

## NEW HORIZONS PLUTO APPROACH NAVIGATION

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The navigation of the New Horizons spacecraft during approach to Pluto and its satellite Charon is described. The great distance of the spacecraft from the Earth and Sun presents several new challenges that are identified and described by analytic formula. The two-body dynamics present a particularly interesting problem of satellite orbit determination. A complete covariance analysis is performed describing navigation and science data acquisition accuracies. The results of the covariance analysis are compared with analytic formula to provide insight into the operation of the navigation system.

### INTRODUCTION

Navigation of the New Horizons spacecraft<sup>1-2</sup> during approach to Pluto and its satellite Charon presents several new challenges related to the distance from the Earth and Sun and the dynamics of two body motion where the mass ratio results in the barycenter being outside the radius of the primary body. Since the Earth is about 30 a.u. from the spacecraft during the approach to Pluto and Charon, the round trip light time is greater than 8 hours making two-way Doppler tracking difficult. The great distance from the Sun also reduces the visibility of Pluto since Pluto receives about 1/900 of the solar radiation as the Earth. The two body motion involves Pluto and Charon moving in elliptic orbits about each other, and the system mass is a simple function of the period and semi-major axis of the orbit. The period can be measured to high precision from Earth based telescope observations and the orbit diameter can be measured to a precision of perhaps 100 km enabling the system mass to be determined within 1 percent. The maximum separation of Pluto and Charon on a star background provides a powerful observation of the total orbit size.

The mass ratio or the allocation of mass between Pluto and Charon is more difficult to discern from Earth based observations. Pluto and Charon orbit about their barycenter in elliptical orbits whose semi-major axes are inversely proportional to their mass. Therefore, the mass ratio can only be determined by observing the motion on a star background over some time and removing the heliocentric orbital motion. Since these measurements are difficult to make from Earth based telescopes, it is expected that the mass ratio and corresponding orbit sizes about the barycenter will not be determined accurately until spacecraft based optical measurements are obtained during approach.

The New Horizons approach navigation strategy must be designed to enable precision determination of the Charon orbit about Pluto and the spacecraft orbit relative to Pluto and Charon as well as to control the spacecraft approach trajectory and deliver the spacecraft to a position for science observations<sup>3-4</sup>. The initial navigation activity after detection of Pluto is to separate the orbit of Charon from the orbit of Pluto about their common barycenter. In order for these observations to be useful, Charon must be separated from Pluto by more than 100 pixels. As a byproduct, a more precise estimate of the system mass and spacecraft trajectory is obtained. As the spacecraft approaches the planetary system, the aim point relative to Pluto and the timing of Charon in its

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orbit is determined to an accuracy that permits an orbit correction maneuver to be executed so that the spacecraft is placed on the correct trajectory for science observations. If a substantial time adjustment is necessary to intercept Charon in its orbit about Pluto, it is important that this maneuver be performed as early as possible. Time change maneuvers are expensive to perform when the spacecraft is close to the Pluto/Charon system. During the approach to Pluto and Charon, the time of closest approach is not well determined. The error in the time of closest approach is proportional to the error in the range from Earth which is dominated by the Pluto and Charon ephemeris error. The distance of the spacecraft from Pluto and Charon cannot be determined with high precision until the spacecraft is close enough to observe the position parallax. This occurs during the final one to two days before encounter for Pluto only observations or during the final two to four days before encounter for observations of both Pluto and Charon. The timing of science observations during flyby is critically dependent on knowledge of the time of closest approach. A late update of the encounter sequence timing is planned based on optical navigation images acquired during approach.

In this paper, navigation of the approach to Pluto and Charon by the New Horizons spacecraft is described. Analytic formulas are developed that characterize the navigation system and provide insight into the dominant error sources. A detailed covariance analysis is performed using high precision, flight quality models of the data and dynamics. This analysis permits a statistical description of the navigation system including propulsive maneuver delta-V requirements and the accuracy of science data acquisition.

## **NEW HORIZONS NAVIGATION SYSTEM**

The New Horizons Navigation System consists of a collection of hardware and software on board the spacecraft and on the ground whose function is to determine and control the flight path of the New Horizons spacecraft. It consists of spacecraft instrumentation and Deep Space Network (DSN) instrumentation that provide data for determining the orbit of the spacecraft, a propulsion system that is used to control the spacecraft's attitude and perform maneuvers, and software on the spacecraft and on the ground that is used to determine the spacecraft's orbit and to carry out its navigation functions including command and control of the spacecraft trajectory.

### **Measurement Subsystem**

The measurement subsystem consists of instruments that provide observations of the spacecraft's motion. Instruments of this kind for the New Horizons mission are the spacecraft imaging system, calibrated non-coherent X-band transmitters and receivers, an inertial measurement unit containing three axis gyros and accelerometers and a star tracker.

