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THE PLANNING OF OPTICAL NAVIGATION PICTURES FOR THE CASSINI EXTENDED MISSION.

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This paper describes the optical navigation image (opnav) planning for the Cassini extended mission, which includes nine low-altitude flybys of the icy satellites including seven of Enceladus, one of Dione and one of Rhea. Two of the Enceladus flybys have closest approach altitudes at or below 50 km. We present studies showing how much the uncertainties in the Enceladus ephemeris can be reduced by the inclusion of opnavs in the orbit determination. We show that the planned opnavs will maintain the precision of the satellite ephemerides to support the close flybys, cover periods of poor radiometric data during solar conjunctions, and provide a backup data type during the short periods between the two double flybys (where an icy satellite is flown by immediately preceding or following a Titan flyby, and Titan alone is targeted). The processes and software needed to compute the windows of observing opportunity for each satellite, making the initial selection of targets, and refining the selections in response to changes in the tour design during the process are dealt with. Opnavs often conflict with proposed science observations. The process for resolving these conflicts is described. The distribution and timing of opnavs in the extended mission navigation plan is presented to show that the plan meets the needs stated above. The need to periodically replan (mostly repoint) pictures during the extended mission in response to reference trajectory updates is explored and it is shown that the same techniques used to plan the opnavs can be used to replan them.

1. THE EXTENDED MISSION OPTICAL NAVIGATION PICTURE PLANNING PROCESS

Cassini-Huygens is the fourth spacecraft to visit the Saturn system. It was the first to be captured into orbit about that planet. The highly succesful execution of the very complex prime mission (PM), the high quality of the science returned, the expectation that there is much more to learn about Saturn and the fact that there will be plenty of propellant left over at the end of the PM (July 1, 2008) led NASA Headquarters to authorize the planning of a two-year Cassini Extended Mission (XM). The XM trajectory includes 27 targeted Titan flybys (T45–T71) and 9 close icy/rocky satellite flybys. Seven of these (E4–E10) are of Enceladus, one is of Rhea and one is of Dione. The satellite flybys and stellar occultations by satellites were the main drivers of the XM trajectory design [1].

Optical navigation picture planning started as soon as an XM reference trajectory for the spacecraft was made available (July 9, 2007). The Cassini optical navigation planning software was used to select optical navigation targets observable from the spacecraft. The first step was to generate a file of observation request windows for each satellite. This is described in more detail later in this section. A Fortran program called PLANIT (via a Linux script called plan) was used to display available satellites during observation periods during the XM. These intervals were chosen to start at the end of a downlink or end at the beginning of a downlink. (These are periods of approximately

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nine hours each day when the spacecraft is Earth-pointed to return science and houskeeping telemetry to the Earth.) The next step was to generate a list containing observation request periods (start and end times) and numbers of pictures per request. This list contained several hundred entries. Each one was then scrutinized using PLANIT and a target chosen out of the several satellites available at each time. PLANIT was also used to adjust the pointing of each chosen picture to ensure that bright stars were present in each one for accurate inertial pointing. The output of PLANIT was a picture list file of putative picture names, observation times, right ascensions and declinations that was then converted, using another script called VERSEQ, to a picture sequence file containing the picture times, expected satellite image centers (in Cassini Narrow Angle camera [NAC] camera coordinates), expected star centers and the expected picture pointing. The picture sequence file was the deliverable between the optical navigation analyst and the analyst carrying out the OD covariance study. It is also the means by which actual satellite image centers are communicated to the operations OD team. (For a description of this process see [2] and references therein.) It was necessary to iterate this process a number of times. Request windows were added or deleted from the observation request file and the updated picture file by hand-editing and replanning carried out using a script called REDO that runs a Fortran program called REPLAN. REPLAN is very similar to PLANIT, except that it uses the picture list generated in the previous step. All the above routines call a Fortran program (TGP) that finds target coordinates from interpolation of the reference trajectory, and planetary and satellite ephemerides. The above scripts are identical to those used in the prime mission except that they use the XM windows file and that the XM version of VERSEQ also adds the optical data weights to the picture sequence file used in prime mission operations.

REDO and VERSEQ will also be used to tweak the pictures selections or pointings during the XM, in response to updates to the reference trajectory and/or satellite and planetary ephemerides.

In mid-August 2007 all 14 Cassini instrument and navigation teams started entering a preliminary list of observation requests into the Cassini Information Management System (CIMS) [2]. The opnav navigation list was the same as the one in the picture sequence file. This step was automated by the use of a script and Fortran program that converted the observing request file into an XML file containing the entries required by CIMS to describe each request. This was uploaded to the database once.

