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SATELLITE EPHEMERIDES UPDATE SCHEDULE FOR THE CASSINI MISSION

Ian Roundhill, Duane Roth
Jet Propulsion Laboratory, California Institute of Technology,
Pasadena, CA 91109-8099

The Cassini mission will arrive at Saturn in July 2004 to explore the Saturnian system including the satellites. The navigation team will update the ephemerides of 9 of these satellites to improve spacecraft navigation and provide information on satellite location for pointing of the spacecraft. This paper outlines the approach used to predict pointing uncertainty when pointing information is generated with a spacecraft prediction and older satellite ephemerides. This modeling is then used to choose times when the satellite ephemerides need to be updated to meet requirements.

Introduction

The purpose of this paper is to describe the satellite ephemerides update schedule for the Cassini mission and the analysis method used. When Cassini enters the Saturnian system in July 2004, the navigation team will be responsible for providing the ephemerides for nine of the natural satellites. Throughout the mission, new sets of satellite and spacecraft ephemerides will be computed by the navigation team and provided to users within the project. One major user is the science planning team, which uses the ephemerides to compute pointing information.

The motivation for this study is the effect of updating the satellite ephemerides. An update requires work by the navigation team to re-compute the spacecraft reference trajectory. This new reference trajectory is then used to update the spacecraft sequences. Updating the spacecraft sequences is not a trivial task and should only be done when necessary. This analysis will help define when the spacecraft sequences need to be updated with a new reference trajectory to satisfy pointing requirements.

This paper is composed of three parts. First, the pointing uncertainty algorithm is described. This algorithm includes a previously utilized method that combines spacecraft and satellite uncertainties from the same data set and a new algorithm for combining information from different data sets. Second, the filter setup used for uncertainty predictions is outlined. This includes the filter timing, data schedule and weights, parameters used, and filter outputs.

The final section of the memo describes the results of applying the filter and pointing uncertainty algorithm throughout the mission. An output of this process is a proposed list of times when the satellite ephemerides need to be updated. The pointing uncertainty validity throughout the tour is shown in a series of plots that indicate when requirements are not being met.

These sections were further divided into two segments. The analyses for the Saturn approach and the tour were conducted separately but only the tour results are presented here. This omission is to reduce the size of this paper and avoid confusion due to different assumptions and processes.

Computation of Pointing Uncertainty

The orbit determination program SIGMA was used to predict position uncertainties for the spacecraft and the Saturnian satellites. This information can then be used to compute the pointing uncertainty due to navigation errors. Two separate algorithms were used and are described below.

When the satellite ephemerides and the spacecraft ephemeris are the result of the same SIGMA filter run, the correlated information is used to predict the pointing. This case would be used when a late

spacecraft update is to be computed and both the spacecraft and satellite ephemerides are updated at the same time. The filter outputs in the RTN frame are used for this computation. These outputs include the relative position uncertainty of the spacecraft with respect to the satellite and this computation was done using the cross correlation of the two bodies in addition to their individual position uncertainties. This relative uncertainty is expressed in a matrix:

$$\Gamma^{sc,sat} = \begin{bmatrix} \Gamma_{rr} & \Gamma_{rt} & \Gamma_{rn} \\ \Gamma_{tr} & \Gamma_{tt} & \Gamma_{tn} \\ \Gamma_{nr} & \Gamma_{nt} & \Gamma_{nn} \end{bmatrix} \tag{1}$$

The square root of Γ_{rr} is the one-sigma uncertainty in the radial direction:

$$\sigma_{radial} = \sqrt{\Gamma_{rr}}\,. \tag{2}$$

The 2×2 lower right-hand submatrix of Γ contains information about the uncertainty ellipse perpendicular to the radial direction. The length of the semi-major axis of this ellipse is the maximum uncertainty in the perpendicular direction and is computed as the square root of the maximum eigenvalue of the ellipse.

$$\sigma_{perpendicular} = \sqrt{max\left(eigenvalue\left(\begin{bmatrix} \Gamma_{tt} & \Gamma_{tn} \\ \Gamma_{nt} & \Gamma_{nn} \end{bmatrix}\right)\right)}\,. \tag{3}$$

The pointing uncertainty is then computed as the ratio of the perpendicular uncertainty to an adjusted range value. This adjusted range is the reference range minus the satellite radius and one-sigma radial uncertainty:

$$pointing\ error_{sc,sat} = \frac{\sigma_{perpendicular}}{range_{sc,sat} - radius_{sat} - \sigma_{radial}}\,. \tag{4}$$

Figure 1 shows a pictorial representation of this ratio and shows how the pointing error is the perpendicular error divided by an adjusted range value.

When the satellite and spacecraft ephemerides are produced with different data cutoffs, the cross

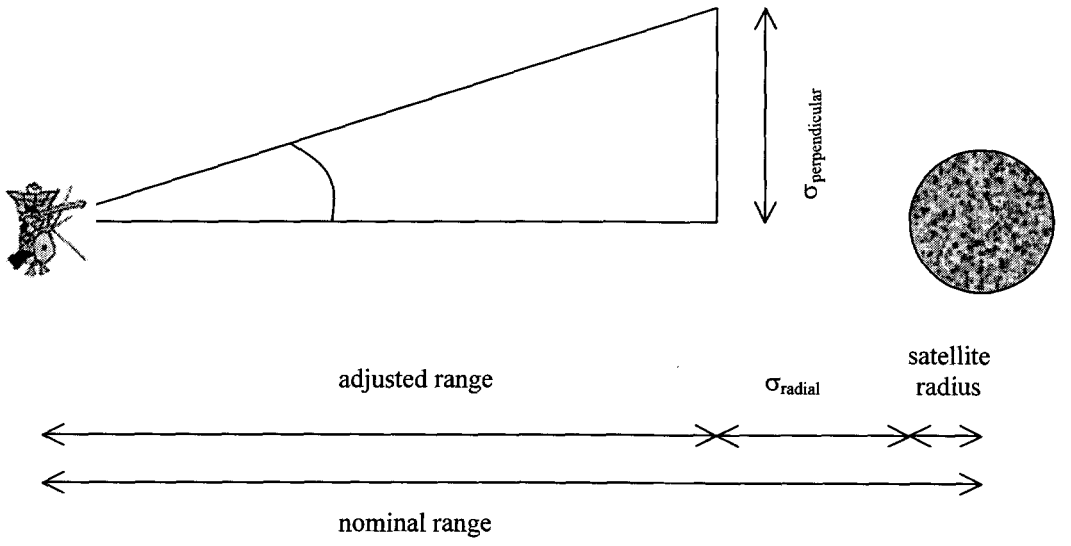


Figure 1: Diagram of Pointing Uncertainty Calculation

correlations are not defined. This is the more common instance that will occur during the tour. Perhaps only a handful of satellite updates will be made but many spacecraft updates will be computed. For this algorithm, the barycentric position uncertainties of the spacecraft and satellite are combined. The SIGMA run for a chosen maneuver solution to update the satellite ephemerides produces the position uncertainty of a satellite in Saturn barycentric EME 2000 coordinates at a given map or predicted time:

