencing these positions. The targeting direction is given by this Orbiter-to-OS inertial vector. In the search phase of the rendezvous experiment, when an accurate position to the OS is not available, the inertial attitudes of the search pictures will be explicitly specified in the command sequence, based on search planning done by the ground portion of the RSCS system.

Image Processing

There are two types of image processing required for the RSC: Search Phase image processing, where the position of the target is unknown, and all other phases, where the position of the target is predicted with certainty to be in the field of view of the camera, or even a small portion of the field. These two types of processing are shown schematically below.

For those cases where knowledge of the target's position in the field is required, the computation is accomplished as follows. The predicted target position in the camera field of view is the inertial s/c to target vector projected and mapped into camera coordinates. If ***SC2OS*** is the inertial predicted Orbiter-to-OS vector, φ is the angular extent of one camera pixel, and **TITV** is the 3x3 ortho-normal transformation from inertial to video (or camera) coordinates, where coordinates 1 and 2 are the horizontal and vertical axes of the camera frame, and coordinate 3 is the normal axis, then the predicted pixel, line position of the OS in the camera field of view is given by

$$\overline{V} = TITV \cdot SC2OS'$$

$$\rho = norm(\overline{V})$$

$$\begin{bmatrix} pixel\_position \\ line\_position \end{bmatrix} = \frac{1}{\varphi\rho}\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} + \begin{bmatrix} pixel\_center \\ line\_center \end{bmatrix}$$

Camera frame line and pixel coordinates are trivially converted into meters in the "camera plane" or "plane of sky" at the target range. For both the search and the targeting image processing, the processing begins by identifying all illuminated pixels above a specified brightness. For the search phase it is sufficient to return this data to the ground for further processing. For targeted image processing, a sub-portion of the picture is searched, and the largest region of illuminated contiguous pixels above threshold is chosen as the target.

A simple "center-of-brightness" calculation is sufficient to locate the image, and the widest extent of the image will be measure of the image diameter, alternatively, the diameter of the object can be inferred to higher accuracy by measuring the number of illuminated pixels associated with the target image. From the diameter of the target (when the target image is large enough) the distance to the target is computed. Then, the three quantities -horizontal position, vertical position and range - form the image "observables" for the subsequent Orbit Determination function, and the nominal positions and range form the "modeled" or "computed" values. Differencing the computed values from the observed values forms the set of "residuals" for this picture, which is a 3-vector ***R***

An additional mode of image processing requires location of the bright object in the field (i.e. the target) to allow extraction of dimmer objects (e.g. stars). Such processing is necessary for Mars-approach optical navigation images, and for high-precision OS navigation frames. Such image processing is accomplished by including, in the command to shutter the image, pre-computed pixel/line vectors from the target to the desired image locations where data is desired for extraction.

Orbit Determination

With the observable quantities – horizontal x, vertical y, and range (all in meters) -extracted from the pictures, the RSCS will update the estimated state, and deliver the updated state offsets to the AOCST. The estimated state is computed using data partials (M2) and covariance (M1) from the Nav-Data File. M2 represents the Observable partial derivatives (partial of the OS position in the camera with respect to the epoch-state of the OS), and M1 is the estimated covariance associated with each observation, and includes the effect of all of the previously scheduled pictures taken in a data-arc of pre-determined length, assuming a predetermined de-weighting decay coefficient. Over a series of pictures, a least squares estimate of the OS (Target) state will be computed by forming the product of the covariance, the observation partials, and the computed residuals $\mathbf{R}_i$ of the Target position in the camera frame. This amounts to a current state Kalman filter. As each picture is processed, the anomalous values of $\mathbf{\Delta X}_i$ are tested for (based on preset limiting parameters) and such pictures are rejected.

$$R_i = \Delta(x, y, range)$$

$$\Delta\overline{X}_i = M1_{i(6x6)} \cdot M2_{i(6x3)} \cdot R_i'$$

As part of the OD process, the position of the Orbiter must be corrected as well. In the case of the orbiter, corrections are based on the Non-Grav File, produced by AOCS. The Non-Grav file provides accumulated translational velocity from all thruster firings. The current updated state of the Orbiter is maintained by incrementally mapping the ephemeris offsets from time-point to time-point, and using the incremented velocity change from the Non-Grav File:

$$\Delta(pos,vel) = (\Delta position_t, \{\Delta velocity_t + \Delta v_{non-grav}\})$$
$$\Delta X_{t+\Delta t} = [M5_{6x6} \cdot \Delta(pos_{1x3}, vel_{1x3})'] \cdot \Delta t$$

