AAS 03-614

AUTONOMOUS LANDMARK TRACKING ORBIT DETERMINATION STRATEGY

James K. Miller† and Yang Cheng††

Determination of the orbit of a spacecraft about an asteroid or comet presents many challenges relating to the dynamic environment and introduction of new data types. Optical tracking of craters on the surface of a central body was first used operationally for navigation by the Near Earth Asteroid Rendezvous (NEAR) mission to the asteroid Eros. The NEAR navigation system relied on a manual system of landmark detection and identification. Development of an autonomous navigation system would require orbit determination to be performed on the spacecraft computer with no human intervention. In this paper, an orbit determination strategy is described that is fully autonomous and relies on a computer-based crater detection and identification algorithm that is suitable for both automation of the ground based navigation system and autonomous spacecraft based navigation.

INTRODUCTION

Determination of the orbit of a spacecraft about an asteroid or comet presents many challenges relating to the dynamic environment and introduction of new data types. Optical tracking of craters on the surface of a central body was first used operationally for navigation by the Near Earth Asteroid Rendezvous (NEAR) mission to the asteroid Eros. The landmark tracking data was integrated with Doppler and range radiometric data and laser altimeter data to determine the orbit of the NEAR spacecraft in conjunction with the physical properties of Eros that are needed for orbit determination and navigation. The NEAR operational orbit determination strategy involved solving for hundreds of parameters that were updated daily as additional measurements were obtained. These parameters included spacecraft state and other parameters related to the spacecraft orbit such as solar pressure and propulsive maneuvers in addition to Eros physical parameters that included gravity harmonic coefficients, pole and prime meridian, inertia tensor, landmark locations and ephemeris. The initial orbit determination emphasis upon arrival at Eros was to physically characterize Eros. The pole, prime meridian, inertia tensor and gravity field were first determined. The principal data type used for this determination was optical tracking of landmarks. The landmarks are craters on the surface of Eros and thousands were identified and cataloged for this purpose. After the physical characterization of Eros was completed to an accuracy necessary to sustain orbit determination, the identification and processing of landmark data became routine but remained time consuming and tedious to the end of the mission.

The development of a totally autonomous navigation system for application to a spacecraft in orbit about an asteroid or comet is far from being realized. The major obstacle is the need for a computer-based algorithm for identification of craters to replace the current manual identification. An evolutionary development is envisioned that will achieve full autonomy in stages. The first stage would be an autonomous system that would determine the spacecraft orbit and point science instruments at features on the asteroid or comet that are of interest. The second stage would execute propulsive maneuvers to control the orbit and automatically execute a mission plan. The third and

† Associate Fellow AIAA, Navigation Systems Section, Jet Propulsion Laboratory, California Institute of Technology

†† Member of the Mobility Systems Concept Development Section, Jet Propulsion Laboratory, California Institute of Technology

final stage would be initiated on approach to a body such as a planet, asteroid or comet and would characterize the asteroid, acquire science data and completely execute the mission plan. The first two stages are well within the current capability of computer systems and algorithms. Since the initial characterization of the asteroid or comet would require algorithms that must anticipate a wide variety of asteroids and comets, it is expected that the third stage would require artificial intelligence and will not be developed in the immediate future.

In this paper, algorithms are described for achieving the first two stages of autonomy. The initial characterization of the body is performed on the ground and the results uploaded to the spacecraft. The autonomous navigation is initialized with a high precision spacecraft state vector and asteroid or comet model. Additional data is acquired and processed to maintain the orbit. The centerpiece of this autonomous system is an algorithm for detection and identification of landmarks. This automatic landmark tracking system is designed for both ground based and space based application and performs the entire spacecraft orbit determination without human intervention. Segments of the NEAR orbit are determined using the new automatic landmark tracking and compared with the conventional orbit determination obtained during NEAR mission operations. An algorithm is also analyzed that would function autonomously.

AUTONOMOUS NAVIGATION

In the past, autonomous spacecraft navigation has been limited to flight regimes where control of the flight path requires a rapid succession of maneuvers that could not be performed by conventional ground based navigation. Examples are the Surveyor landing on the Moon in the late sixties and the Viking landing on Mars during the mid seventies of the last century. The military has used sophisticated autonomous navigation schemes for control of missiles since the beginning of the space age. The application of autonomous navigation to deep space missions has been limited by computer speed, mass storage requirements and the reliance on radio metric data types as the primary method of orbit determination. With the development of small high speed computers, the constraints of computer speed and mass storage no longer pose a problem for implementing autonomous navigation. A personal computer the size of a lunch box can easily perform all the navigation computations required for deep space navigation in a timely manner.