$$\Gamma^{sat} = \begin{bmatrix} \Gamma_{xx}^{sat} & \Gamma_{xy}^{sat} & \Gamma_{xz}^{sat} \\ \Gamma_{yx}^{sat} & \Gamma_{yy}^{sat} & \Gamma_{yz}^{sat} \\ \Gamma_{zx}^{sat} & \Gamma_{zy}^{sat} & \Gamma_{zz}^{sat} \end{bmatrix} \tag{5}$$

A separate SIGMA run for the maneuver being considered produces the position uncertainty of the spacecraft in the same barycentric EME 2000 coordinates at the same map time:

$$\Gamma^{sc} = \begin{bmatrix} \Gamma_{xx}^{sc} & \Gamma_{xy}^{sc} & \Gamma_{xz}^{sc} \\ \Gamma_{yx}^{sc} & \Gamma_{yy}^{sc} & \Gamma_{yz}^{sc} \\ \Gamma_{zx}^{sc} & \Gamma_{zy}^{sc} & \Gamma_{zz}^{sc} \end{bmatrix} \tag{6}$$

Note that no cross correlations between the spacecraft and satellite are present. These two position uncertainties can then be combined and rotated to a radial, transverse, and normal (RTN) coordinate frame:

$$\Gamma^{sc,sat} = R\left(\Gamma^{sc} + \Gamma^{sat}\right)R^T \tag{7}$$

where the rotation matrix R is defined as:

$$R = \begin{bmatrix} \hat{r} \\ \hat{t} \\ \hat{n} \end{bmatrix} = \begin{bmatrix} \dfrac{\left(\vec{r}_{sc} - \vec{r}_{sat}\right)}{\left|\vec{r}_{sc} - \vec{r}_{sat}\right|} \\ \hat{n} \times \hat{r} \\ \dfrac{\left(\vec{r}_{sc} - \vec{r}_{sat}\right) \times \left(\vec{v}_{sc} - \vec{v}_{sat}\right)}{\left|\left(\vec{r}_{sc} - \vec{r}_{sat}\right) \times \left(\vec{v}_{sc} - \vec{v}_{sat}\right)\right|} \end{bmatrix} \tag{8}$$

This matrix $\Gamma^{sc,sat}$ can then be used in Eqs (1)-(4). These equations compute a radial and perpendicular error. A conservative range value is computed by subtracting the uncertainty in the range and the satellite radius from the nominal range. The pointing error is the ratio of the perpendicular error and the adjusted range value.

Pointing Requirements

The navigation pointing requirements used throughout this analysis are 1.02 mrad for ranges between 20,000 and 30,000 km and 0.79 mrad for ranges above 30,000 km[7]. These values will typically be shown as a stair step line as the requirements change over time. These requirements are used for all 9 satellites during all phases of the mission.

Filter Setup

Tour Filter Times

A separate filter run was conducted for every maneuver. During the tour of Saturn these filter runs will be required for maneuver design and will be available for pointing updates. The data spanned from the beginning of the filter to a data cutoff point before the maneuver. The filter then continued past the data cutoff to compute the predicted uncertainty of the spacecraft and satellites. The end filter time varies depending on the maneuver. For maneuvers for which a satellite ephemeris update will be computed, the end filter time was beyond the beginning time of the next satellite ephemeris update. For maneuvers without a satellite ephemeris update, the end filter time was the time of the second subsequent maneuver. The time step chosen for predictions was 1 day nominally and 15 minutes near close approaches to satellites.

Table 1: Filter Timing

Timing Item	Tour Analysis
Begin Filter Span	Apoapse time before previous Saturn periapse
Data cutoff	2 days before the maneuver

End Filter Span	If maneuver OD is not being used for satellite ephemeris update time of second subsequent maneuver plus 2 days, otherwise time of next satellite ephemeris update implementation.
Start of uncertainty predictions	4 days after data cutoff
Prediction Time Step	15 minutes near flybys and 1 day otherwise

Data Schedule and Weights

Radiometric doppler and ranging data was simulated for the entire tour and weighted at 0.2 mm/s and 100 m respectively. The tracking schedule included daily passes alternating between Goldstone and Madrid. All data within 12 hours of a targeted flyby was removed because of science observations. During solar conjunction, data was deweighted and removed based on the Sun-Earth-Probe (SEP) angle. This information is summarized in Table 2.

Optical data was included using a Picture Sequence File (PSF) prepared by the navigation team. The data includes pictures of nine Saturnian satellites (Mimas, Enceladus, Tethys, Dione, Rhea, Titan, Hyperion, Iapetus, and Phoebe) and background stars. The optical data was weighted at 0.5 pixels for the satellites except for Titan, which was weighted at 1 pixel. The background stars were weighted at 0.25 pixels. This information is also presented in Table 2.

Table 2: Data Weights

	Doppler	Ranging	Satellites other than Titan	Titan	Background Stars
Normal weights	0.2 mm/s	100 m	0.5 pixels	1.0 pixels	0.25 pixels
SEP angle: 7.5° – 15.0°	1 mm/s	100 m			
SEP angle: 3.0° – 7.5°	5 mm/s	Deleted			
SEP angle: 0.0° – 3.0°	Deleted	Deleted			
Within 12 hours of targeted flyby	Deleted	Deleted			

Estimated, Stochastic, and Considered Parameters

The filter includes various estimated, stochastic, and considered parameters. The spacecraft dynamical model is adjusted by estimating the spacecraft state, antenna reflectivity, maneuvers (OTMs), and reaction control system (RCS) usage. The state includes the position and velocity of the spacecraft at the start of the filter. The RCS usage is designed to model the use of RCS instead of reaction wheels during targeted flybys to attain higher turn rates. This event is modeled as an impulsive maneuver at closest approach. The spacecraft dynamical model also includes uncorrelated stochastic accelerations computed every 8 hours that are intended to model forces caused by the radioisotope thermoelectric generators (RTG).