#### *Radiometric Data*

Radiometric tracking data provide observations of the spacecraft motion with respect to the stations that comprise the DSN. The DSN tracking stations transmit radio-frequency signals to the spacecraft and receive signals via the spacecraft transceiver and antenna. The received signals constitute observations of Doppler and range data. Doppler data provide a direct measure of line-of-sight velocity of the spacecraft relative to a tracking antenna. The accuracy of this measurement is about 0.1 mm/s at the X-band frequency when the two-way Doppler count is calibrated and integrated for one minute. Because of the great distance from Earth to the spacecraft, the round trip light time results in the spacecraft being in two-way lock for only a few hours during each station pass. Therefore, 3-way Doppler data is planned to be processed which involves two tracking stations, one to transmit and one to receive. As a result, the Doppler data is not coherent and inter station timing errors will degrade the accuracy. For 3-way Doppler, the measurement error is assumed to be about 1.1 mm/s. A single Doppler measurement provides no information on position and velocity normal to the line of sight; however, a series of Doppler measurements enables a precise determination of certain orbit parameters by observing the signatures due to the Earth's rotation and orbit dynamics in the data<sup>5</sup>. The size, shape, and mean motion of the heliocentric orbit are well determined and the orientation is marginally determined.

Range data provide a direct measure of the line-of-sight distance from an Earth tracking station to the spacecraft. The absolute range measurement is useful for determining the interplanetary spacecraft orbit and the ephemeris of the Pluto/Charon system during encounter, but is only

marginally useful for determining the orbit of the spacecraft relative to Pluto during approach. For determination of the approach spacecraft orbit, the difference of successive range measurements is more directly useful. Differenced range may be obtained by differencing two range measurements taken over an interval of time or by integrating the Doppler data over the same time interval. Since the integrated Doppler data are more accurate, this data type is used as the primary source of differenced range information. However, range data does provide the constant of integration that is needed to fix the position of the orbit in space relative to the Earth and Sun.

Delta differential one way range ( $\Delta$ DOR) provides position information orthogonal to the line-of-sight. This doubly differenced measurement uses two DSN stations to alternately receive signals from the spacecraft and an angularly nearby quasar to produce an equivalent angular offset of the spacecraft line-of-sight from the baseline connecting the two DSN antennas.

#### *Optical Imaging of Pluto and Charon*

Optical imaging of Pluto and Charon provides a powerful data type for the determination of the spacecraft approach trajectory and describing certain characteristics of Pluto and Charon. Optical data alone are insufficient for complete orbit determination but are an essential complement to the Doppler data. When optical data are combined with Doppler data, an accurate determination of orbit orientation during encounter is obtained and the singularities normally associated with Doppler data alone are removed. It provides a direct relative measurement to the target body.

The optical measurement is obtained from an image of either Pluto or Charon using the LORRI or MVIC camera. The accuracy of this data type is a function of the picture element (pixel) spacing and the focal length of the camera optics. For the LORRI camera, the resolution is about  $5 \mu\text{rad}$  per pixel and for the MVIC the resolution is about  $20 \mu\text{rad}$  per pixel.

#### *Inertial Measurement Unit and Attitude Sensors*

Orbit determination accuracy is directly dependent on the accuracy of spacecraft attitude determination and the accuracy of accelerometer measurements of spacecraft velocity changes during propulsive maneuvers and attitude thruster firings. Of particular interest is the determination of the direction in inertial space of the camera boresight at the time optical navigation images are shuttered. For optical navigation, the direction of the camera boresight relative to the inertially fixed star field is determined on the spacecraft to an accuracy of  $5 \mu\text{rad}$ .

A precise measurement of the velocity change associated with propulsive maneuvers is necessary in order to predict the trajectory of the spacecraft. A one millimeter per second velocity error will map into a spacecraft position error of over a kilometer in 10 days. The Inertial Measurement Unit (IMU) has four accelerometers that provide three axis measurements of acceleration. The fourth accelerometer provides redundancy. In order to predict the spacecraft trajectory following propulsive maneuvers, the integrated accelerometer measurement must be good to a few millimeters per second.

#### *Spacecraft Nongravitational Accelerations*

For a spacecraft, the orbit determination error is a function of errors associated with the measurement system and errors associated with modeling the dynamics of the spacecraft motion. Spacecraft dynamics are the direct result of forces acting on the spacecraft. These forces may be separated into two categories: gravitational forces arising from the central body and other bodies in the solar system and nongravitational forces arising from a variety of sources including solar radiation pressure and attitude control system gas leaks or thruster imbalance. The gravitational accelerations are determined by observing the motion of the spacecraft and, in the absence of a sufficiently sensitive accelerometer, the nongravitational accelerations are determined the same way. The determination of the spacecraft orbit is thus dependent on the development of accurate models of the gravity field and the nongravitational force environment. The gravity field is generally easier to model in structural terms than nongravitational forces; however, the nongravitational forces are generally several orders of magnitude smaller. The stronger the gravitational forces and the weaker the nongravitational forces, the easier it is to determine the spacecraft's orbit. Nongravitational accelerations that are constant may be modeled as bias parameters and are relatively easy to determine. Rapidly varying nongravitational accelerations tend to statistically average out over time. The most troublesome nongravitational accelerations are time varying at frequencies commensurate with the length

of the data arc. The assumed *a priori* nongravitational accelerations associated with out gassing and attitude control gas leaks are  $5.0 \times 10^{-12}$  km/s constant bias and  $5.0 \times 10^{-13}$  km/s variable stochastic acceleration with a correlation time of 5 days. The solar pressure model has an effective cross section area of  $10 \text{ m}^2$  with a momentum transfer coefficient of 1.5. The error in the momentum transfer coefficient is 10%.