The navigation of spacecraft in deep space has traditionally been achieved by making extensive use of radio metric data types for orbit determination. Since the spacecraft is nearly in continuous communication with the Earth, the orbit determination can be performed by gathering all the data on the spacecraft or on the ground, performing the maneuver computations and executing the propulsive maneuvers or computing science instrument pointing and pointing the science instruments. If the data is gathered on the ground, the navigation computations can be computed with high reliability and up linked to the spacecraft and this has been the preferred method. The ground based navigation computations permit extensive human intervention and are thus presumably more reliable.

During the orbit phase of the NEAR mission to the asteroid Eros, the primary data type was optical imaging of craters supplemented by Doppler tracking and laser altimetry. Initial navigation operations were concerned with determining the gravity field and rotation parameters of Eros in addition to the spacecraft state and propulsive maneuvers. A major effort was initially expended in detecting landmarks on the surface of Eros and identifying these landmarks or craters on more than one image. Only the information obtained by stereoscopic observation of a landmark is useful for orbit determination and success is critically dependent on reliable identification of a landmark on more than one image.

After the initial characterization of Eros's gravity field and rotation was completed, the orbit determination became more routine. For long periods of time, the spacecraft performed science observations from a nearly circular orbit that varied in radii from 100 km to 25 km. These orbital operations could have been performed autonomously by making use of laser altimetry as was demonstrated in Ref. 1. These orbital operation could also have been performed making use of automatic crater detection and identification freeing the DSN from a considerable amount of radiometric tracking. An even better approach would be to combine automatic landmark tracking with laser altimetry to determine the orbit but for now only landmark tracking is being studied.

ORBIT DETERMINATION STRATEGY

The orbit determination strategy for both ground based and autonomous operations is divided into two parts. The first part is concerned with determination of the spacecraft orbit and characterization of the central body physical properties. The second part is concerned with determination of the spacecraft orbit given additional data starting from a precision spacecraft orbit initial state and physical parameters describing the central body gravity field and rotational state determined in the first part. The first part of the orbit determination strategy is essentially the same as was performed during the NEAR mission and is performed on the ground for both ground based and autonomous navigation. The major difference is that the landmarks are processed by computer software exclusively and the NEAR mission relied on human detection and identification of landmarks. The second part of the orbit determination strategy omits radio metric data for autonomous operations and relies only on landmark tracking.

The orbit determination strategy is defined as the procedure for selecting the data to be processed, the parameters to be estimated and any algorithms for operating the orbit determination filter to obtain convergence. The NEAR orbit phase strategy is described in Ref.2 and involves processing optical, Dopper, range and laser altimetry data in a Square Root Information Filter (SRIF). The estimated parameters are spacecraft state, propulsive maneuver parameters, stochastic accelerations, Eros attitude parameters and Eros physical parameters. Eros attitude parameters include initial attitude, pole, prime meridian and rotation rate. Eros physical parameters include gravity harmonic coefficients, inertia tensor, the location of landmarks and shape harmonic coefficients.

For the first part of the orbit determination strategy, the only difference between the NEAR orbit determination strategy and autonomous orbit determination strategy is in preparation of the landmark tracking data. For the NEAR mission, all landmark tracking data was obtained by human inspection of images to identify landmarks. An automated procedure has been developed for automatic preparation of landmark tracking data files and is described in Ref.3. The first step in automatic processing of landmark tracking data is to obtain an *a priori* initial spacecraft state vector, initial Eros attitude and spin, and Eros shape model. The data arc length is defined, typically about one month, and all images acquired in the data arc are assembled. The spacecraft attitude is obtained from spacecraft telemetry and the direction of the sun vector is computed from the *a priori* spacecraft trajectory, Eros attitude and Eros shape model. The sun vector is supplied to a crater detection program and all the images are processed to identify craters in the images. Each crater is assigned a number and the line and pixel location in the image along with crater identification parameters are recorded. The crater identification parameters include size, shape and lighting of each crater. An actual crater on the surface of Eros may appear in several images and may thus have more than one number. Fig.1 shows a typical image of Eros with an ellipse fit to the crater rims. The procedure for detecting craters and fitting the ellipse to the rim is described in Ref.3.

The next step in preparing landmark tracking data is to compute the *a priori* location of each landmark from the spacecraft location, camera pointing direction, crater location in an image and the Eros shape model. The list of landmarks are processed to identify potential crater matches based on the *a priori* landmark location. A list of image pairs are supplied to the crater matching program for identification of crater matches. The only purpose of the this list of image pairs is to narrow the search of images that may contain the same landmark.

Crater matching involves finding one or more craters in two images as described in Ref. 3. Two typical image pairs are shown in Fig. 2. A single crater in the top left image can be easily found in the top right image by the eye. But the identification is certain only if the two larger craters can be identified by the computer. The two images at the bottom of Fig. 2 contain several craters that can be identified in the context of there location with resect to other craters in the image. In this case the identification is less obvious when made by a human observer. A list of image pairs are produced by the crater matching program with the matched craters identified.