The five main Cassini science disciplines, icy/rocky satellites (Mimas, Enceladus, Tethys, Dione, Rhea, Hyperion, Iapetus and Phoebe), Titan, Saturn Magnetosphere (Mag), Rings, and Saturn atmospheric science (Saturn) are represented respectively by the Saturn Orbiter Science Team (SOST), Titan Orbiter Science Team (TOST), the Mag Target Working Team (TWT), Rings TWT, and Saturn TWT. Strawman observing schedules, including Opnavs, are negotiated and refined in consultation with representatives of all the teams at weekly TWT meetings. A major responsibility of the TWTs is determination of the spacecraft attitude waypoints from which all observations must start and to which they must return. Opnavs are scheduled between downlinks and waypoints. [2]. Waypoints are frequently chosen to maximize science return for one or more science instruments. Becuase the Optical Navigation team plans its own waypoint turns it has no special attitude requirements and accepts the waypoints generated by the TWTs. By this means the science observations and opnavs are integrated orbit by orbit. These will be assembled into sequences of thirty to forty days over the next two years. The sequence boundaries were determined by the science planning team before the above process started.

The first subsequence (S42) of the XM is scheduled for delivery to the Cassini project on February 20, 2008. It must contain the final targets and turns to the targets, waypoints and downlinks. These will be available from the TWTs by January 25. A 95% complete pointing design must be completed in the 26 days between then and February 20. Changes will made between then and June 14, 2008 primarily in response to the need to minimize wear and tear on the spacecraft's reaction wheels. S42 starts execution July 2, 2008 at 19:08 UTC. This aggressive sequence development schedule is typical of the extended mission.

Table 1 Start and End Times of the Covariance Study Tour Legs

Leg	*ET Start and End Dates*		*Leg*	*ET Start and End Dates*	
s01	05-MAY-2008	14-MAY-2008	s34	09-JAN-2009	19-JAN-2009
s02	14-MAY-2008	21-MAY-2008	s35	19-JAN-2009	28-JAN-2009
s03	21-MAY-2008	29-MAY-2008	s36	28-JAN-2009	17-FEB-2009
s04	29-MAY-2008	15-JUN-2008	s37	07-FEB-2009	20-FEB-2009
s05	05-JUN-2008	12-JUN-2008	s38	20-FEB-2009	13-MAR-2009
s06	12-JUN-2008	19-JUN-2008	s39	03-MAR-2009	15-MAR-2009
s07	19-JUN-2008	26-JUN-2008	s40	15-MAR-2009	27-MAR-2009
s08	26-JUN-2008	13-JUL-2008	s41	27-MAR-2009	14-APR-2009
s09	03-JUL-2008	10-JUL-2008	s42	04-APR-2009	16-APR-2009
s10	10-JUL-2008	17-JUL-2008	s43	16-APR-2009	12-MAY-2009
s11	17-JUL-2008	25-JUL-2008	s44	02-MAY-2009	17-MAY-2009
s12	25-JUL-2008	31-JUL-2008	s45	17-MAY-2009	12-JUN-2009
s13	31-JUL-2008	18-AUG-2008	s46	02-JUN-2009	17-JUN-2009
s14	08-AUG-2008	15-AUG-2008	s47	17-JUN-2009	13-JUL-2009
s15	15-AUG-2008	22-AUG-2008	s48	03-JUL-2009	18-JUL-2009
s16	22-AUG-2008	30-AUG-2008	s49	18-JUL-2009	13-AUG-2009
s17	30-AUG-2008	16-SEP-2008	s50	03-AUG-2009	19-AUG-2009
s18	06-SEP-2008	14-SEP-2008	s51	19-AUG-2009	18-SEP-2009
s19	14-SEP-2008	21-SEP-2008	s52	08-SEP-2009	12-OCT-2009
s20	21-SEP-2008	28-SEP-2008	s53	02-OCT-2009	23-OCT-2009
s21	28-SEP-2008	16-OCT-2008	s54	23-OCT-2009	11-NOV-2009
s22	06-OCT-2008	13-OCT-2008	s55	11-NOV-2009	30-NOV-2009
s23	13-OCT-2008	20-OCT-2008	s56	30-NOV-2009	18-DEC-2009
s24	20-OCT-2008	28-OCT-2008	s57	18-DEC-2009	13-JAN-2010
s25	28-OCT-2008	14-NOV-2008	s58	03-JAN-2010	19-JAN-2010
s26	04-NOV-2008	12-NOV-2008	s59	19-JAN-2010	14-FEB-2010
s27	12-NOV-2008	20-NOV-2008	s60	04-FEB-2010	22-FEB-2010
s28	20-NOV-2008	28-NOV-2008	s61	22-FEB-2010	12-MAR-2010
s29	28-NOV-2008	15-DEC-2008	s62	12-MAR-2010	29-MAR-2010
s30	05-DEC-2008	13-DEC-2008	s63	29-MAR-2010	17-APR-2010
s31	13-DEC-2008	21-DEC-2008	s64	17-APR-2010	18-MAY-2010
s32	21-DEC-2008	31-DEC-2008	s65	08-MAY-2010	26-MAY-2010
s33	31-DEC-2008	19-JAN-2009	s66	26-MAY-2010	11-JUN-2010
—-	———————	———————	s37	11-JUN-2010	27-JUN-2010