## PLUTO AND CHARON APPROACH NAVIGATION

The Pluto/Charon approach phase begins at about 120 days prior to Pluto encounter. Navigation activities that are performed during the approach phase include initial detection of Pluto, search for co-orbitals, ephemeris refinement, and a sequence of approach maneuvers that are designed to place the spacecraft on a trajectory that is optimum for science observations.

### Initial Detection of Pluto

The detection of Pluto as early as possible is advantageous from the standpoint of ephemeris verification and improvement to assure early tracking in support of the initial approach TCM and subsequent maneuvers. Detection depends, on Pluto's brightness as seen from the spacecraft and the imaging cameras sensitivity. The sensitivity of the camera depends on its light gathering capability (i.e. its aperture), the lens/filter/sensor light transfer and conversion efficiency, and the various electronic processes that produce image noise. The MVIC and LORRI cameras are able to detect an object when the brightness is greater than magnitude 10. Figure 1 gives the apparent magnitude of Pluto and Charon as the spacecraft approaches the system. The figure shows the point on approach at which the theoretical apparent magnitude is brighter than magnitude 10 for Pluto and Charon. Pluto reaches apparent magnitude 10 at about 510 days prior to closest approach, and Charon is about 210 days prior to closest approach.

As the spacecraft/asteroid range closes, Pluto's image will become brighter and expand thus improving the optical navigation image location accuracy. Optical navigation begins to exceed the performance of Earth-based observations approximately when the spacecraft camera resolution exceeds that of Earth-based telescopes. Figure 2 shows the resolution of the two spacecraft cameras as a function of time from Pluto. A value of 0.043 arc sec / pixel is used as the reference Hubble resolution of the Wide Field Planetary Camera. (The Hubble telescope may not even exist in this time frame, but the Hubble numbers are used as an example of very good Earth-based observations.) The plot shows that resolution of the primary MVIC camera becomes better than that of Earth-based observations at 44 days before the encounter, whereas the LORRI camera resolution exceeds the Earth-based resolution at 170 days before the encounter.