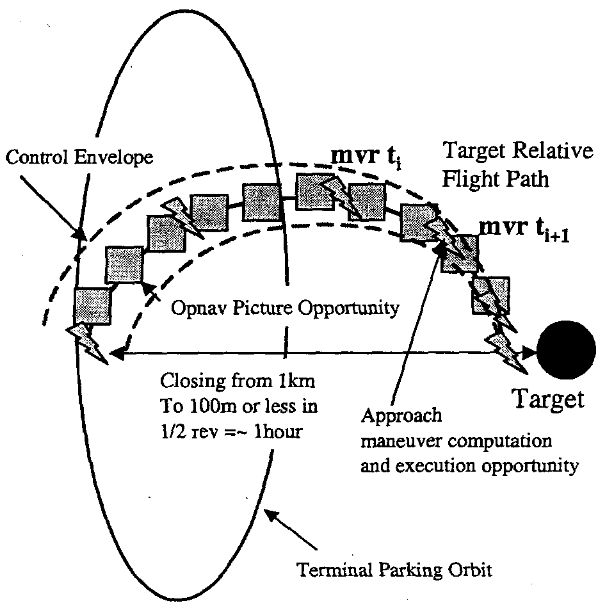
When the estimation of the OS ephemeris offset is complete, and the mapping of the Orbiter position is complete, $\mathbf{\Delta X_i}$ **for** both is sent to AOCST with the state transition matrix M4, its reference epoch time, and its rate of change matrix M5, as discussed above.

Maneuver Computations

With the estimated Orbiter state offsets complete, it is possible to compute the magnitude and direction of a pair of maneuvers that will bring the Orbiter back onto the nominal trajectory. This process can be repeated as necessary to keep the trajectory "in trim," where the frequency of such maneuvers is determined a priori, and the opportunities to perform them is imbedded in the Command Sequence. This process is shown schematically in the following figure.

It must be emphasized that all maneuvers are planned ahead, and initial values of some maneuvers are pre-computed on the ground. These are the deterministic maneuvers that define the trajectory, e.g. obtaining or leaving a "football" orbit, landing or leaving "v-bar". Other maneuvers are preplanned as well, and are entered into the Maneuver File with "null" a priori

Approach and Rendezvous Maneuvering Computations



Targeting Computations

- At discrete intervals, evaluate position within Control Envelope, and adjust s/c velocity as necessary. If $\Delta SC2OS$ is the estimated relative Orbiter-OS offset vector, then the pair of maneuvers is given by:

$$M3_{6x6} = \begin{bmatrix} M3_{11} & M3_{12} \\ M3_{21} & M3_{22} \end{bmatrix}$$
$$\Delta\bar{v}_1 = [\Delta SC2OS_{1:3} \cdot M3_{11} + \Delta SC2OS_{4:6} \cdot M3_{21}] \cdot M3_{21}^{-1}$$
$$\Delta\bar{v}_2 = [\Delta SC2OS_{1:3} \cdot M3_{12} + (\Delta SC2OS_{4:6} - \Delta\bar{v}_1) \cdot M3_{22}]$$

- Where Δv_1 for mvr at t_i is computed to null position offset from nominal at t_{i+1}, and a Δv_2 for mvr at t_{i+1} to null velocity offset from nominal at t_{i+1}.
- The maneuver matrix, M3, is computed on Earth, and uplinked for all of the maneuver opportunities.