The dynamical model for the Saturnian system is adjusted by estimating various parameters for Saturn and the nine satellites. The Saturn parameters include the Saturn state, GM, J2, J4, and pole orientation. The satellite parameters are the states and GMs.

The observation model includes stochastic and considered parameters. For every optical picture three uncorrelated stochastic parameters, (RA, DEC and TWIST), are computed to adjust the direction and rotation of the picture to fit the satellite and background stars. The radiometric observation model includes considered parameters for the Earth-Moon barycenter, Earth polar motion and timing, troposphere, ionosphere, and station locations.

The apriori uncertainties for these parameters come from various sources. The spacecraft state, maneuvers, targeted flyby RCS usage, and antenna reflectivity apriori uncertainties are unchanged for each filter. The maneuver apriori matrices are the result of simulations using the nominal OD solution and are intended to model the expected variations from the nominal maneuver design[1,2]. The station location correlated matrix is the result of VLBI measurements and conventional and GPS surveys. The Saturn and satellite ephemeris, GM, J2, J4, and pole orientation terms apriori uncertainties are the post-fit uncertainties

of the data used for a previous fit. The first fit uses the apriori values from SAT077 and Claude Hildebrand's Phoebe solution.[4]

Table 3: Estimated, Stochastic, and Considered Parameter Uncertainties

Estimated Parameters	**Tour Apriori uncertainty**
Spacecraft state	150 m and 100 m/s
Maneuvers (3-axis magnitudes)	3×3 Covariance Matrices
Targeted Flyby RCS usage (3-axis magnitudes)	160 mm/s diagonal
Antenna reflectivity (specular and diffuse reflectivity coefficients)	0.0213 and 0.0158
Saturn state	DE405 planetary solution scaled by 5^2
Saturn GM, J2, J4, pole orientation	Uncertainty at apoapse as described below.
Satellite states & GMs	
Stochastic Parameters	
Spacecraft acceleration	4.5×10^{-12} km/s^2 in 3 axes
Camera pointing	1° in Right Ascension, Declination, and Twist angles.
Considered Parameters	
Earth-Moon barycenter	DE405 planetary solution formal covariance scaled by 5^2
Earth Polar Motion and Timing	10 cm per axis
Troposphere	1 cm for dry & 1 cm for wet
Ionosphere	5 cm for daytime & 1 cm for nighttime
Station Locations	Covariance determined from VLBI solutions and conventional and GPS surveys accurate to about 10 cm.

Satellite Uncertainty Processing

For tour analysis, the filter span for each maneuver begins at a previous apoapse and not at the beginning of the tour. This means that the filter does not include any optical or radiometric data before the beginning of the filter span. For the Saturnian dynamical model, this information needs to be available in the filter. The information is provided by the apriori covariance of the associated parameters. Obviously this covariance is not constant for each apoapse and improves throughout the tour as more data is applied. To provide these covariance matrices, a separate set of filter runs were conducted. For these auxiliary runs the filter setup was the same but with a different filter span and outputs. These filters began at apoapse and ended at the next apoapse and did not provide predicted uncertainty information. The output instead was the covariance for the Saturnian parameters at the end apoapse. This chain of filters began at Saturn Orbit Insertion (SOI) and proceeded with each output Saturnian covariance being used as the input Saturnian covariance for the next orbit revolution. The Saturnian covariance at each apoapse was saved and used as the apriori covariance for the primary filter runs described previously. This process was conducted by Rodica Ionasescu[5]. The initial Saturnian covariance used at SOI is the product of a previous Saturn Approach analysis by John Bordi[6].

Additional Filter Inputs

The trajectory and partial derivatives used for the spacecraft is intended to match the T2002-01 reference trajectory. To account for numerical errors in the integrator, the reference trajectory during the tour was integrated in pieces from each apoapse for 2 orbit revolutions. This short length is acceptable because the spacecraft trajectory is only mapping forward through two maneuvers, which is typically less than one orbit. For the cases when mapping through two maneuvers is beyond 2 orbits (e.g. OTM-24), the mapping ends at the end of the second orbit. The trajectory and partial derivatives used for the Earth and Saturn is the DE405 solution and the trajectory and partial derivatives used for the Saturnian satellites is SAT077 with a Phoebe solution created by Claude Hildebrand.

Filter Output

The filter was configured to provide two sets of uncertainties. The first set was the relative uncertainty of the spacecraft with respect to eight satellites in the RTN frame. The eight satellites used were Mimas, Enceladus, Tethys, Dione, Rhea, Titan, Hyperion, and Iapetus; Phoebe was removed due to a limitation in the number of mappings that SIGMA can compute. The radial direction is away from the satellite towards the spacecraft. The transverse direction is perpendicular to the radial direction and along the relative velocity vector. The normal direction is perpendicular to the orbit plane along the angular momentum direction and is also perpendicular to the radial and transverse directions.

The second set was the position uncertainty of the spacecraft and satellites with respect to the Saturn Barycenter oriented along the Earth Mean Equator of 2000. These two sets of position uncertainties were then used to compute the pointing uncertainty outside of SIGMA.