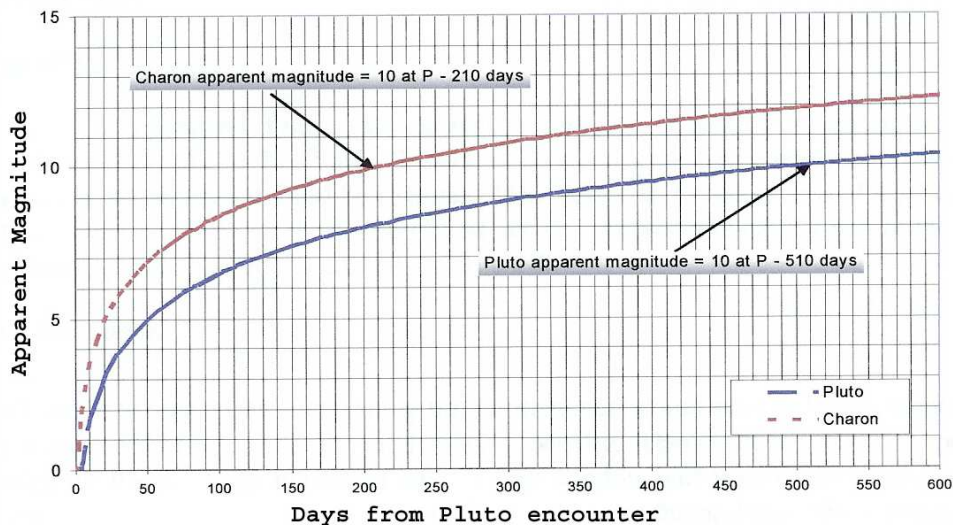


Figure 1 Pluto/Charon Apparent Magnitude

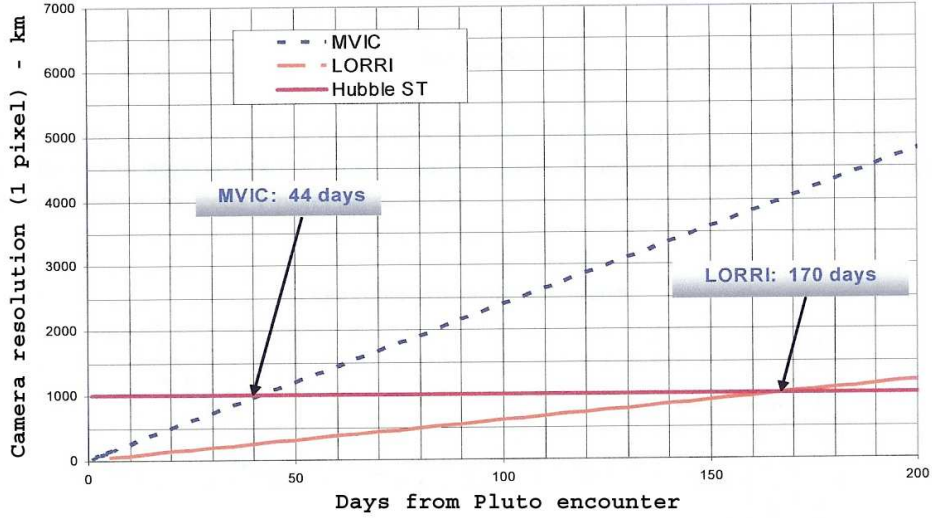


Figure 2 Camera Resolution Versus Hubble Space Telescope

### Pluto Approach Time-of-Flight Determination

As the spacecraft approaches Pluto and Charon from a great distance, the orbit determination error relative to Pluto is a statistical combination of the independently determined spacecraft and Pluto ephemeris errors. The spacecraft is initially too far from Pluto to make use of direct observation of Pluto. As the spacecraft enters Pluto's sphere of influence, the Doppler and range measurements are able to detect the gravitational acceleration of the Pluto/Charon system and the onboard optical navigation camera is able to detect the Pluto and Charon angular position on the star background. These measurements, either processed separately or in combination, can determine the approach velocity and position in the B-plane, a plane normal to the approach velocity vector, with high precision. The velocity determination error is within 1 mm/s in all three Cartesian components and the position error is about  $5 \mu\text{rad}$  times the range from the spacecraft to Pluto for the two Cartesian components in the B-plane. The third component of position, along the down track or time-of-flight direction, is not very well determined. The time-of-flight error is determined by observation of the Pluto gravitational acceleration by the Doppler and range data or the position parallax associated with the angular motion of Pluto and Charon on the star background.

For Doppler data, an approximate analytic formula for the time-of-flight error may be derived that provides insight into the problem of time-of-flight or range-to-go determination. The time-of-flight error is simply the range-to-go distance error times the approach velocity ( $V_\infty$ ). The geometry is illustrated on Figure 3. As the spacecraft approaches Pluto, it is accelerated by Pluto's gravity. The approach velocity magnitude and direction is known to very high precision as a result of tracking the spacecraft and observing Pluto's motion for years. The velocity along the line-of-sight from Earth ( $\dot{\rho}$ ) can also be measured with high precision by the DSN. The change in velocity magnitude is given by,

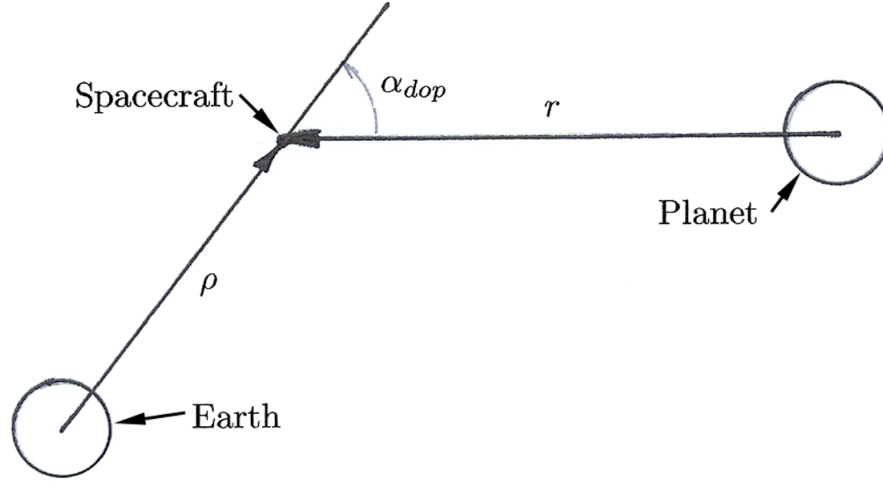
$$\Delta v = \dot{r} - V_\infty \quad (1)$$

The velocity change can be obtained by integrating the gravitational acceleration during approach to Pluto.

$$\Delta v = \int_{-\infty}^t \frac{GM_p}{r^2} dt \quad (2)$$

Since the integrated acceleration is small relative to  $V_\infty$ , the range may be approximated by

$$r \approx V_\infty t$$



**Figure 3 Planetary Approach Doppler Measurement Accuracy**

and

$$\Delta v \approx \int_{-\infty}^t \frac{GM_p}{V_\infty^2 t^2} dt \quad (3)$$

resulting in

$$\Delta v \approx \frac{-GM_p}{V_\infty^2 t} \quad (4)$$

The sensitivity of the approach velocity with respect to time-of-flight variation is obtained by taking the partial derivative.

$$\delta \Delta v \approx \frac{GM_p}{V_\infty^2 t^2} \delta t \quad (5)$$

The sensitivity of the Earth line-of-sight range rate to approach velocity is simply its projection onto the approach velocity vector and

$$\delta \dot{\rho} \approx \frac{GM_p \cos \alpha_{dop}}{V_\infty^2 t^2} \delta t \quad (6)$$

A formula for the time-of-flight error ( $\sigma(t)$ ) as a function of time from Pluto and Doppler measurement error is then given by

$$\sigma(t) \approx \frac{V_\infty^2 t^2}{GM_p \cos \alpha_{dop}} \sigma(\dot{\rho}) \quad (7)$$

For optical data, another approximate formula may be derived for the time-of-flight error. The geometry is illustrated on Figure 4. As the spacecraft approaches Pluto from a great distance, images of Pluto on a star background provide a strong determination of the direction of the approach asymptote. As the spacecraft approaches Pluto, the angular position of Pluto on the star background will begin to move away from the approach asymptote direction because of position parallax. The observation of Pluto's motion on the star background may be used to determine the range-to-go and time-of-flight.