The final step of the landmark tracking data file preparation is to put the images in time order and assign a unique landmark number to each crater. A landmark tracking data file is written with the image data that includes spacecraft attitude, unique land mark number and landmark location in image. A separate landmark location file is written with the landmark number and *a priori*

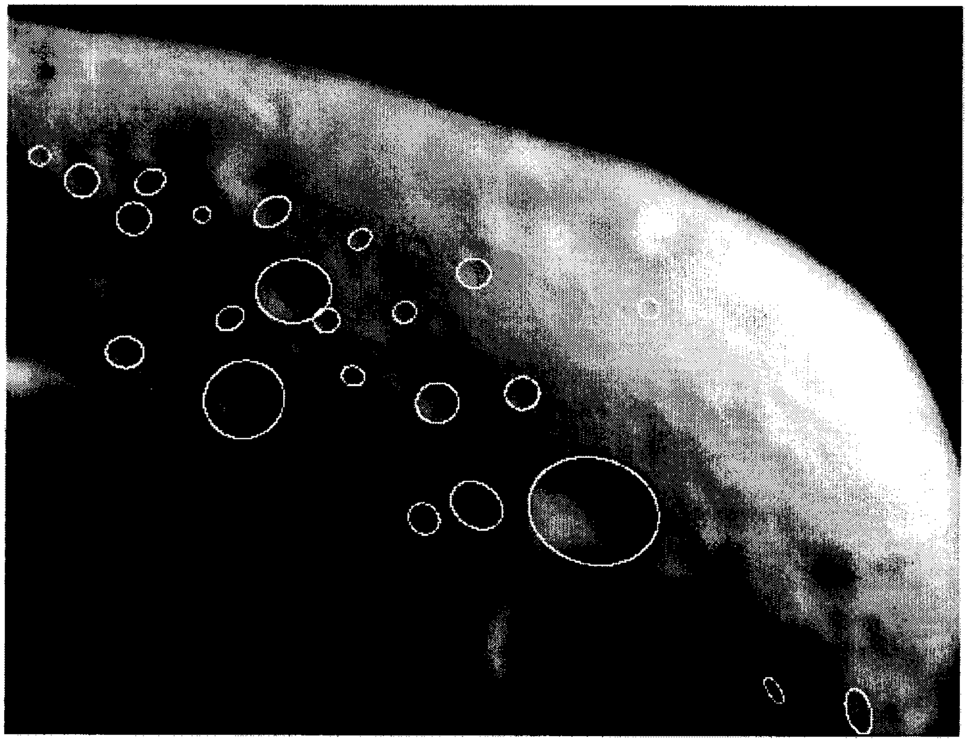

Figure 1 Crater Detection

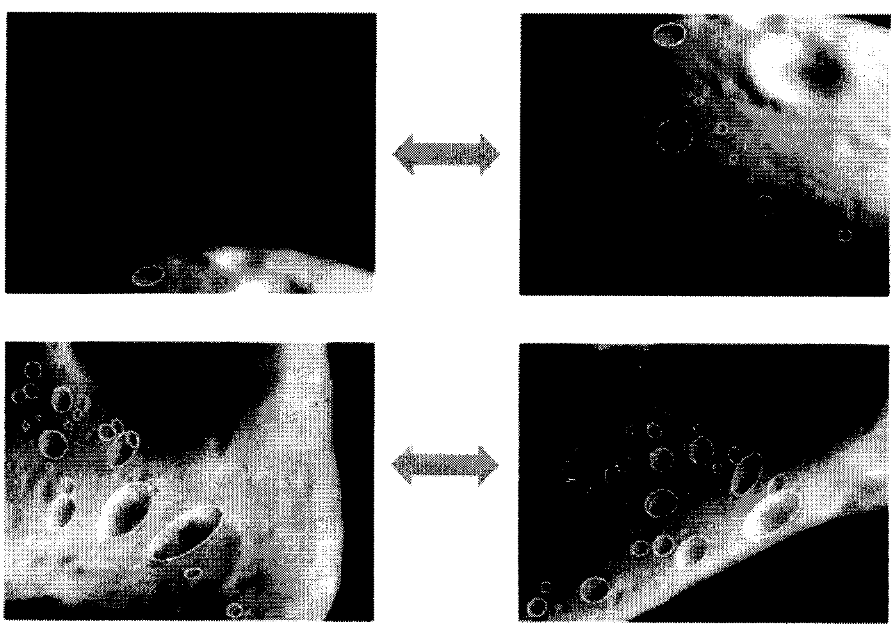

Figure 2 Crater Matching

landmark location. These files are input to the orbit determination filter.