2. OPTICAL NAVIGATION PICTURE SCHEDULE

Three optical picture sequence files were provided, based on the 070918 [1] reference trajectory, for use in the OD covariance study for the XM. They were used to determine whether the inclusion of optical navigation pictures would reduce targeting errors at the flybys and if they could be used to control satellite ephemeris errors. The first schedule included opnav requests approximately every four days. This was considered to be a good starting point because the spacecraft orbital periods are often rough multiples of four days. This rate of picture taking would provide several optical data samples per orbit. A second picture schedule was supplied with 20 extra requests (approx. 60 pictures) around the solar conjunction periods (herein referred to as the "full" schedule) in 2008 and 2009. A third schedule was created with approximately half the opnav request frequency of the second schedule (herein called the "half" schedule); except around the solar conjunction periods, where all the pictures in the second schedule were retained. The final choice of schedule was intimately related to the tour legs chosen in the covariance study. For this reason the following discussion is presented in terms of the tour legs. Their start and end times are given in table 1. The optical navigation picture schedule is presented in table 2.

Large numbers of pictures at approximately regular intervals of longitude are not needed in the XM to determine the satellite orbits because, except for the long period variations in the orbital longitudes of Mimas, Tethys, Dione, Enceladus, their ephemerides are now very well determined. It is shown in section 6 that a relatively low frequency of opnavs, compared to the PM phases around Saturn orbit insertion, will be sufficient to mitigate against secular buildup of ephemeris errors.

We continue, with the exceptions described below, to follow the prime mission philosophy of negotiating for generic observing time rather than specific pictures [3]. The picture schedules provided for the covariance analyses contained the best choices we could make for individual targets at this time.

The main purpose of the opnavs is to maintain the ephemerides of Mimas, Enceladus, Tethys, Dione and Rhea through the XM. The bulk of the observations are of the inner satellites because they have short periods (0.94, 1.4, 1.9, 2.7 and 4.5 days resp.) requiring observations at relatively short intervals. Hyperion, Iapetus and Phoebe have periods of 21.3, 79.3 and 550.3 days [**?**] and will will not require ephemeris maintenance. Covariance studies show that these satellites' ephemeris uncertainities do not grow significantly over the XM if opnavs of them are not included in the orbit determination.

The following criteria were applied to the selection of each picture.

1) Saturn's limb should be greater than one diagonal NAC field of view (8.7 milliradians) from the satellite limb. This prevents image contamination by Saturn light scattered off the elements of the NAC optical system into its focal plane.

2) The satellite image diameter should be smaller than 392 pixels. A 300-pixel buffer is placed around the image to prevent it being partially outside the NAC frame if the actual and expected pointing differ.

3) The satellite image diameter should be larger than 20 pixels for Mimas, Enceladus, Tethys, Dione, Rhea and Titan, 15 pixels for Hyperion, 50 pixels for Iapetus, and zero for Phoebe. This ensures that their images have enough pixels for accurate centroiding.

4) Pictures cannot be taken when the spacecraft is inside the E-ring (latitude should be greater