Approach and Rendezvous Maneuvering Computations

Figure 6: Diagrammatic representation of Approach and Rendezvous Maneuvering Computations

values. When the RSCS is asked to compute a maneuver, it reads the Maneuver File to determine the next pair of maneuver opportunities, and simultaneously reads the Nav-Data/Matrix-File for the K-Matrix (M3) for this pair of maneuvers. Then, having previously obtained the current best estimated and determined positions of the OS and the Orbiter, the Spacecraft to OS vector is computed, ***SC2OS***, and the difference vector from the nominal to the estimated vector, ***ΔSC2OS***, and the pair of maneuvers can be computed, the values of which are added to the current values on the Maneuver File, and that file is then updated with the sum:

$$M3_{6x6} = \begin{bmatrix} M3_{11} & M3_{12} \\ M3_{21} & M3_{22} \end{bmatrix}$$

$$\Delta\bar{v}_1 = [\Delta SC2OS_{1:3} \cdot M3_{11} + \Delta SC2OS_{4:6} \cdot M3_{21}] \cdot M3_{21}^{-1}$$

$$\Delta\bar{v}_2 = [\Delta SC2OS_{1:3} \cdot M3_{12} + (\Delta SC2OS_{4:6} - \Delta\bar{v}_1) \cdot M3_{22}]$$

Operational Considerations

The operation of the RSCS is completely deterministic, even though it is an autonomous system, exhibiting only statistically predictable behavior, and responding to only statistically predictable inputs. Deterministic operation of the system is possible because the method of the navigation and trajectory control is to always drive the orbit of the spacecraft back to the nominal pre-computed, and therefore perfectly known, trajectory. This is the basis of being able to precompute all navigational quantities, as the deviations from the nominal are never allowed to get larger than what would result in non-linear estimation effects. With the operation of the system being deterministic, it is possible to plan all of the rendezvous activities before the rendezvous sorties, with a known time of "capture" pre-determined. All picture-taking events, all maneuver computations, and all maneuver executions can be pre-planned and placed in the operational sequences. Table 2 presents a summary of the commands used by the system.

Another aspect of the operation of the RSCS is the provision of the data files. Long before the execution of a rendezvous sortie, the desired trajectories for the spacecraft and the OS are computed, based on reasonable expectations of locations of both at the time of the desired rendezvous. Control of the relative orbit of the spacecraft might well be managed by the ground

COMMAND NAME	DESCRIPTION	FREQUENCY of USE
CAM_POINT	Request the AOCST to point camera at target, specifying particular camera.	One request at beginning of tracking session.
PICT_ACQ	Take a picture and deliver to the RSCS, the command will trigger OD calculations	One command per picture
PLAN_MAV	Plan a maneuver based on current OD, and store result on the Maneuver File.	One command per maneuver opportunity.
SET_DFILE	Assignment of data file to the RSCS, specify one of several files.	Assignments all occur before autonomous activity begins.
RESET_DATA	Null currently estimated state biases.	At start of rendezvous event.

Table 2: Rendezvous System Commands

to a point near the nominal trajectories before the autonomous system is invoked. In the meantime, the uplink files are prepared, including the nominal ephemerides, a file containing the nominal deterministic maneuvers, and locations to record computed statistical maneuvers (the Maneuver File), and the file containing the precomputed matrices of navigational data (the Navigation Data File). These will be uplinked to the spacecraft well before the start of a rendezvous event. It is not the case that data in the Nav Data File need represent every picture to be taken. For long periods of time, perhaps days, the RSCS will maintain the spacecraft orbit relative to the OS. For these periods, one or a few orbits worth of matrix/data, used repetitively will be adequate, and will be cyclically reused.

System Simulation

A computer simulation of the system has been constructed, as a proof of concept demonstration. All aspects of the RSCS were simulated with realistic noise models, with the exception of the image processing. Random observational errors were introduced to "ideal" optical observables. Another limitation of this early simulation is that modeling of the Wide-Angle camera has not yet been introduced into this simulation, and the system relies on the Narrow Angle camera alone.