From the geometry, the tangent of the angle between Pluto and the approach velocity vector is given by,

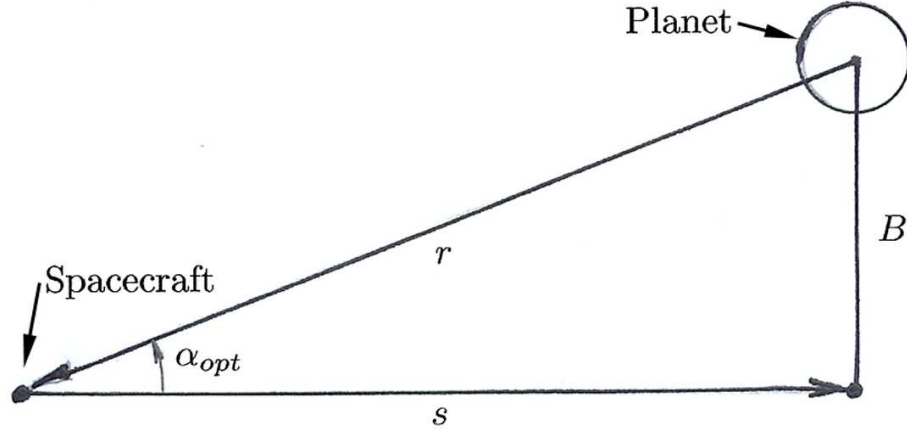


Figure 4 Planetary Approach Optical Measurement Accuracy

$$\tan \alpha_{opt} = \frac{B}{s} \quad (8)$$

The distance ( $s$ ) from the spacecraft to the B-plane may be approximated by

$$s \approx V_{\infty} t$$

Taking the partial derivative of  $\alpha_{opt}$  with respect to  $t$  gives.

$$\sec^2 \alpha_{opt} \delta \alpha_{opt} \approx \frac{-B}{V_{\infty} t^2} \delta t \quad (9)$$

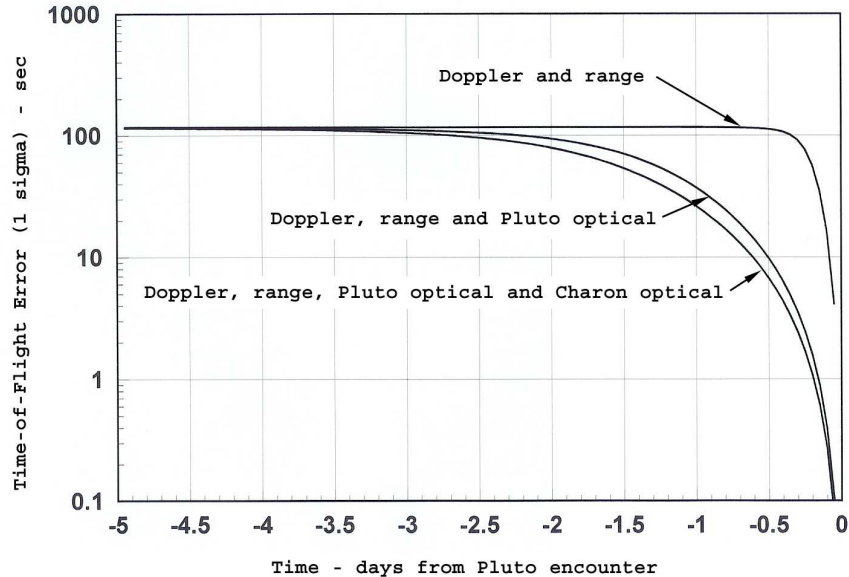
The formula for the time-of-flight error as a function of time from Pluto closest approach and optical measurement error is then given by

$$\sigma(t) \approx \frac{V_{\infty} t^2}{B \cos^2 \alpha_{opt}} \sigma(\alpha_{opt}) \quad (10)$$

The error in the time-of-flight estimation as a function of time from Pluto closest approach is shown on Figure 5 for Doppler data (Equation 7), Doppler and Pluto optical data (Equation 10) and Doppler, Pluto optical and Charon optical data (Equation 10). When Charon optical data is included in addition to Pluto optical data, Equation 10 is evaluated with  $B$  equal to the Charon orbit radius. For this analysis  $V_{\infty}$  is 13.7 km/s,  $B$  is 13,000 km for the aim point and 19,000 km for the radius of Charon's orbit and  $\alpha_{dop}$  is 14 degrees. The Doppler and optical measurement errors are 1.1 mm/s and 5  $\mu$ rad respectively assuming the LORRI camera. Pluto observation science requires knowledge of the time-of-flight to be less than 100 seconds which corresponds to about 1300 km down track error. As shown on Figure 3, the Doppler only orbit determination error does not decrease below 100 sec until about 6 hours before closest approach, too late to be of use for a science instrument pointing update. With optical data, the time-of-flight error is about 39 sec one day before Pluto closest approach. The addition of Charon optical data decreases the error about 50% from that obtained with only Pluto optical data. The Charon orbit baseline is about 50% greater than the baseline provided by the approach asymptote aim point and Pluto.