Table 2 Optical Navigation Picture Schedule

Request Date	*UTC of 1st Obs.*	*1st Target*	*2nd Target*	*3rd Target*
2008-JUL-03	16:07	Mimas	Rhea	Enceladus
2008-JUL-18	2:16	Mimas	Enceladus	Dione
2008-JUL-24	2:01	Tethys	Hyperion	Rhea
2008-JUL-25	14:53	Mimas	Enceladus	Dione
2008-JUL-27	7:22	Mimas	Enceladus	Hyperion
2008-JUL-29	14:37	Mimas	Hyperion	Iapetus
2008-AUG-01	14:40	Enceladus	Dione	Tethys
2008-AUG-03	0:55	Mimas	Enceladus	Dione
2008-AUG-05	17:45	Enceladus	Enceladus	Iapetus
2008-AUG-07	6:40	Enceladus	Iapetus	Rhea
2008-AUG-09	14:10	Mimas	Enceladus	Iapetus
2008-AUG-12	14:12	Mimas	Dione	
2008-AUG-17	13:40	Enceladus	Dione	Enceladus
2008-AUG-19	13:40	Tethys	Mimas	Enceladus
2008-AUG-21	13:25	Mimas	Tethys	Rhea
2008-AUG-23	19:57	Mimas	Enceladus	
2008-AUG-24	6:10	Hyperion	Iapetus	Iapetus
2008-AUG-27	13:10	Enceladus	Tethys	Rhea
2008-AUG-29	5:25	Enceladus	Tethys	Rhea
2008-AUG-31	5:42	Tethys	Dione	
2008-SEP-01	5:10	Enceladus	Tethys	Rhea
2008-SEP-02	5:10	Enceladus	Dione	Mimas
2008-SEP-07	5:10	Enceladus	Rhea	Mimas
2008-SEP-08	5:12	Rhea	Iapetus	
2008-SEP-11	4:25	Tethys	Dione	Enceladus
2008-SEP-12	4:40	Iapetus	Mimas	Enceladus
2008-SEP-14	12:10	Enceladus	Mimas	Iapetus
2008-SEP-16	12:12	Mimas	Tethys	
2008-SEP-18	4:35	Mimas	Enceladus	Enceladus
2008-SEP-20	11:40	Tethys	Dione	Rhea
2008-SEP-21	11:40	Tethys	Dione	Enceladus
2008-SEP-24	4:12	Iapetus	Mimas	
2008-SEP-28	11:11	Enceladus	Tethys	Dione
2008-OCT-02	3:00	Hyperion	Mimas	
2008-OCT-06	10:56	Enceladus	Tethys	Rhea
2008-OCT-10	10:58	Enceladus	Enceladus	
2008-OCT-14	10:27	Dione	Tethys	Dione
2008-OCT-18	10:29	Tethys	Dione	
2008-OCT-22	2:27	Dione	Rhea	Hyperion
2008-OCT-26	2:30	Iapetus	Mimas	
2008-OCT-30	9:28	Mimas	Mimas	Tethys
2008-NOV-04	9:16	Iapetus	Dione	
2008-NOV-07	8:59	Dione	Enceladus	Hyperion
2008-NOV-11	9:01	Hyperion	Enceladus	
2008-NOV-15	1:00	Enceladus	Iapetus	Mimas
2008-NOV-20	8:33	Enceladus	Mimas	
2008-NOV-23	14:40	Mimas	Enceladus	
2008-NOV-27	8:03	Dione	Tethys	
2008-DEC-01	13:47	Dione	Rhea	Enceladus
2008-DEC-06	7:35	Iapetus	Tethys	
2008-DEC-09	13:18	Iapetus	Enceladus	Phoebe
2008-DEC-13	7:06	Phoebe	Mimas	
2008-DEC-17	12:49	Enceladus	Tethys	Phoebe
2008-DEC-22	6:22	Rhea	Enceladus	
2008-DEC-26	22:20	Enceladus	Tethys	Hyperion
2008-DEC-29	22:23	Tethys	Dione	
2009-JAN-02	5:36	Tethys	Enceladus	
2009-JAN-06	5:39	Dione	Rhea	
2009-JAN-10	5:07	Rhea	Enceladus	Iapetus
2009-JAN-14	21:25	Iapetus	Hyperion	
2009-JAN-18	4:23	Enceladus	Enceladus	Rhea
2009-JAN-22	20:56	Tethys	Hyperion	
2009-JAN-27	3:54	Dione	Rhea	Enceladus
2009-JAN-30	20:26	Phoebe	Mimas	
2009-FEB-03	3:25	Enceladus	Mimas	Iapetus
2009-FEB-08	3:27	Mimas	Iapetus	
2009-FEB-11	2:55	Mimas	Enceladus	Tethys
2009-FEB-16	2:43	Tethys	Dione	
2009-FEB-19	2:26	Dione	Rhea	Mimas