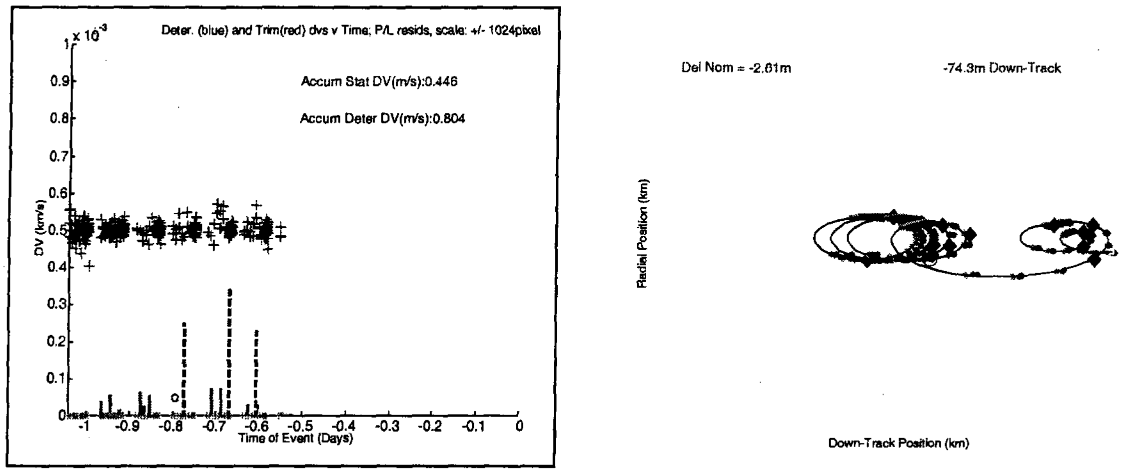


Figure 7a, b: First half-day of operations of a representative rendezvous sortie; picture and maneuver timeline, residuals and magnitudes; downtrack v. radial trajectory residual and maneuver display.

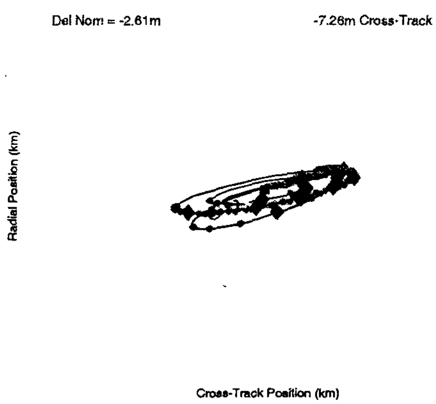


Figure 7c: crosstrack v. radial trajectory residual and maneuver display.

No translational dynamics of the spacecraft due to turns necessary to track the OS were considered. None of these limitations are believed to cast substantial doubts upon the overall feasibility of the technical approach, but such factors will be included in future simulations.

Fig. 7 shows the first approximately 10 hours of operations of a rendezvous sortie. Fig. 7a presents a timeline of events, including picture occurrences (crosses on time-axis), picture residuals (crosses across the horizontal mid-line, with a scale of +/- 1 NAC frame) and maneuver occurrences and magnitudes; dashed bars represent deterministic burns, and solid