### Pluto and Charon Approach Covariance Analysis

A detailed covariance analysis was performed of navigation and orbit errors during approach to Pluto and Charon. This analysis included all the error sources that affect navigation accuracy and the data acquisition strategy that will be used. The orbit determination error is determined by filtering simulated data using the same square root information filter that will be used for flight



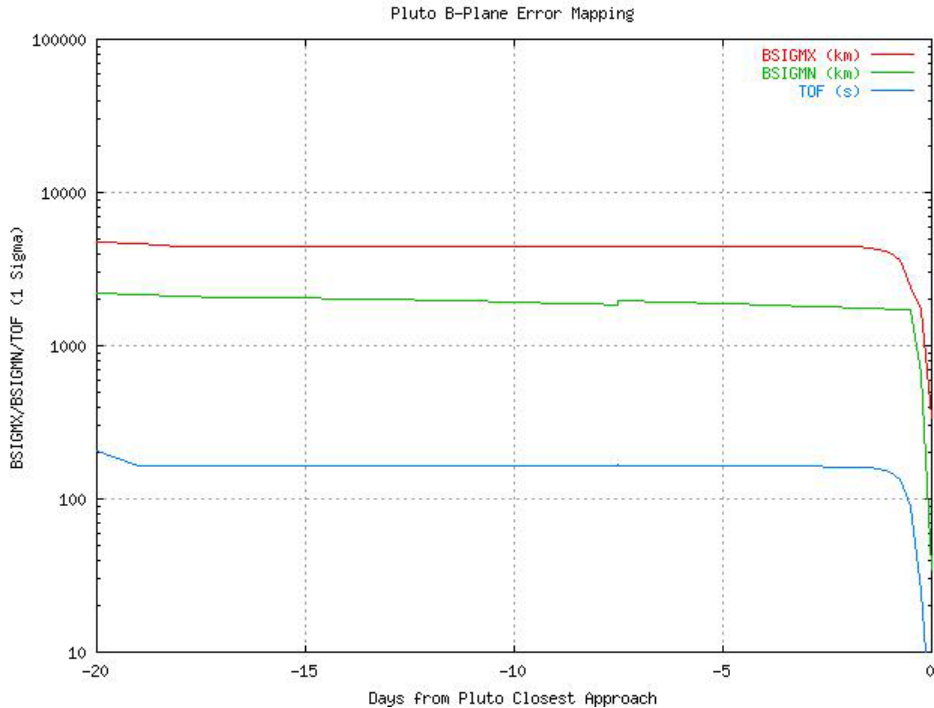
**Figure 5 Analytic Pluto Approach Time-of-Flight Error**

operations. The filtered best estimate of the orbit is mapped to Pluto closest approach to provide a common basis for comparison.

During approach to the Pluto/Charon system, the spacecraft orbit determination error relative to Pluto is a statistical combination of the spacecraft ephemeris error and the planet ephemeris error. Both of these ephemerides are determined by Earth based observations. The spacecraft ephemeris error is determined by radio metric tracking data acquired by the DSN and the planet ephemeris error is determined by telescope observations. Both of these determinations are accurate to about one thousand kilometers. For the Pluto ephemeris error, it is assumed that an observation campaign will be conducted about one year before Pluto encounter to reduce the effect of long term velocity mapping errors. An approach ephemeris error of several thousand kilometers is sufficient to ensure initial acquisition of Pluto and control the approach to Pluto/Charon until optical data is acquired by the imager onboard the spacecraft. The approach navigation strategy is to acquire radio metric and optical data during the distant approach and refine the spacecraft orbit relative to Pluto. A sequence of maneuvers are planned to maneuver the spacecraft to the desired aim point in the Pluto B-plane. These maneuvers are scheduled after performing a trade between the improved knowledge of the spacecraft orbit as more data is acquired and the cost in propellant of delaying the adjustment to the aim point.

The estimated parameters during approach to Pluto and Charon include spacecraft state, propulsive maneuver components, solar pressure model parameters, stochastic accelerations and Pluto and Charon ephemerides, gravity, pole, prime meridian and rotation rate. For navigation, the accuracy of spacecraft ephemeris estimation is of prime interest. The sensitivity of the spacecraft ephemeris estimation for various data acquisition strategies are shown on Figures 6 through 8. On these figures, the spacecraft position error is shown as a function of time from Pluto closest approach mapped to the Pluto B-plane. Figure 6 shows the spacecraft orbit determination error for Doppler and range data starting at 20 days before Pluto encounter and continuing to encounter. Prior to encounter minus 20 days, the Doppler and range data cannot measure the Pluto/Charon gravitational acceleration and the orbit is determined from Earth based observations. As can be seen on Figure 6, the Doppler and range orbit determination error does not improve until a few





**Figure 6 Pluto Approach - Doppler and Range Data Only**

hours before encounter which is consistent with the analytic result shown on Figure 5 for the time-of-flight error. Studies of planetary approach orbit determination<sup>6-7</sup> show that the B-plane position errors are theoretically twice the down track position error. Since the down track ( $s$ ) position error is equal to  $V_\infty$  times the time-of-flight error the numerical values shown on Figure 6 a few hours before encounter for the B-plane position are roughly a factor of 26 times the time-of-flight numerical values allowing for the mixed units.