Table 2 Optical Navigation Picture Schedule, continued

Request Date	*UTC of 1st Obs.*	*1st Target*	*2nd Target*	*3rd Target*
2009-FEB-23	2:28	Dione	Rhea	
2009-FEB-28	1:41	Rhea	Enceladus	Iapetus
2009-MAR-03	18:13	Iapetus	Phoebe	
2009-MAR-07	1:11	Mimas	Enceladus	Tethys
2009-MAR-11	1:13	Enceladus	Dione	
2009-MAR-15	17:11	Dione	Rhea	Enceladus
2009-MAR-19	0:43	Rhea	Hyperion	
2009-MAR-22	0:11	Phoebe	Hyperion	Phoebe
2009-MAR-27	23:58	Dione		
2009-MAR-28	0:26	Rhea		
2009-MAR-29	23:41	Dione		
2009-MAR-30	0:05	Enceladus	Mimas	
2009-APR-04	23:27	Iapetus	Phoebe	
2009-APR-07	22:55	Mimas	Enceladus	Tethys
2009-APR-12	5:12	Tethys	Dione	
2009-APR-16	22:24	Dione	Rhea	Hyperion
2009-APR-20	22:26	Iapetus	Phoebe	
2009-APR-24	21:54	Mimas	Enceladus	Dione
2009-APR-28	4:10	Dione	Rhea	
2009-MAY-02	13:53	Rhea	Hyperion	Iapetus
2009-MAY-06	21:24	Iapetus	Phoebe	
2009-MAY-10	20:52	Mimas	Rhea	Tethys
2009-MAY-14	3:08	Dione	Rhea	
2009-MAY-18	12:36	Rhea	Iapetus	Mimas
2009-MAY-22	20:07	Hyperion	Phoebe	
2009-MAY-26	19:35	Mimas	Dione	Enceladus
2009-JUN-01	22:21	Enceladus	Dione	
2009-JUN-03	11:33	Mimas	Enceladus	Tethys
2009-JUN-07	19:05	Phoebe	Phoebe	
2009-JUN-11	1:02	Mimas	Enceladus	Dione
2009-JUN-15	18:34	Enceladus	Tethys	
2009-JUN-19	10:31	Enceladus	Rhea	Hyperion
2009-JUN-23	16:48	Iapetus	Phoebe	
2009-JUN-27	0:00	Enceladus	Tethys	Dione
2009-JUL-01	17:32	Dione	Tethys	
2009-JUL-05	9:29	Enceladus	Tethys	Dione
2009-JUL-09	16:01	Hyperion	Phoebe	
2009-JUL-12	9:29	Enceladus	Rhea	Iapetus
2009-JUL-13	8:58	Enceladus	Tethys	Dione
2009-JUL-17	9:00	Dione	Rhea	
2009-JUL-21	8:27	Dione	Enceladus	Phoebe
2009-JUL-25	8:27	Iapetus	Hyperion	Iapetus
2009-JUL-27	8:29	Mimas	Dione	
2009-JUL-29	7:57	Mimas	Enceladus	Tethys
2009-AUG-02	15:28	Iapetus	Enceladus	
2009-AUG-06	14:56	Tethys	Dione	Enceladus
2009-AUG-12	14:57	Enceladus	Enceladus	
2009-AUG-14	14:25	Enceladus	Tethys	Mimas
2009-AUG-18	14:27	Dione	Enceladus	
2009-AUG-22	20:25	Enceladus	Hyperion	Hyperion
2009-AUG-26	22:49	Tethys		
2009-AUG-27	23:39	Dione		
2009-AUG-30	6:10	Tethys	Enceladus	Dione
2009-SEP-03	13:41	Enceladus	Enceladus	
2009-SEP-05	19:39	Enceladus	Dione	Rhea
2009-SEP-07	19:24	Rhea	Dione	Tethys
2009-SEP-09	19:24	Enceladus	Dione	Mimas
2009-SEP-11	13:11	Rhea	Hyperion	
2009-SEP-13	12:54	Tethys	Enceladus	Iapetus
2009-SEP-15	12:39	Iapetus	Phoebe	Enceladus
2009-SEP-21	12:24	Mimas	Mimas	Rhea
2009-SEP-23	12:09	Enceladus	Enceladus	Dione
2009-SEP-25	12:09	Mimas	Enceladus	Dione
2009-SEP-28	4:41	Mimas	Enceladus	
2009-SEP-30	18:09	Enceladus	Dione	Hyperion
2009-OCT-02	4:09	Mimas	Tethys	Dione
2009-OCT-04	17:54	Enceladus	Tethys	Iapetus
2009-OCT-06	4:26	Enceladus	Tethys	
2009-OCT-09	3:55	Dione	Iapetus	Dione

Table 2 Optical Navigation Picture Schedule, continued

Request Date	*UTC of 1st Obs.*	*1st Target*	*2nd Target*	*3rd Target*
2009-OCT-13	3:57	Iapetus	Iapetus	
2009-OCT-17	17:10	Mimas	Enceladus	Dione
2009-OCT-21	17:12	Tethys	Dione	
2009-OCT-22	16:55	Enceladus	Mimas	Dione
2009-OCT-25	2:55	Dione	Enceladus	Dione
2009-NOV-03	2:26	Mimas	Dione	Enceladus
2009-NOV-06	2:29	Dione	Rhea	
2009-NOV-10	2:26	Mimas	Dione	Hyperion
2009-NOV-10	15:57	Rhea	Hyperion	Mimas
2009-NOV-14	15:59	Tethys	Rhea	
2009-NOV-22	15:30	Tethys	Dione	
2009-NOV-26	0:59	Tethys	Rhea	Mimas
2009-NOV-30	1:01	Dione	Rhea	
2009-DEC-04	0:30	Mimas	Iapetus	Hyperion
2009-DEC-08	14:32	Hyperion	Iapetus	
2009-DEC-13	0:01	Iapetus	Mimas	Enceladus
2009-DEC-16	0:03	Enceladus	Tethys	
2009-DEC-19	23:32	Enceladus	Dione	
2009-DEC-20	0:19	Rhea		
2009-DEC-24	13:34	Dione	Iapetus	
2009-DEC-28	23:03	Iapetus	Enceladus	Tethys
2010-JAN-01	23:06	Tethys	Dione	
2010-JAN-05	22:34	Mimas	Tethys	Mimas
2010-JAN-09	12:37	Iapetus	Iapetus	
2010-JAN-13	22:05	Dione	Rhea	Hyperion
2010-JAN-17	22:08	Dione	Mimas	
2010-JAN-21	21:36	Mimas	Tethys	Rhea
2010-JAN-25	11:24	Tethys	Rhea	
2010-JAN-29	21:07	Rhea	Mimas	Enceladus
2010-FEB-03	4:25	Enceladus	Rhea	
2010-FEB-07	3:53	Dione	Rhea	Hyperion
2010-FEB-10	20:25	Mimas	Hyperion	
2010-FEB-14	19:54	Mimas	Enceladus	Dione
2010-FEB-18	3:26	Enceladus	Tethys	
2010-FEB-22	2:54	Enceladus	Dione	Rhea
2010-FEB-26	9:26	Enceladus	Iapetus	
2010-MAR-06	8:57	Rhea	Dione	
2010-MAR-10	18:25	Enceladus	Tethys	Mimas
2010-MAR-14	8:12	Mimas	Tethys	
2010-MAR-18	17:40	Hyperion	Iapetus	Hyperion
2010-MAR-22	7:42	Iapetus	Enceladus	
2010-MAR-29	7:55	Mimas	Rhea	Tethys
2010-MAR-30	16:57	Mimas	Tethys	Rhea
2010-APR-03	6:25	Tethys	Rhea	Iapetus
2010-APR-07	6:49	Rhea	Hyperion	
2010-APR-8	6:25	Dione		
2010-APR-11	16:10	Dione	Rhea	Enceladus
2010-APR-15	23:41	Enceladus		
2010-APR-16	0:09	Mimas		
2010-APR-19	5:24	Dione	Tethys	Rhea
2010-APR-22	23:11	Mimas	Dione	
2010-APR-26	22:39	Hyperion	Phoebe	Hyperion
2010-APR-28	14:54	Enceladus	Tethys	Dione
2010-MAY-01	22:10	Dione	Hyperion	Enceladus
2010-MAY-05	21:53	Rhea	Enceladus	Mimas
2010-MAY-09	21:54	Mimas	Enceladus	
2010-MAY-13	3:37	Enceladus	Tethys	Dione
2010-MAY-17	3:39	Iapetus	Enceladus	
2010-MAY-21	20:51	Phoebe	Mimas	Enceladus
2010-MAY-25	3:08	Mimas	Tethys	
2010-MAY-29	2:35	Tethys	Mimas	Rhea
2010-JUN-02	12:52	Tethys	Phoebe	
2010-JUN-06	19:49	Mimas	Enceladus	
2010-JUN-6	20:36	Rhea		
2010-JUN-11	12:20	Enceladus	Dione	
2010-JUN-14	1:33	Tethys	Dione	Rhea
2010-JUN-18	11:19	Hyperion	Iapetus	
2010-JUN-22	18:47	Hyperion	Enceladus	Enceladus
2010-JUN-26	18:48	Dione	Rhea	
2010-JUN-30	0:31	Rhea	Phoebe	Dione