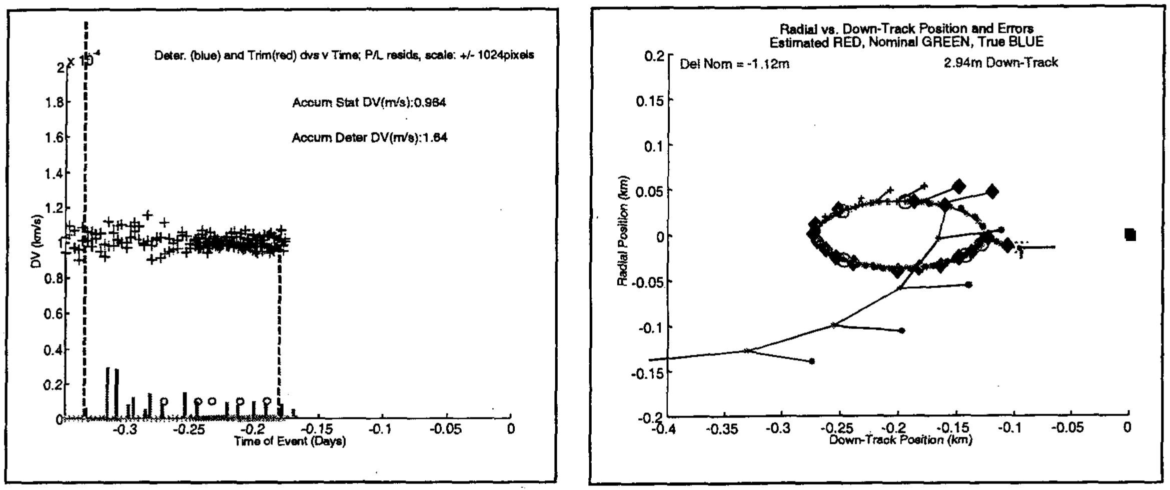


Figure 8a, b: Middle hours of operations of a representative rendezvous sortie; picture and maneuver timeline, residuals and magnitudes; downtrack v. radial trajectory residual and

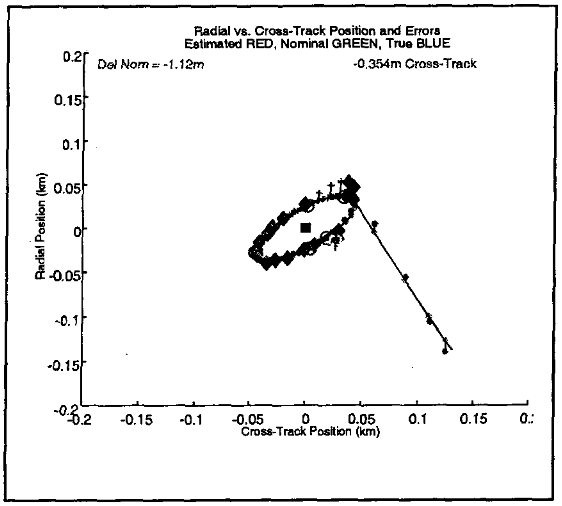


Figure 8c: crosstrack v. radial trajectory residual and maneuver display.

bars represent statistical burns. Accumulated magnitudes are shown from the start of the sortie, and represent an absolute-value sum across the three axes, giving measure of total delta-v consumed. Fig. 7b displays the trajectory of the OS relative to the spacecraft, in radial-downtrack and out-of-plane coordinates; in this case radial verses downtrack components. Maneuvers are shown on the trajectory trace as diamonds. Deviations from the nominal are noted at each observation point by a line and differently colored marker. The deviation from the desired nominal trajectory at the end of this time period is shown at the top of the plot. Figure 7c shows identical information in radial verses crosstrack directions. The projected position of the spacecraft is shown as a square.

Figs. 8 displays a period of several hours in the central portion of the sortie timeline. Figs 8a-c show the information from this time as was described for Figs. 7. Figs. 9 displays the same plots for the final 14 minutes of the rendezvous sortie, in the same format. The trajectory geometry plots present the final mistargeting of the simulation. In this particular instantiation of the statistical noise sources, the trajectory error was less than 10cm in all directions.

Table 3: Characteristics and Assumptions of the Rendezvous Navigation Filter

6 State (Spacecraft Position, Velocity) Kalman Filter	Maneuver execution errors, 1.5% relative, 1mm/sec bias
Exponential "Knowledge Decay" time of 4 hours	Camera pointing biases unmodeled
1mrad pointing knowledge, 0.5mrad pointing noise	Control requirement: 1% of spacecraft/OS range
Diameter measurement noise of 0.5pixels	Illumination of OS is required inside of 250m range
Increased Data Frequency Prior to entering Eclipse	Narrow Angle Camera data only
Initial orbit errors: 1m, 5cm/sec spherical	Maneuvers forbidden immediately before eclipse

Rough characterization of the performance of the rendezvous system has been made using the simulation. Success rates are high (where success is determined by an accurate delivery of the OS along a trajectory consistent with a hypothetical capture mechanism), but are clearly dependent upon the initial assumptions, which, for this instantiation are given in Table 3, along with general characteristics of the filter.