Tour Results

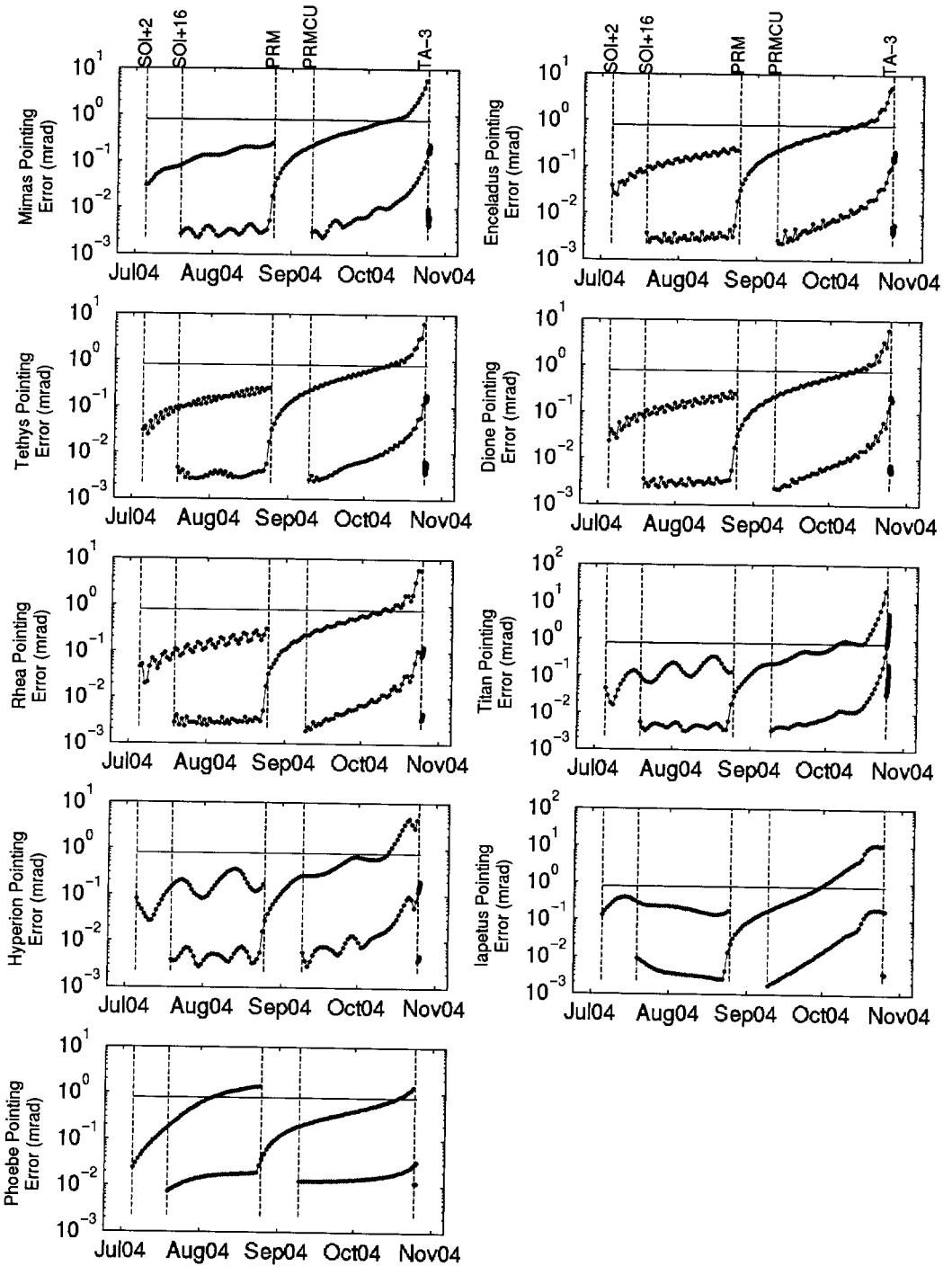
The previous sections of this memo have described the filter setup that is used and the pointing uncertainty algorithm that transforms the filter outputs into pointing errors. For every maneuver the filter was run with the appropriate data start and stop times. The filter produces both correlated RTN uncertainties and uncorrelated barycentric position uncertainties and these outputs are saved. A MATLAB script was prepared to read these filter outputs and apply the pointing uncertainty algorithm.

A set of satellite ephemerides update times was chosen and modified throughout the study and these times dictated which pointing algorithm was used for each maneuver filter. The satellite ephemeris update times used are shown in Table 4. For each update the table indicates the maneuver name, data cutoff time, and when this update was implemented. For the first four update times the impact of the update was considered to be instantaneous. This means that satellite and spacecraft ephemerides are to be updated within the four days and uploaded to the spacecraft and the correlated pointing uncertainty algorithm was used. For the final two satellite ephemerides updates a 15 week dwell period was used to allow time for replanning of the reference trajectory and observation planning. For all maneuvers other than the first four shown in Table 4, the uncorrelated pointing uncertainty was used. For these maneuvers the spacecraft position uncertainty for that maneuver was combined with the latest previous implementation date of a satellite ephemerides update. For example, a maneuver on January 12, 2006 would produce a spacecraft prediction uncertainty that would be combined with a satellite prediction uncertainty from the E2-6 filter run.

Table 4: Proposed Satellite Ephemerides Update Times for Tour

Maneuver Name	Data cutoff date	Implementation Date
SOI+2 days	July 1, 2004	July 5, 2004
TA-3	October 21, 2004	October 25, 2004
TB-3	December 8, 2004	December 12, 2004
TC+2	January 14, 2005	January 19, 2005
E2-6	July 6, 2005	November 3, 2005
Post T24 Apoapse	February 5, 2007	May 26, 2007

The result of this algorithm is the pointing uncertainty for each satellite that is a function of time. An example plot of these results is shown in Figure 2. For this plot the satellite ephemerides are updated at the SOI+2 and TA-3 maneuvers but the spacecraft ephemeris is updated at each of the five listed maneuvers (SOI+2, SOI+16, PRM, PRMCU, and TA-3). The pointing requirement is also depicted in the figure.



All x–ticks for first of indicated month

Figure 2: Predicted Pointing Uncertainty During First Orbit of Saturn

All of the pointing uncertainties and requirements can be combined to produce a chart for when the requirements are not met. These charts are shown in Figures 3-8 and have the following characteristics:

- The x-axis indicates time during the tour
- The y-axis indicates a maneuver number.
- The shaded bar shows the time period for which the pointing information is valid. A bar may be discontinuous during times of close approaches to satellites.
- The shaded bar for each maneuver has been collapsed to bottom of the chart to show a combined interval of valid pointing predictions.
- Some of the maneuver names are provided at the beginning of the bar. The maneuver names are in the typically defined as relative to a satellite flyby. A letter defines the satellite flyby (Enceladus, Dione, Rhea, Hyperion, or Iapetus), a number or letter defines which flyby, and then the number of days is given. The nomenclature has undergone various alterations, but a '-3' maneuver is three days before a flyby.
- The tick marks attached to the shaded bar that extend vertically denote endpoints of the shaded bar. Areas with multiple tick marks are accurate but difficult to interpret on this time scale.
- The diamond symbol indicates a maneuver OD that will be used for updating of satellite ephemeris.
- The square symbol indicates when the satellite ephemeris is implemented and the time is indicated.