than 3 degrees and distance to Saturn greater than 542,410 km). The E-ring extends from the orbit of Mimas to near the orbit of Rhea (mean radius 527,040 km). It consists of microscopic ice and dust particles that make up a highly absorbing and scattering medium resulting in reduced contrast between the target and the background.

5) The satellite image should be separated (in the picture) by at least ten pixels from the F-ring. This prevents the satellite being confused photometrically with the F-ring resulting in centroids biased toward it or centroiding failure.

6) The satellite solar phase angle should be less than 120 degrees (90 degrees for Phoebe). Image centers measured at larger phase angles are unreliable.

7) The solar limb should be more than 15 degrees from the Cassini Composite Infrared Imaging Spectrometer (CIRS) boresight. This is a flight rule intended to protect CIRS from damage due to overillumination. It also protects the NAC which shares the CIRS boresight.

8) The Sun-Earth-Spacecraft angle should be more than 3 degrees. This constraint prevents scheduling opnavs during Solar conjunctions when the spacecraft is Earth-pointed and quiescent.

When these constraints are combined, a set of satellite observing windows results. The first step in the planning process was to generate these windows based upon the 070918 reference trajectory and the satellite and planetary ephemerides used to construct it.

The distribution of acceptable Enceladus picture opportunities can be found by counting the number of Enceladus observing windows that overlap potential opnav request periods. These may be just before a downlink or immediately after one. The list of overlaps was then grouped by tour leg. Opnav requests were, for this simple analysis, assumed to be 90 minutes long. It was also assumed that there would be a maximum of one picture of Enceladus per request period becuase a second picture of the same satellite only 15 minutes after the first does not add significantly to our knowledge of the orbit of that satellite. Turns were included to the first target and from the last target to the waypoint. Thus, opnav observing periods are shorter than the request periods by the total turn time. Opnav turns in the prime mission typically take 15 to 25 minutes. The 25 minute turn will be more common in the XM becuase turn rates will be reduced for slews greater than 60 degrees. This simplifies the sequence integration process by adding extra turn time to avoid the need for reintegration due to reference trajectory updates. The accuracy of this analysis can be judged by comparing the distribution of picture opportunities in figure 1 with the distribution of those selected. This is shown in figure 3.

There are 91 potential observation periods that coincide with observation windows (51 before downlinks and 40 after them) between tour legs s10 and s67, if the average turn time is 15 minutes. The distribution is plotted in figure 1. The number of opportunities drops to 65 if turns of 25 minutes duration are assumed. There are 105 planned Enceladus pictures between s10 and s67. From figure 1 it can be seen that there are no good opportunities to support E4, E5, or E6 with opnavs in the tour legs containing the DCOs for those flybys.