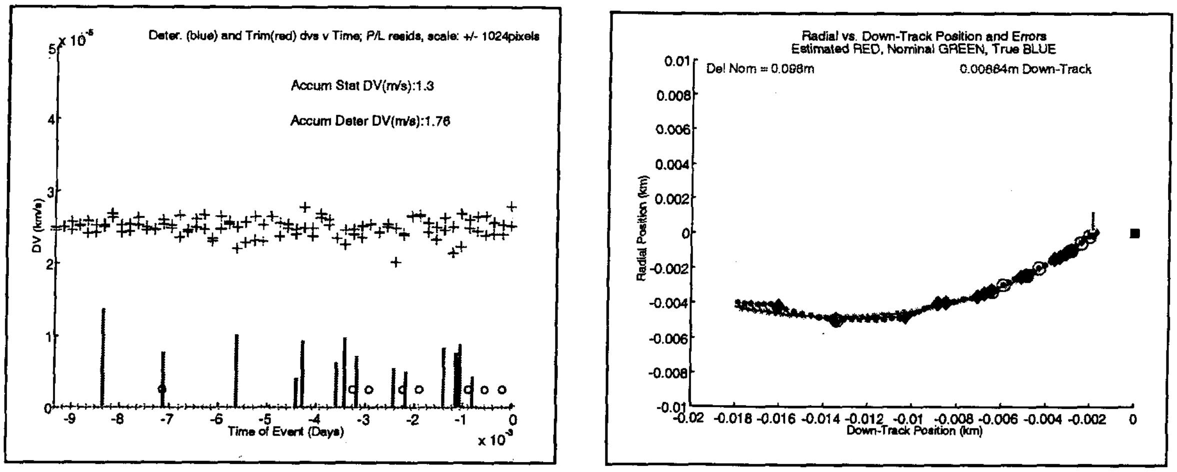


Figure 9a, b: Middle hours of operations of a representative rendezvous sortie; picture and maneuver timeline, residuals and magnitudes; downtrack v. radial trajectory residual and maneuver display.

Important aspects of the operations of the system were discovered with the simulation; two of these are the need for illumination of the OS inside of 250m range, and a determination of the size of the imaging mosaics necessary when the OS comes out of eclipse when the range is greater than 250m. Such mosaics are necessitated by loss of orbital information during eclipse. Further refinements of the simulation will include adding observations from the wide-angle camera, and adding the translational delta-v effects due to turns.

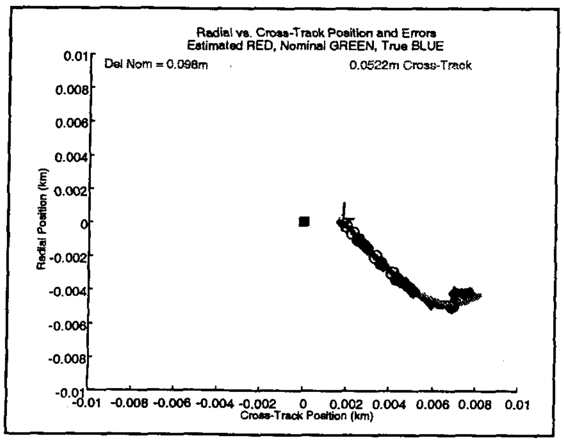


Figure 9c: crosstrack v. radial trajectory residual and maneuver display.

The Radio-Based Search Experiment

Overview

During a real MSR mission, the search phase of the mission will likely make use of several redundant data types, to absolutely guarantee success of initial contact with the OS. One very robust and adaptable instrument for this purpose is a one-way radio beacon. Depending upon the accuracy of the transmitting beacon, good to very good navigation accuracy can be achieved with a single receiver, and even with a relatively low-accuracy transmitter, extremely good results can be achieved with multiple orbiting receivers. The radio receiver, unlike the optical sensor, can also provide an extremely robust "proximity detection" capability, which, if the receiver is positioned in an orbit of substantially different altitude, can provide a very useful initial determination of OS orbital period and mean anomaly, without the need for a wide sky search. The following discussion will show results from analysis of the one-way radio beacon link during the MSR search phase, and which is intended to be part of the Premier Rendezvous Technology Demonstration.

Proximity Detection Capability

Evaluation of the CNES Electra onboard radio received signal strength can provide a crude OS detection capability. At search distances closest approach times can be inferred and used to assess the OS orbital period and mean anomaly. Signal power at closer distances can be helpful in determining pointing directions needed for recovery from situations where the OS is not in the expected field-of-view of the cameras. If multiple orbiters with UHF-band receive capability are available, simple direction finding can also be performed.