The results indicate that the pointing requirements are being met for the vast majority of the tour. The updates for TA and TB are required because of the pointing requirements during the Titan flyby. Some highlights of these figures include:

- The pointing may fail after a flyby and before the information from the next maneuver is available. This can be seen after many of the Titan flybys.
- The probe mission pointing is not met by using the OD delivery from the ODM maneuver. This fact is already known and probe mission pointing will be addressed as a separate issue by the navigation team.
- During extended periods of no maneuvers, the pointing fails. This can be seen in the time after Titan 5, Titan 20, and Titan 36. This problem can be easily remedied by providing additional spacecraft solutions during these times.
- The first four satellite ephemeris updates are considered instantaneous. This was done to come close to meeting the pointing requirements for flybys early in the tour; Titan A and Titan B will require late satellite ephemeris updates. The first update at SOI was chosen for convenience of analysis and will most likely be performed prior to SOI.

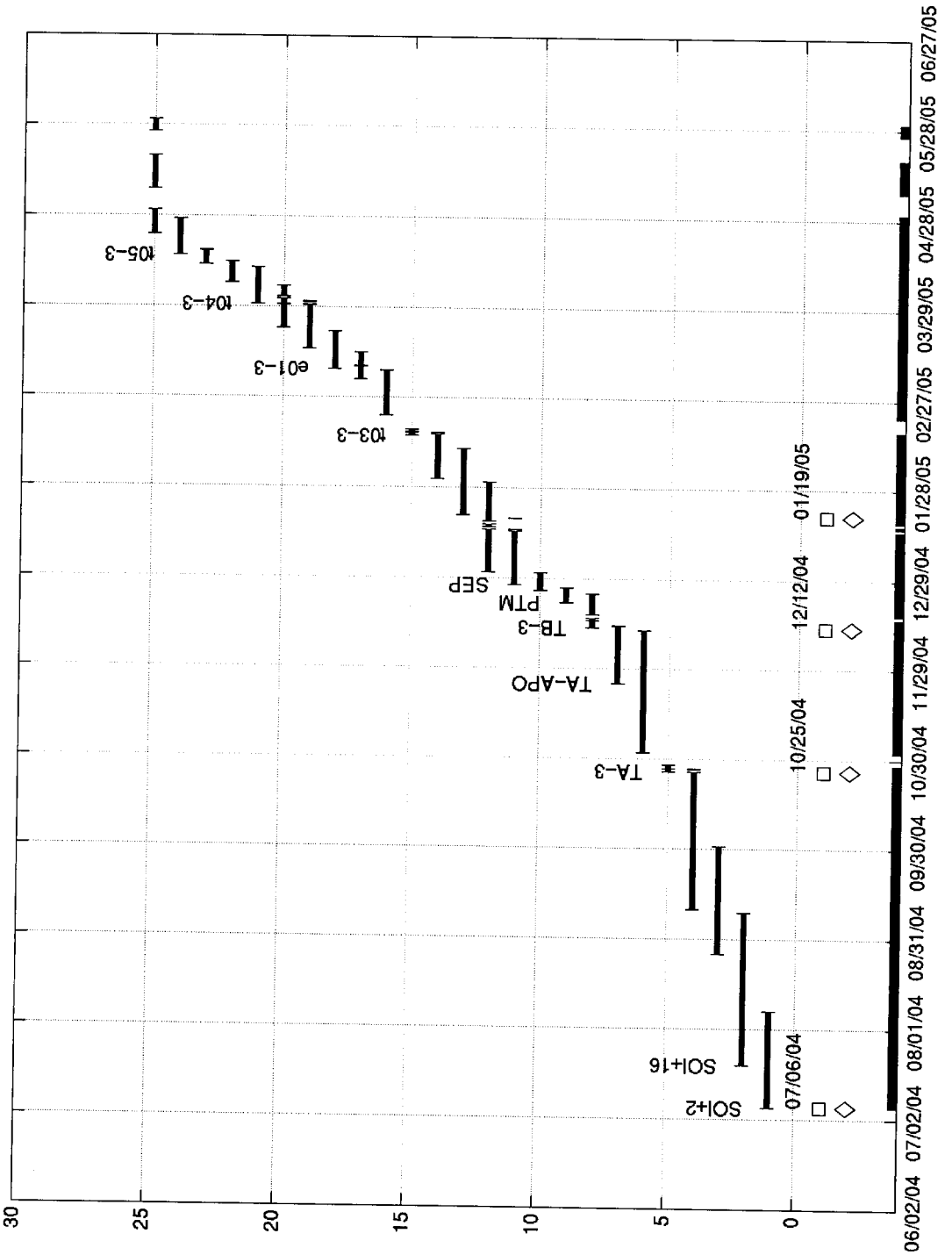


Figure 3: Time Periods of Meeting Navigation Pointing Requirements (6/2/04 – 6/27/05)