Figure 7 shows the spacecraft orbit determination error when optical observations of Pluto are included with the radio metric data. The components of the spacecraft position error in the B-plane, the plane normal to the approach velocity vector, are reduced proportional to the range from Pluto times the angular measurement error. The angular measurement error is  $5 \mu\text{rad}$  associated with the LORRI camera. For the MVIC camera, these results should be inflated by about a factor of four ( $20 \mu\text{rad}$ ). Several events occur during approach that temporarily distort this simplified analysis. Most notably, a propulsive maneuver executed at encounter minus 7 days inflates the mapped orbit determination error until the Doppler and range data are able to resolve the spacecraft velocity a couple of days later. At about encounter minus 13 days, the B-plane errors are suddenly reduced by the introduction of new optical images. A uniform reduction in B-plane position error occurs when the images are acquired on a uniform time schedule as occurs from encounter minus 13 days through encounter. Throughout the approach to Pluto, until a few days before encounter, the time-of-flight error remains essentially the same as for the Doppler and range only case shown on Figure 6. As discussed above, the time-of-flight error is reduced when the position parallax can be observed as shown on Figure 5. This occurs about one day before Pluto closest approach.

When observations of Charon are included during approach, the approach orbit determination errors are essentially the same as obtained with only Pluto observations until about 2 days before encounter as shown on Figure 8. Since the baseline provided by the Pluto/Charon orbit is about 50% larger than the baseline provided by the Pluto/B-plane aim point, the time-of-flight error is about 50% smaller. This provides significantly more margin for a late science instrument pointing update. It should be noted that introduction of Charon data adds some complexity to the approach