Detailed pointing designs and flight rules checking of each XM sequence will be carried out only weeks from sequence uplink to the spacecraft. The XM planning process provided an opportunity to plan pictures well enough to provide good input to this process. This included adjusting pointing so that at least two reasonably bright stars were in each picture. This avoids ambiguity in the estimated angle of rotation about the direction perpendicular to the image plane. The same data weights, dependent upon the target's apparent diameter, were applied to the predicted centers as are applied

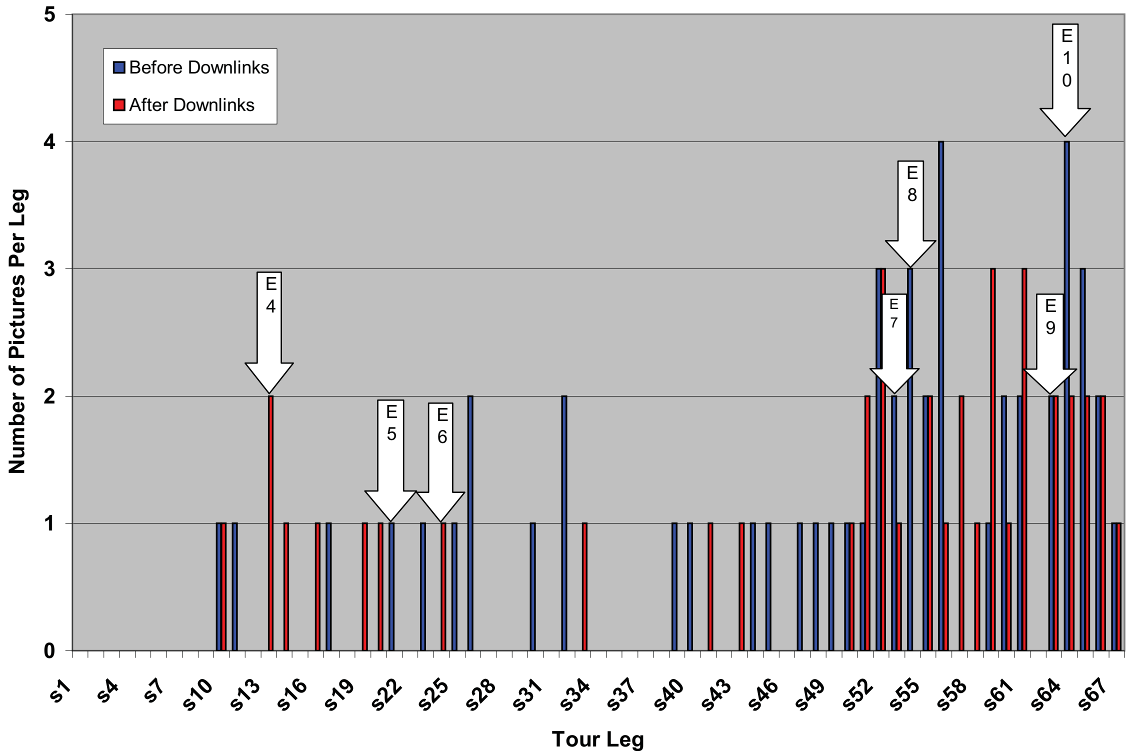

Figure 1 Distribution of Enceladus picture opportunities before downlinks (red bars) and after downlinks (blue bars) in each tour leg. The arrows indicate the legs containing the OD data cutoff for each Enceladus flyby.

to the measured centers in operations.

During the prime mission it was determined that satellite centroids should be weighted proportionally to the image diameter. This was motivated by the fact that the weights applied to the opnav data (measured satellite image centers) when it was combined with the radiometric data during operations OD analysis were consistently larger than center-finding internal errors. Pixel and line components of the centroid are weighted equally according to equation 1

$$\epsilon = (f^2 + (dD)^2 + (s\epsilon_i)^2)^{1/2} \tag{1}$$

where ϵ is the weight, ϵ_i is the error in the measured center calculated by the centerfinding software, f is a minimum value of ϵ, d is a factor scaling the predicted apparent diameter D and s scales ϵ_i.

The constants f, d, and s were determined from inspection of the differences between optical estimates of satellite centers and predictions from the satellite ephemeris (which is influenced over short time spans more by the radiometric tracking data than the optical data). The minimum, f, is set to 0.25 pixel for all the satellites except Hyperion, for which a minimum of 0.5 pixel is used. Stars are given a minimum of 0.1 pixel because their positions are known very accurately. The coefficient s is set to zero for the satellites and unity for the stars. This replaces the internal centerfinding errors for the satellites with an estimate of the errors arising from the varying size of the body. These are almost always larger than the internal errors. When these are larger they are kept. The values of d for the satellites are roughly inversely proportional to their physical radii. See Table 3. The parameter, d, is set to zero for the stars. This reflects the fact that stars have no size and that their errors are photometric and not astrometric.