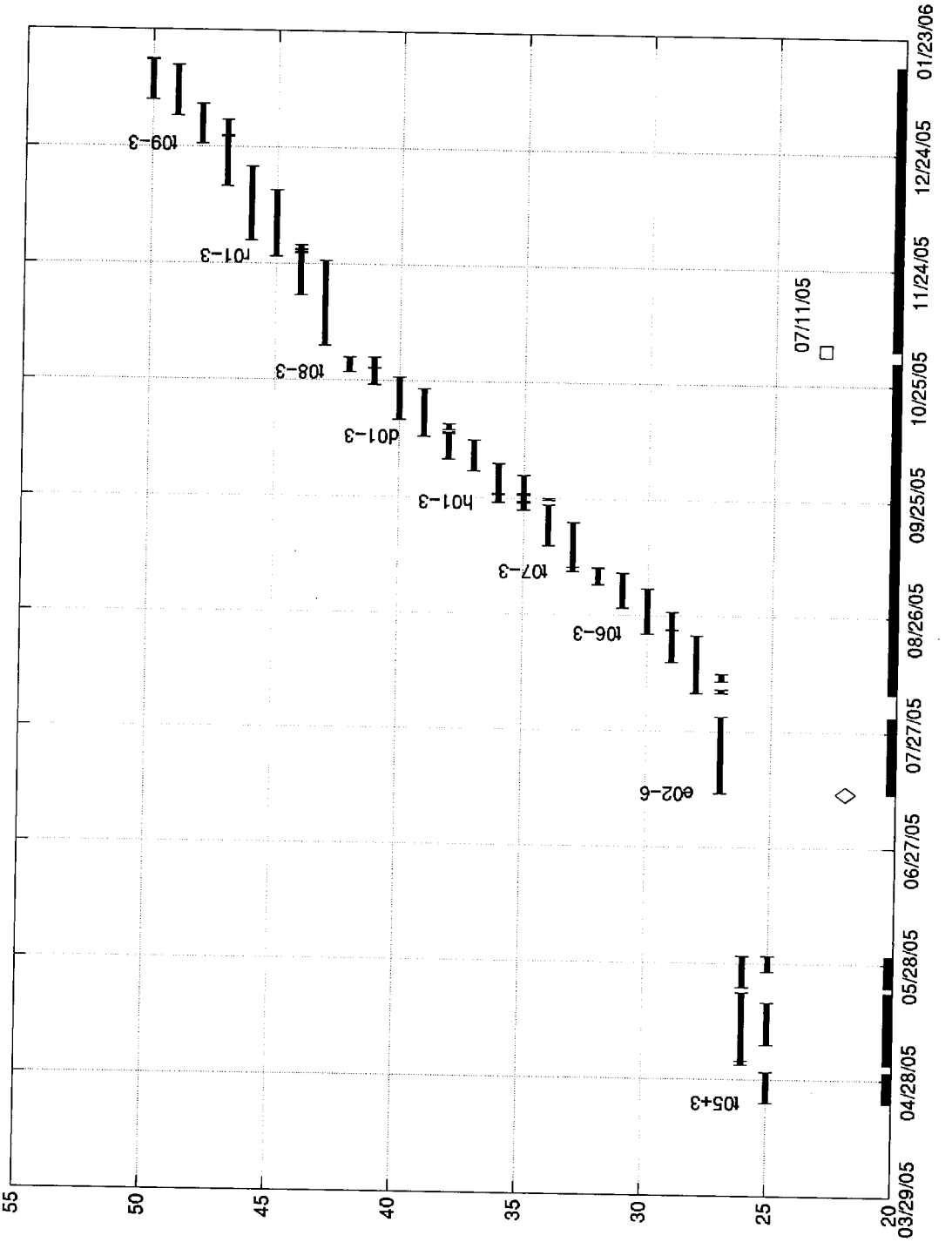


Figure 4: Time Periods of Meeting Navigation Pointing Requirements (3/29/05-1/23/06)

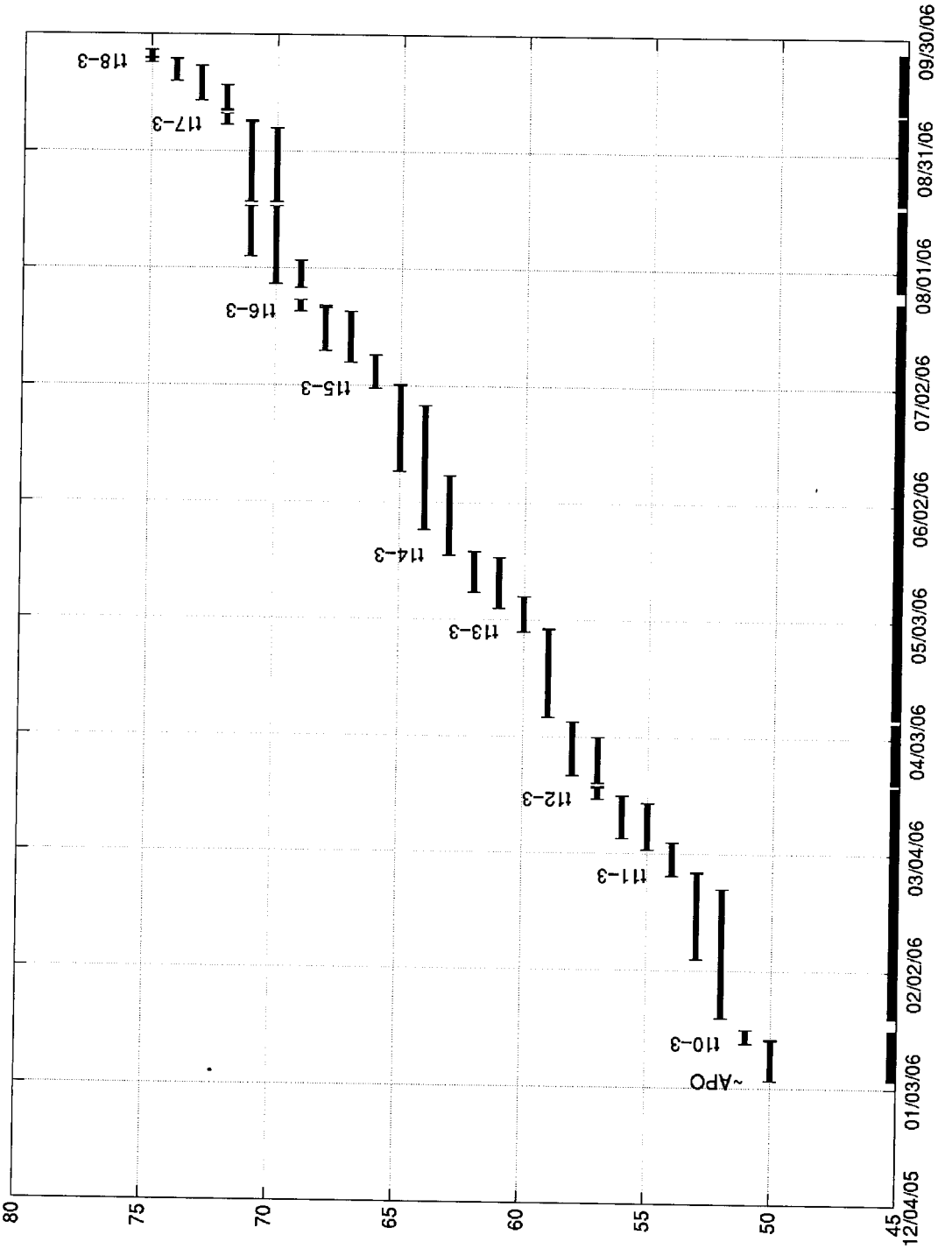


Figure 5: Time Periods of Meeting Navigation Pointing Requirements (12/4/05-9/30/06)