Radiometric Orbit Determination

For search and intermediate rendezvous operations one-way Doppler measurements, from the OS UHF-band radio beacon, can be produced by the CNES Electra onboard radio. For search distances larger than 1500 km, the Doppler observations are computed from a Fourier reconstruction of an "open-loop" or full spectrum recording of the received beacon signal. At shorter distances, the measurements are stored and transmitted to Earth where in all cases the OS

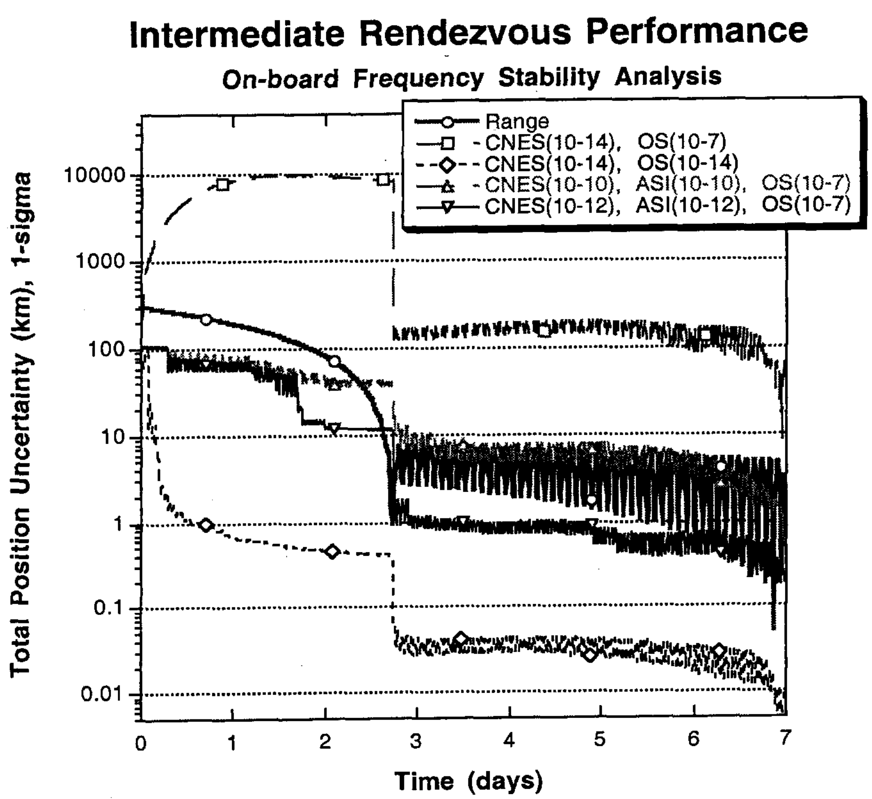


Figure 10: Radio-based covariance analysis results for various OS Beacon and orbiter clock stabilities

orbit is reconstructed. Taken alone, the CNES one-way Doppler measurements provide OS location information at the 100-200km levels. The poor OS radio frequency stability (oscillator expected to be 10^{-7} s/s Allan deviation over 10-100 seconds) limits accuracy. Figure 10 shows the bounding performance resulting from 10^{-7} and 10^{-14} oscillators on the OS. Collecting one-way measurements simultaneously with another orbiting spacecraft, in this case the proposed Italian Space Agency (ASI) G. Marconi Orbiter (GMO) also equipped with Electra, allows the common frequency instabilities to be cancelled by forming differenced one-way Doppler measurements. Figure 10 additionally presents the performance of these differenced Doppler combinations. For comparison, the relative range is also shown between the CNES orbiter and the OS (bold red line). Thus, simultaneous Doppler collected by the CNES and ASI orbiters with oscillators stable at least to 10^{-10} can provide reconstructed knowledge at the 10 km level. The CNES and ASI orbiters as well as future NASA Mars orbiters have baseline oscillator stabilities of 10^{-12}. While not autonomous, this Earth-based processing radiometric technique is valuable in assisting initialization of autonomous terminal rendezvous and, if necessary, rapid recovery from terminal rendezvous abort conditions.

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