Since the orbit determination SRIF filter is based on linear theory, convergence may not be readily obtained because of non linearity. A number of filter solution algorithms or "tricks of the trade" are often needed to coax a solution depending on how close the *a priori* input parameters are to the solution. Typically the range of convergence using linear theory is within several hundred meters and the solution is accurate to tens of meters. Some techniques that are use to achieve convergence involve adding data to the filter in small increments of a day or two and discarding bad data points based on examination of pre-fit residuals. Other techniques involve changing data weights and constraining the solution based on *a priori* information. One procedure that requires more discussion when landmark tracking data is involved is clipping and discarding bad data points whose pre-fit residual exceeds some tolerance determined by examination of the residual statistical distribution. Fig. 3 illustrates typical landmark tracking data pre fit residuals for three iterations that converge to an orbit solution. After the first iteration, shown at the top of Fig. 3, the statistical distribution of the landmark tracking residuals are given in lines and pixels. The center of the distribution is the *a priori* computed measurement for each data point. The actual measurements for good data points will cluster around the true measurement and are assumed to be normally distributed as illustrated. The bad data points are assumed to be uniformly distributed and are less than 10% of the total number of data points. The assumption of uniform distribution is convenient for analysis and appears to be consistent with actual observed data sets. However, it is more important that the bad data points be unbiased. It is equally likely that sign of a bad data point residual is positive or negative. The crater associated with the bad data point is equally likely to be on one side as the other of the actual crater that it is assumed to represent. A limit is placed on the data points with respect to the computed measurement that is assured to include all the good data points out to at least 4 sigma. This will exclude the really bad data points and is a standard data editing technique widely practiced. The filter processes the remaining measurements, good and bad, and a new solution for all the estimated parameters is obtained. The bad data points will exacerbate the problem of nonlinearity. If there are not too many bad points, the solution will yield pre-fit residuals for the next iteration as illustrated in the middle of Fig.3. For a linear system, the computed measurement will move to the center of mass of the residual plot at the top of Fig.3. The limits are moved in with respect to the computed measurement to capture the good data points and

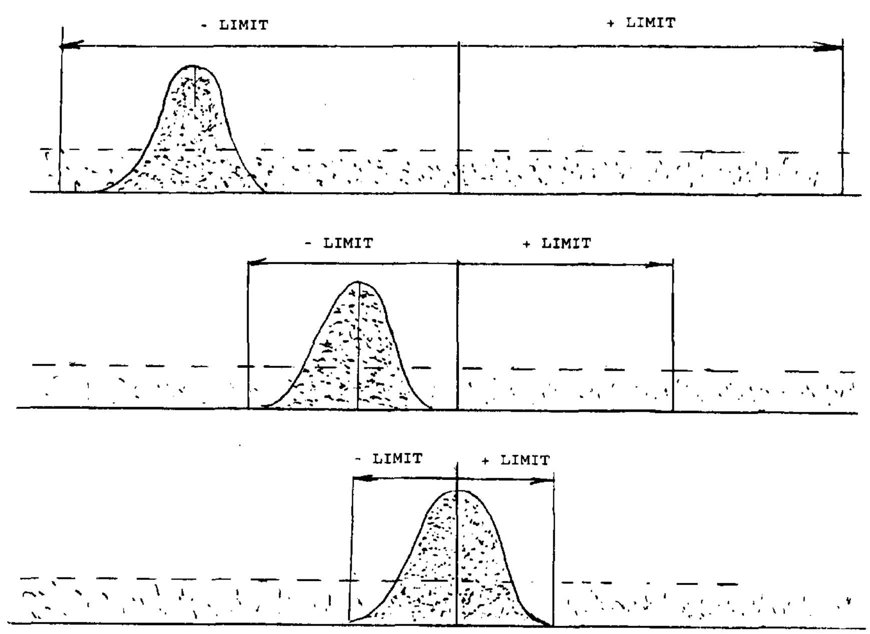

Figure 3 Mismatched Crater Rejection

exclude more bad data points. Several more iterations are executed until the solution is obtained as illustrated at the bottom of Fig.3. A small number of bad data points will still be hidden among the good data points and the result will be a slight degradation in the accuracy of the solution. The accuracy of the final solution is thus dependent on the reliability of the crater matching algorithm. The crater detection and matching programs have program controls that may be adjusted to achieve a very high confidence that there are few bad data points.