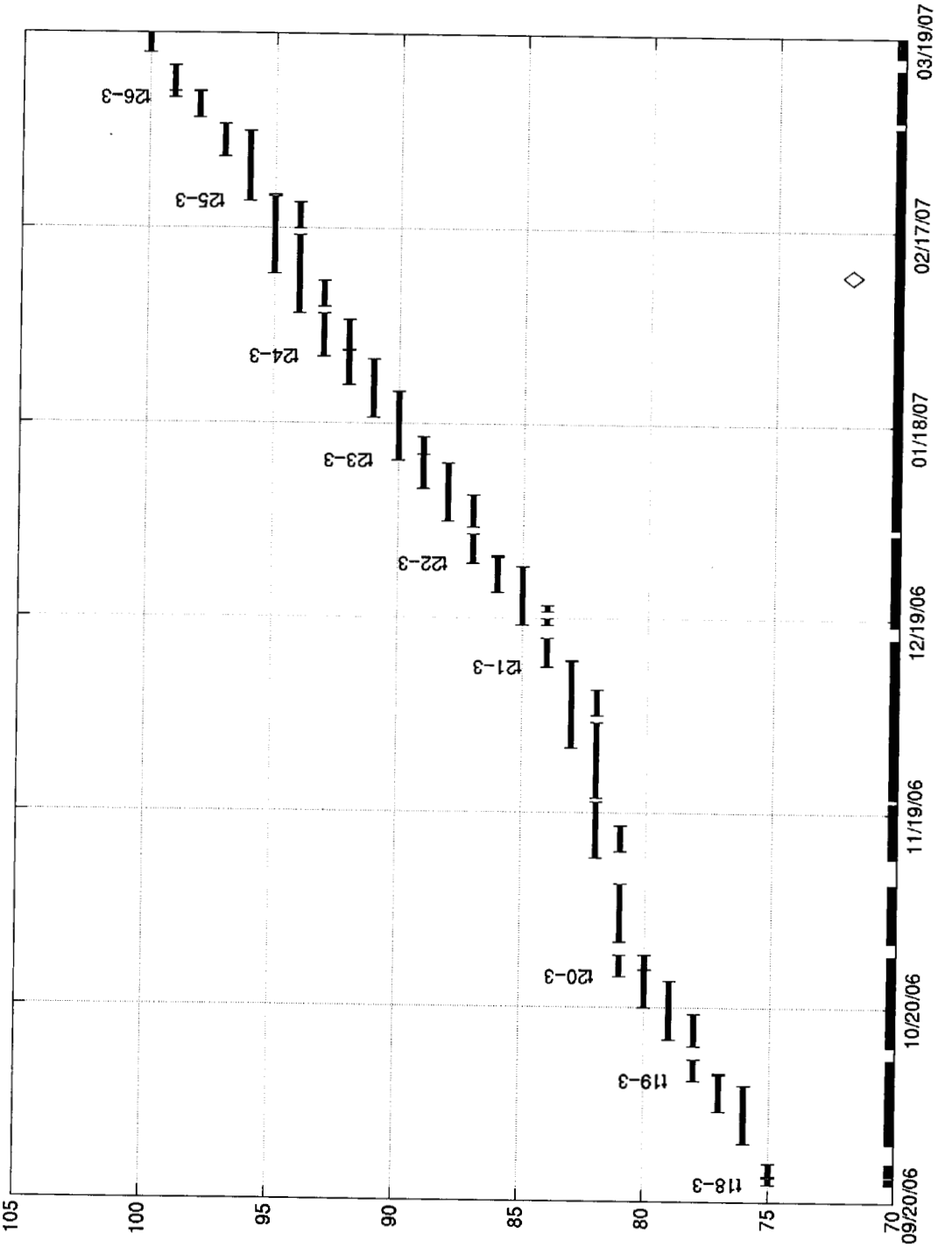


Figure 6: Time Periods of Meeting Navigation Pointing Requirements (9/20/06-3/19/07)