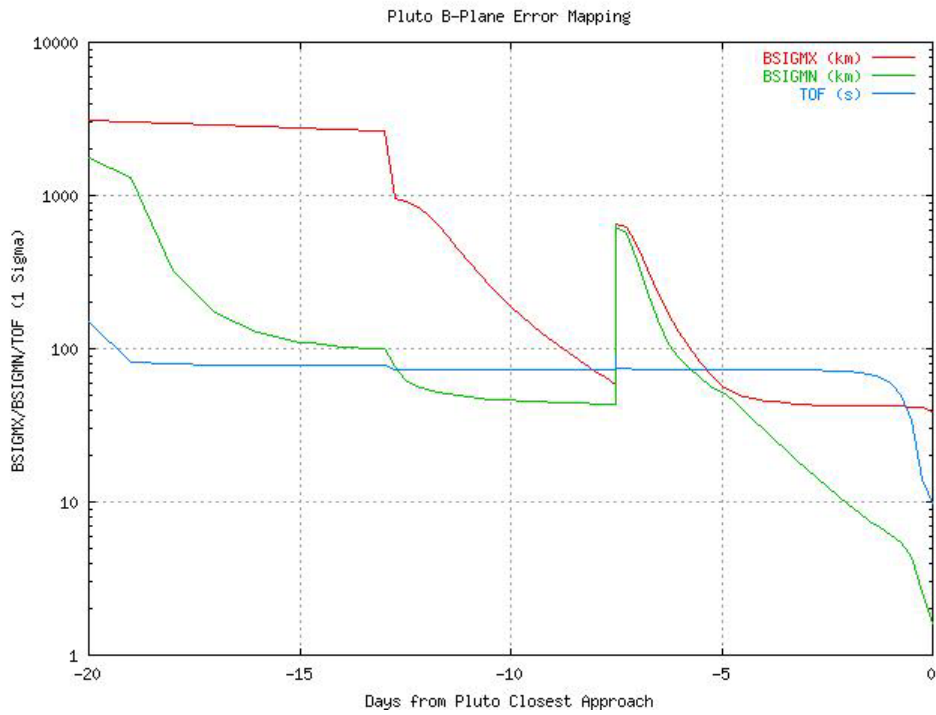


Figure 7 Pluto Approach - Doppler, Range and Optical Imaging of Pluto

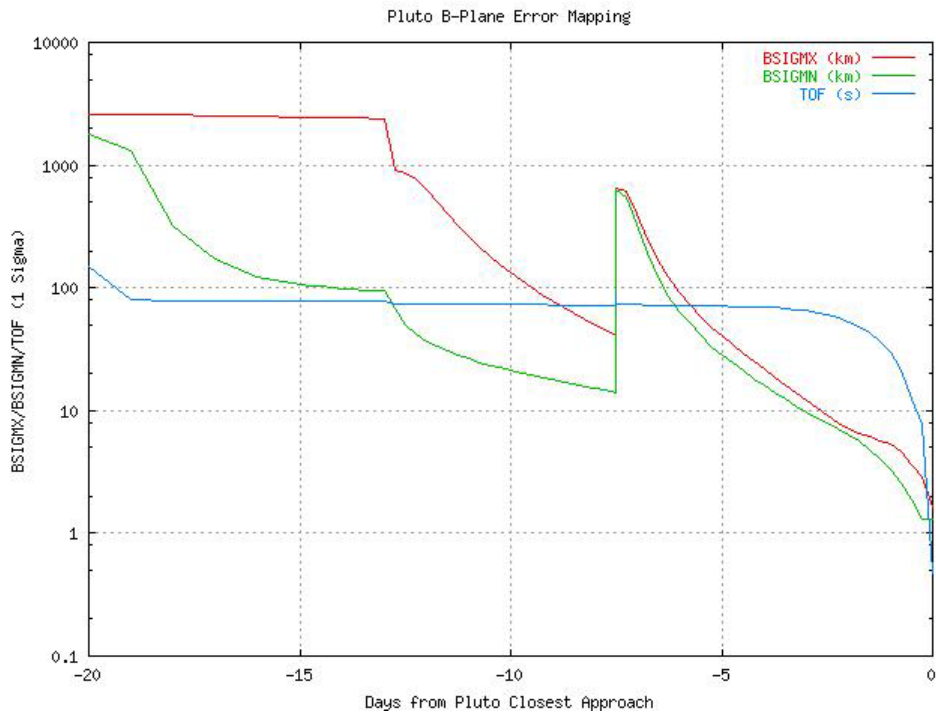


Figure 8 Pluto Approach - Doppler, Range and Optical Imaging of Pluto and Charon

orbit estimation strategy. The orbit determination filter must be able to solve for the Charon orbit and gravity with considerably more accuracy than has been determined by Earth based observations. However, even with Pluto only observations, the dynamics of Pluto and Charon's orbit must be included in the solution. The barycenter of Pluto/Charon is outside the surface of Pluto and uniform motion of Pluto on a star background during approach cannot be assumed.

## RECONSTRUCTION

As the spacecraft encounters the Pluto/Charon system, the gravitational perturbation of the spacecraft and observation of craters on both Pluto and Charon permit an accurate determination of the spacecraft trajectory and certain physical parameters that characterize both Pluto and Charon. The improvement in the spacecraft ephemeris during the encounter phase is useful for determining where the spacecraft is headed after encounter. An extended mission to the Kuiper belt is planned. The determination of Pluto and Charon physical parameters is useful for future missions to Pluto/Charon and is of interest for science investigations.

During the encounter phase, radio metric data and many images of Pluto and Charon are obtained. Table 2 shows the results of processing this data from before encounter until several days after encounter. In addition to the parameters estimated for approach navigation, some additional parameters are estimated that describe Pluto and Charon. These include the pole and prime meridian angles, rotation rate, gravitational parameters and the location of craters on the surface of Pluto and Charon. Optical imaging of Pluto and Charon when combined with Doppler tracking data should enable determination of the location of craters relative to the respective centers of mass to an accuracy of about 100 m. The observations that are most useful are obtained within several hours of encounter. During this time interval, the bodies rotate several degrees enabling a determination of the poles, prime meridians and rotation rates. The accuracy is optimistically estimated to be about 0.05 degrees as given in Table 2. The *a priori* values for the poles and rotation rates assume that both Pluto and Charon rotate at the orbital period of the Charon orbit about Pluto and are thus in gravity lock. This assumption is not necessary for determination of these parameters since the data obtained during encounter will be much more powerful than Earth based observational data including the Hubble space telescope. The solution will not be *a priori* limited. If Pluto and Charon are in gravity lock and the orbit is not exactly circular, the pole and prime meridian angles will librate about their nominal values. Further study is needed to determine if the libration angles will be large enough to be detected.

Table 2

### PLUTO AND CHARON PARAMETER ESTIMATION ERRORS

Parameters	Pluto/Charon nominal values	Error (1 sigma)	
		Pluto	Charon
<u>Pole and prime meridian</u>			
$\alpha$ (deg)	313.02	0.05	0.075
$\delta$ (deg)	9.09	0.05	0.075
$W$ (deg)	236.77	0.05	0.075
$\dot{W}$ (deg/day)	-56.3623195	$3.0 \times 10^{-4}$	$4.5 \times 10^{-4}$
<u>Mass properties</u>			
GM (km <sup>3</sup> /s <sup>2</sup> )	874.05/73.16	$0.41 \times 10^{-3}$	$0.33 \times 10^{-2}$
<u>Gravity harmonics</u>			
$C_{20}$	0/0	$0.81 \times 10^{-2}$	not available

Pluto and Charon gravitational parameters are determined from the Doppler tracking data acquired during encounter. The values for the errors given in Table 2 were obtained by detailed covariance analysis of simulated data. When combined with the volume of the bodies obtained from optical imaging, a refined estimate of the bulk densities may be obtained that will be at least an order of magnitude better than obtained from Earth based observations. Also, observation of the Charon orbit about Pluto will enable an even more precise determination of the system mass, an artifact of the equations of motion, that is of marginal interest to physical science but is essential for accurate ephemeris development. The normalized gravitational harmonic  $C_{20}$ , which is related to the oblateness, can be resolved to an accuracy of about 0.008 which is at least an order of magnitude greater than the nominal value expected from analysis of the spin and hydrodynamics. The flyby distances will probably be too great for the Doppler data to detect gravity harmonics.

In addition to the physical parameters of Pluto and Charon, the orbit of Charon about Pluto and the heliocentric orbit of the Pluto/Charon barycenter will be determined. This "normal point" will permit an improved ephemeris for these bodies when added to the existing ephemeris development data base.

## CONCLUSION

This paper has presented a description of navigation of the approach phase of the New Horizons mission. The great distance of Pluto and Charon from Earth presents several challenges. Using a combination of radio metric and optical data, it is shown that navigation accuracies sufficient for successful delivery of the spacecraft to Pluto and Charon and acquisition of science data can be achieved.

## ACKNOWLEDGMENT

The work described in this paper was carried out at KinetX Inc. under a contract with the Applied Physics Laboratory of the Johns Hopkins University.

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