NEAR AUTOMATIC LANDMARK TRACKING EXAMPLE

For a test of automatic ground based landmark tracking, a strategically important data arc from the NEAR mission is processed. The data arc covers the time interval from July 3, 2000 till July 24, 2000. During this time the spacecraft is initially in a nearly circular 50 km orbit and a maneuver is executed to place the spacecraft in a 50 km by 35 km elliptical transfer orbit. The period of the transfer orbit is about 1 day and the spacecraft remains in the elliptical orbit for $6\frac{1}{2}$ revolutions about Eros from July 7, 2000 until July 14, 2000. On July 14, 2000, a maneuver is performed to circularize the orbit at a radius of 35 km. Since the orbit is highly perturbed by the irregular gravity field of Eros, the actual orbits are achieved only on average. The actual perturbed spacecraft trajectory is obtained by a targeting procedure that removes the effect of gravity perturbations on the long term trajectory propagation.

During the time interval covered by the data arc, several thousand images are obtained for use by both navigation and science. These images were manually inspected during the NEAR mission operations to identify landmarks and prepare optical data tracking files and *a priori* landmark locations. This data was processed by a SRIF filter to estimate the spacecraft orbit and physical parameters that characterized the gravity and rotational state of Eros. The final post fit residuals for the optical landmark tracking and radio metric Doppler tracking are shown on Figs. 4 and 5 respectively.

The RMS error of the tracking data residuals are about $2\frac{1}{2}$ lines and pixels and the Doppler residuals are about 3 mHz. This data set is sufficient to determine the spacecraft orbit to about 20 m. Later in the mission, when long unperturbed data arcs were processed, the spacecraft orbit

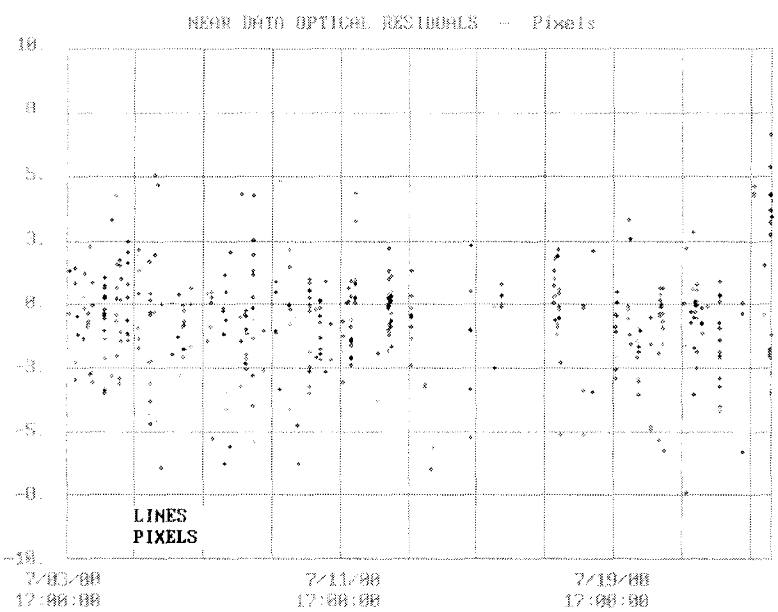

Figure 4 NEAR Mission Optical Residuals

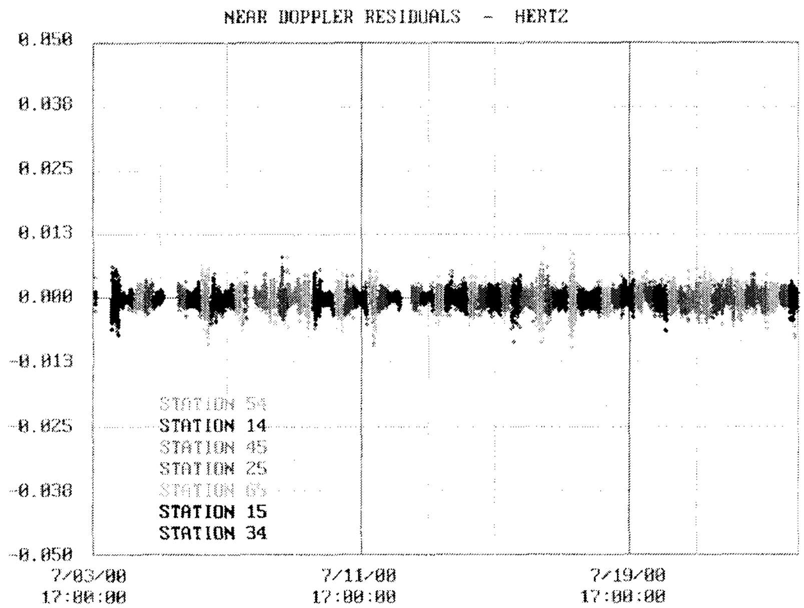

Figure 5 NEAR Mission Doppler Residuals

determination error was less than 10 m. The same images processed manually during the NEAR mission were processed by the crater detection and crater matching software developed for this study. Approximately 16,000 craters were identified during the time interval covered by the above data arc. From these identified craters, 80 landmarks were selected and 309 data points extracted from 208 image pairs. It took several iterations to identify the "best" landmarks and data points. The criteria for selection included geometric separation of landmarks, number of images containing a specific landmark and confidence level associated with crater matching. Curiously, few of the landmarks selected by the machine vision algorithms were included in the manual, human vision selected, data set.