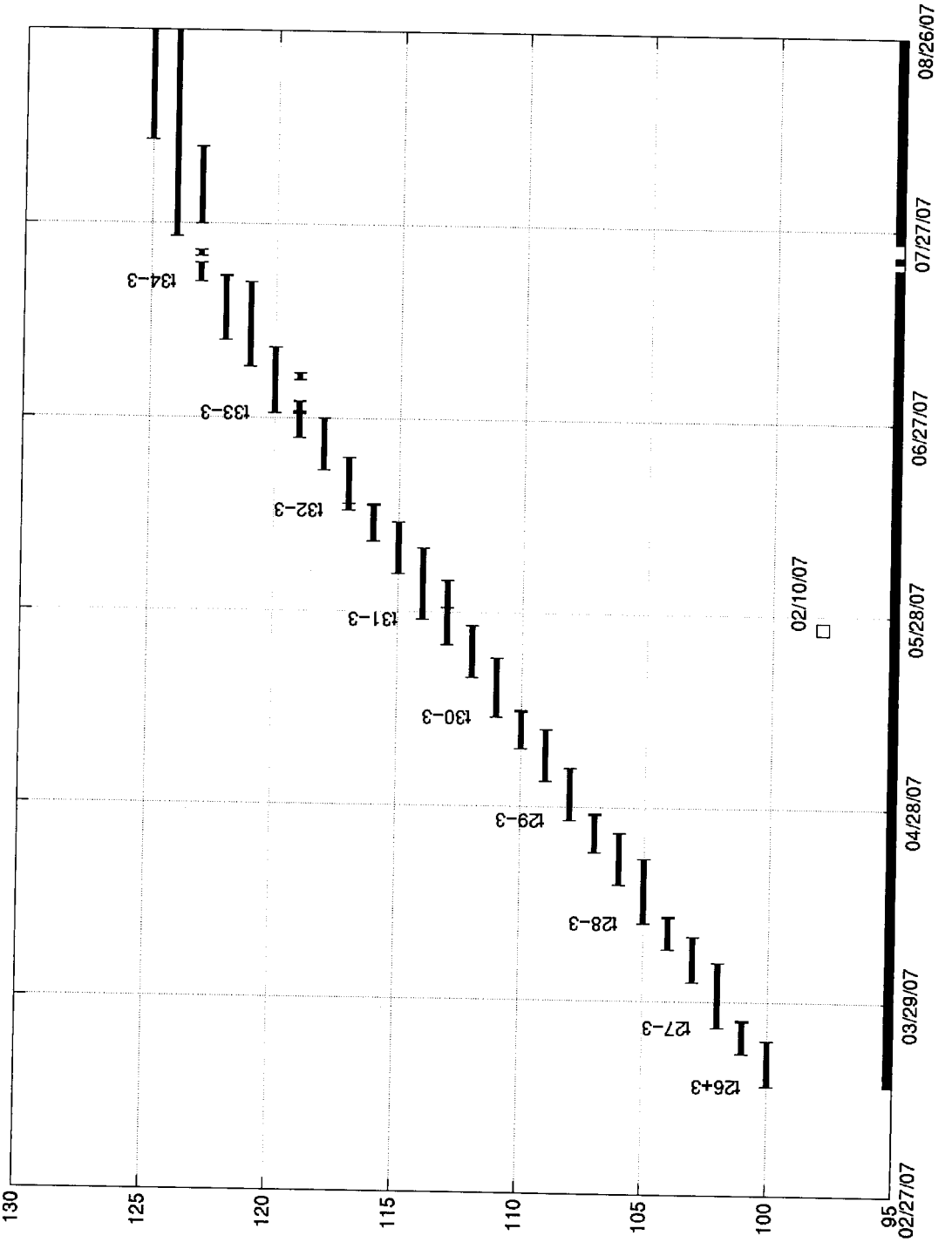


Figure 7: Time Periods of Meeting Navigation Pointing Requirements (2/27/07-8/26/07)

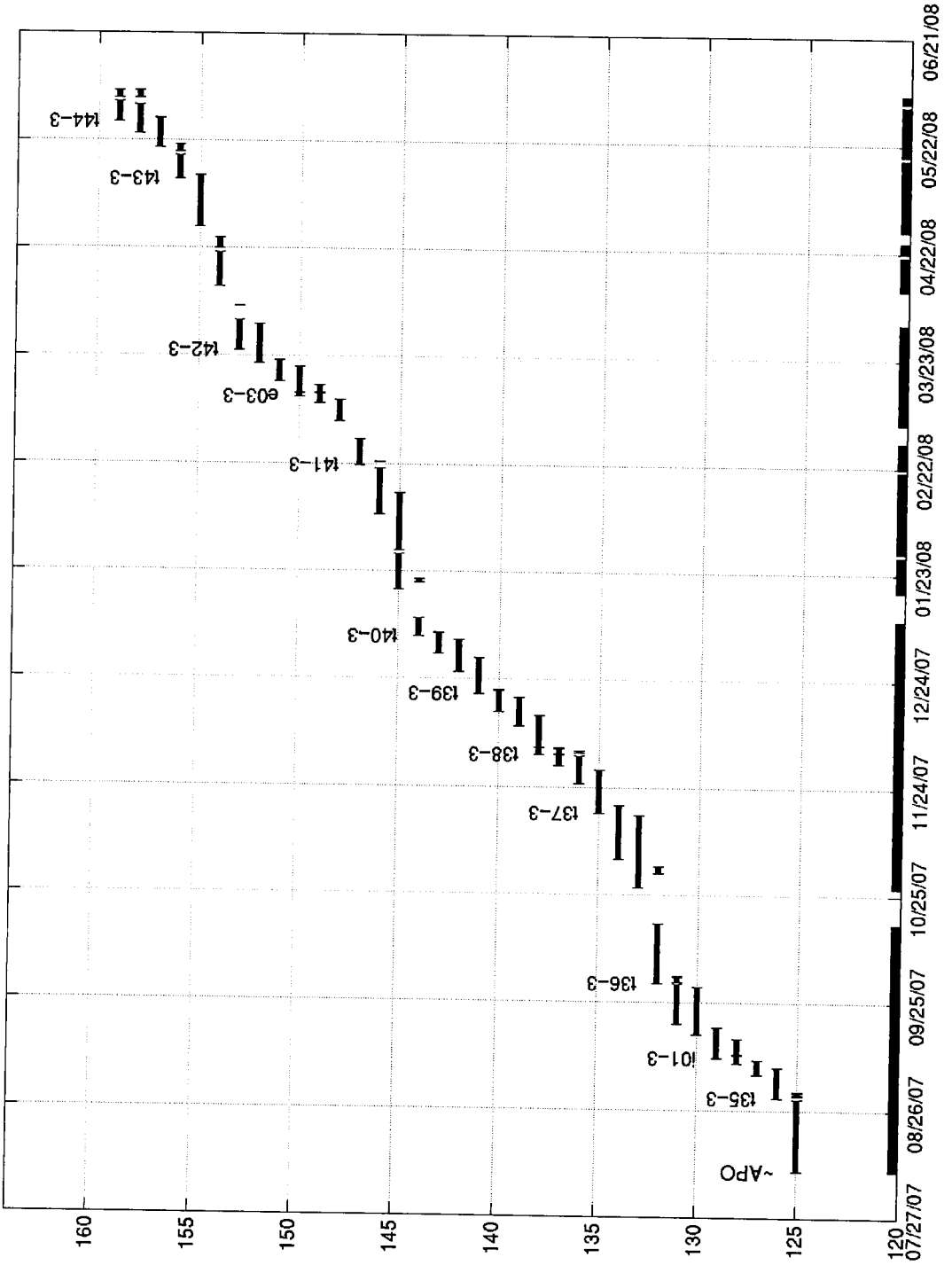


Figure 8: Time Periods of Meeting Navigation Pointing Requirements (7/27/07-6/21/08)

Conclusions

The pointing requirements due to navigation error can be met for most of the tour. The current set of maneuvers already defines a set of orbit determination solutions that can be used to meet requirements for a large portion of the tour. In addition, areas of non-compliance during times of a low frequency of maneuvers can easily be covered with additional solutions. Unfortunately, some time periods after Titan flybys may have uncorrectable violations of requirements. This paper also outlines a preliminary set of satellite ephemeris update times. These times will be used for further iteration based on the expectations and abilities of the science and spacecraft teams.

Acknowledgements

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