The pre-fit *a priori* solution for automated landmark tracking is obtained by perturbing the solution obtained from the Near mission enough to realistically represent the orbit and Eros physical parameter errors that would exist at the onset of automated operations. Since the initial state estimate is highly correlated with the gravity field and other estimated parameters, arbitrary perturbation of the state and estimated parameters does not yield satisfactory initial conditions for analysis. A technique that was used for generating perturbed initial conditions on the NEAR mission is to add a large amount of new data or add a new data type to an existing converged solution. If the system is linear, the filter will immediately converge to a new solution with small perturbations of the estimated parameters. If the system is highly nonlinear, the filter will diverge to initial conditions near the limit of convergence and then it will take several iterations to converge to the new solution or the filter will continue to diverge and some other procedure must be used to obtain a solution. The new solution is generally close to the original converged solution and the response of the filter provides an indication of the orbit determination stability. The result of applying this technique to the new automated landmark tracking data set is shown on Figs. 6 and 7. Fig. 6 shows the simulated pre-fit automated landmark tracking residuals and Fig. 8 shows the simulated pre-fit Doppler residuals. A perturbation of up to 50 lines and pixels is about a quarter of the camera field of view and represents a substantial error in the *a priori* initial estimated parameters.

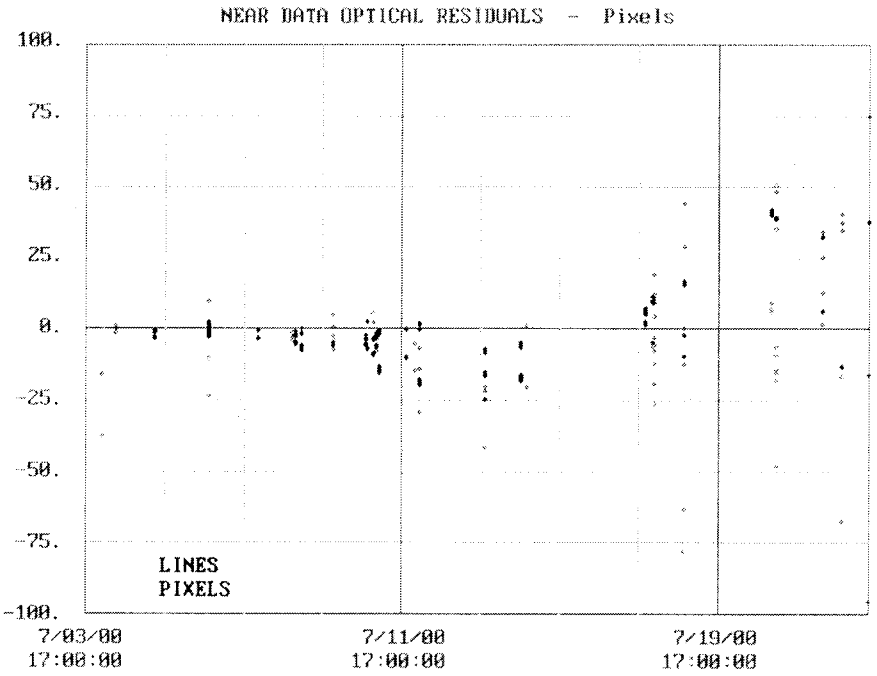

Figure 6 Pre-fit Automated Optical Residuals

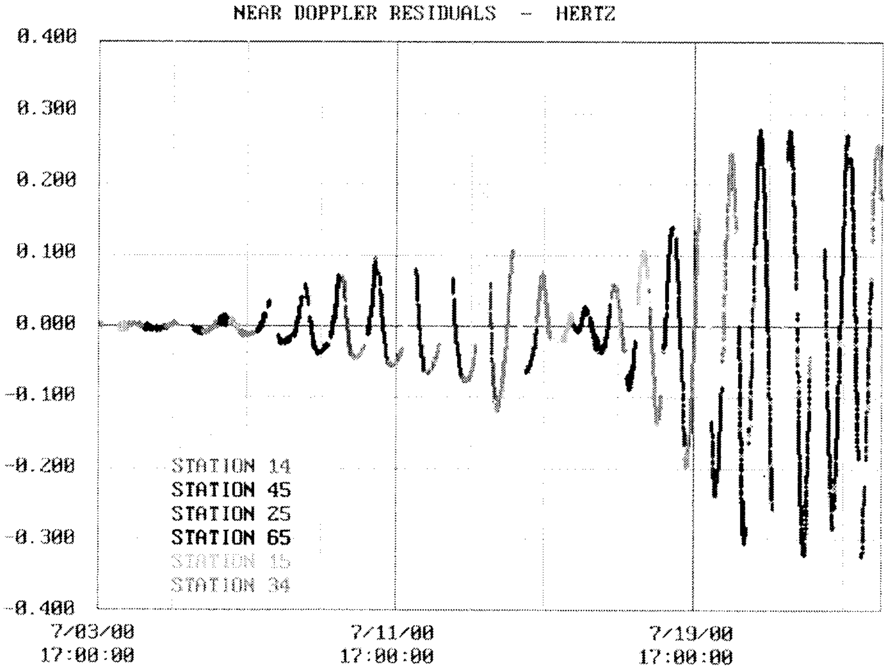

Figure 7 Pre-fit Automated Doppler Residuals

The results of the automated tracking data after processing by the same SRIF filter and same set of estimated parameters are shown on Fig. 8. The RMS error of the tracking data residuals for the machine vision selected data points is less than 2 line or pixels. The spacecraft orbit solution is within 30 m of the results obtained during the NEAR mission. Comparison of Fig 8 residuals with those shown on Fig. 4 indicate that the machine vision did better in identifying landmarks than human vision. There are about 20% more landmark data points on Fig. 8 than on Fig. 4 and the post-fit residuals are smaller. The comparison of man verses machine is not as close as the classic contest between John Henry and the steam pile driver. The machine detection and identification of landmarks can be performed in about an hour whereas the manual process involves several weeks of intense labor.

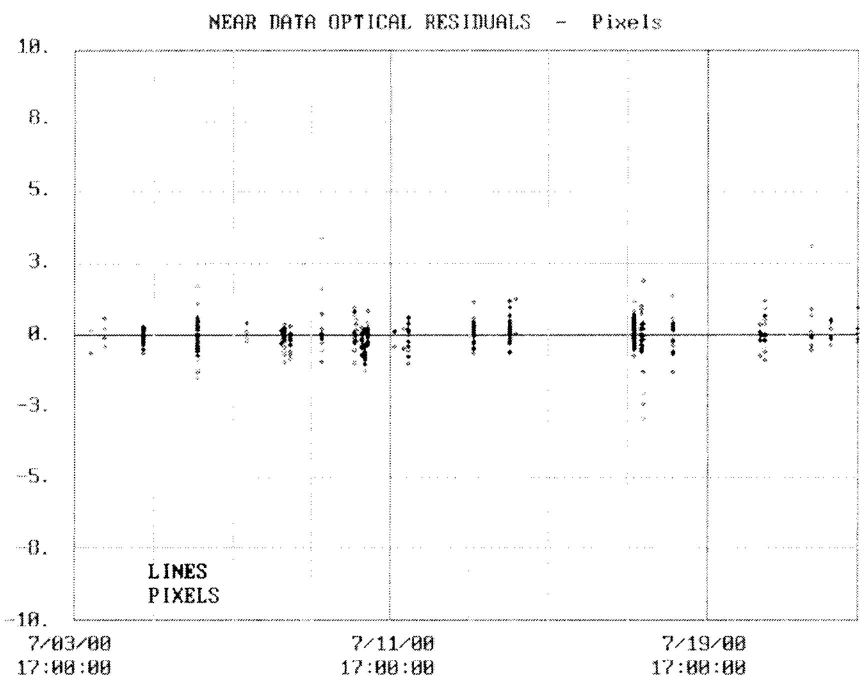

Figure 8 Automated Post-fit Optical Residuals

AUTONOMOUS ORBIT DETERMINATION EXAMPLE

For a practical example of autonomous navigation, consider the problem of acquiring imaging science data during the NEAR mission. During the time that the spacecraft was in a circular orbit, a solution for the spacecraft orbit was obtained on the ground and a file generated of the predicted spacecraft trajectory over the next several days. Science observations were planned and a sequence of imager shutter times and camera pointing angles (spacecraft attitude) were up linked to the spacecraft computer. The planned images were acquired and down linked to the ground for processing by navigation software. The landmark tracking data was extracted from the images manually and combined with radio metric Doppler and range data. A new spacecraft orbit solution was generated and the above procedure repeated until the end of the orbit phase. The NEAR orbit phase mission required almost continuous spacecraft tracking by the Deep Space Network (DSN).

A considerable amount of tracking time could be saved by performing imaging science orbital operations autonomously. An autonomous system would involve up linking imaging targets and a precision solution for the spacecraft state and Eros physical parameters. The spacecraft on board computer would command the spacecraft to the proper attitude for image acquisition and command the imaging system to acquire images. The images would be saved for down link to the ground and processed by the navigation system to update the spacecraft orbit. Since the spacecraft orbit would be updated more frequently than for ground based navigation, the orbit accuracy requirement would be much less stringent. Ground based navigation requires orbit estimates at the meter level in order to predict the orbit several days into the future. Autonomous orbit determination could achieve comparable results with 100 m orbit estimation errors.

The orbit determination strategy for autonomous orbit determination is considerably simpler than used for ground based orbit determination. There is no radio metric data available for autonomous navigation and only optical landmark tracking data is processed. Optical data is only capable of measuring angles. In order to determine the size of the spacecraft orbit a measure of length is required. When Doppler data is available, the length measurement is obtained by integrating the Doppler data over an interval time. Thus the Doppler and optical data complement each other and provide a three dimensional position determination. The singularities associated with orbit determination when Doppler is the only data type is removed by including optical data. For orbit determination with only optical data a measure of length must be implicitly obtained. This is accomplished by inputting a precision gravity field, determined on the ground earlier by processing optical data in conjunction with Doppler data, and removing gravity harmonic coefficients and the central body gravity from the list of estimated parameters. The size of the orbit is thus determined implicitly by measuring the period of the orbit with optical data.

A test case was devised to simulate autonomous orbit determination using the NEAR data set. The procedure is essentially the same as was used above to simulate automated ground based orbit determination. The Doppler data is deleted and the Eros gravity field is removed from the estimated parameters. The pre fit residuals are shown on Fig.9. After several iterations the filter converges to within 100m of the NEAR mission solution.

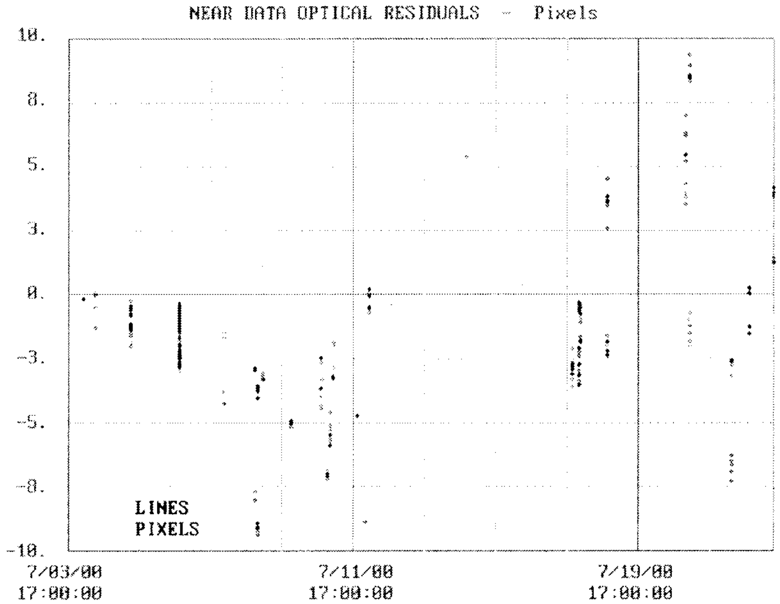

Figure 9 Autonomous Pre fit Optical Residuals

CONCLUSION

An orbit determination strategy has been devised for processing landmark tracking data for use on the ground for automated orbit determination and on board the spacecraft for autonomous orbit determination. The ground based automatic orbit determination compared favorably with the manual approach used during NEAR mission operations. The automatic landmark tracking orbit determination system performance exceeded the manual approach in accuracy, speed and ease of operation. When applied to the autonomous on board orbit determination problem, the autonomous version performance was comparable to the ground based performance with considerable saving of Deep Space Network tracking time.

ACKNOWLEDGMENT

The work described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology under a contract with the National Aeronautics and Space Administration.

REFERENCES

1. Weeks, C., "A Test of Autonomous Navigation Using NEAR Laser Rangefinder data", AAS 01-137, AAS/AIAA Space Flight Mechanics Meeting, Santa Barbara, CA, Feb. 12, 2001.
2. Miller, J. K., et. al. "Determination of Eros' Physical Parameters from Near Earth Asteroid Rendezvous Orbit Phase Navigation Data", AIAA paper 2000-4422, AAS/AIAA Astrodynamics Specialist Conference, Denver, CO, 2000.
3. Cheng, Y. and J. K. Miller,"Autonomous Landmark Based Spacecraft Navigation System", Paper AAS 03-223, 13th AAS/AIAA Spaceflight Mechanics Meeting, Ponce, Puerto Rico, Feb. 9-13, 2003.