Table 3 Satellite Apparent Diameter Data-Weighting Scale Factors

Satellite	*Radius (km)*	*Scale Factor, d*
Hyperion	110	0.06
Phoebe	110	0.04
Mimas	196	0.02
Enceladus	250	0.015
Tethys	530	0.01
Dione	560	0.01
Rhea	765	0.01
Iapetus	730	0.02
Titan	2575	0.02

The obvious exceptions to this observation are listed at the bottom of Table 3. Titan has a very extensive atmosphere with multiple detached cloud layers above the optical limb. Iapetus, as alreday mentioned, has a 1:10 variation in its albedo.

Opnavs were included near the solar conjunctions in 2008 and 2009 when the Sun-Earth-probe angle will be less than $15°$. The frequency of picture requests was increased to approximately one per two days to act as a backup data type in the case of loss or systematic corruption of radiometric tracking data during solar conjunction.

Titan was dropped as an opnav target due to centering errors up to 12.5 pixels (approx 270 km). These were much larger than the 25–50 km estimated prior to launch [5].This is probably due to the haze layers in Titan's atmosphere. A fuller discussion of this issue can be found in [2]. Hyperion is also difficult to analyze because of its chaotic rotation. Titan will not be used in the extended mission and pictures of Hyperion will be taken approximately monthly to maintain its ephemeris. The use of Iapetus will also be minimized because it has a 1:10 variation in its albedo (between the Cassini Regio and the rest of its surface) that is not reflected in the weighting scheme.

Phoebe will continue to be 10 to 12 million km distant. The inner stallites are nearer, have much larger apparent motions, and will be more useful for daily navigation of Cassini. Errors in Phoebe's ephemeris have very little effect on the ephemerides of the other satellites or the spacecraft. There are no flybys of this satellite planned for the XM. Pictures of Phoebe will be taken approximately once a month to maintain its ephemeris. The distribution of satellites observations is shown in figure 2.

The results presented elsewhere in this document used a picture schedule derived in two parts. The first part contains the already-integrated observations from May 5 to July 1, 2008 that are in the prime mission. This included a section from May 31 to July 1, 2008 (sequence 41) that was re-integrated because it is the overlap between the PM and the XM. The section from July 1, 2008 to June 30, 2010 (sequences 42–61) was generated using the philosophy described above. Requests of 1.25 hours (two pictures) alternating with request of 1.5 hours (three pictures) were timed to end at the starts of downlinks given in the Mission Planning strawman downlink schedule [6].

The operational picture schedule will differ from the one discussed here as requests are moved to accommodate high-value science, particularly at Saturn periapses. Typically, these involve moving

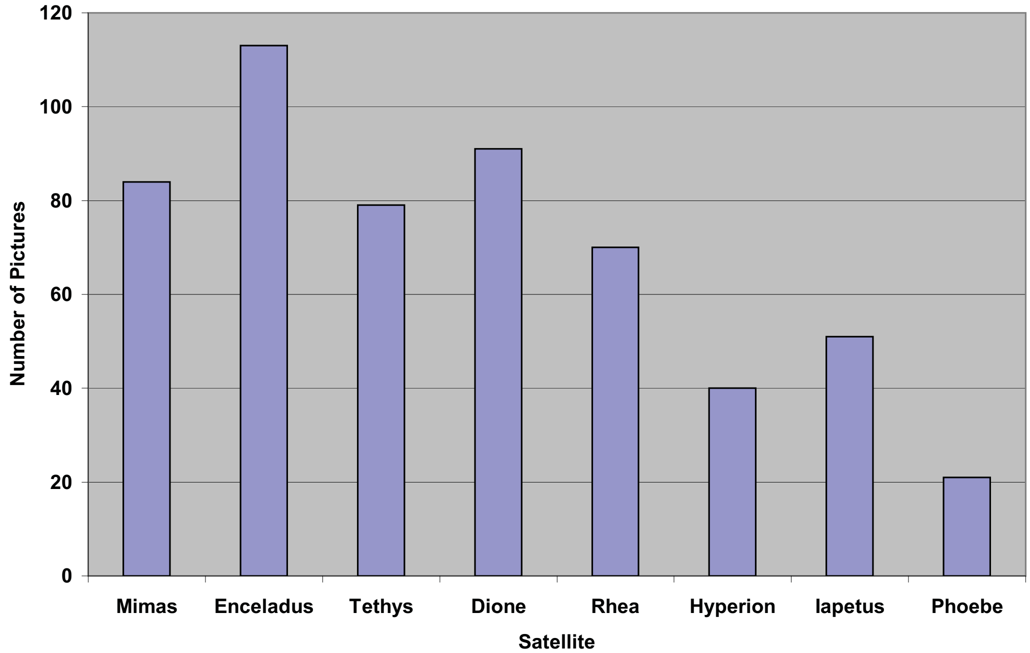

Figure 2 Distribution of Opnav Observations of Satellites.

a request to an adjacent downlink. Since no requests have been identified that must be executed at a particular date and time, all the opnav requests can be moved by a day or so with no adverse effects to navigation. Changes will continue to be made as the target working teams integrate the remainder of the extended mission. There will also be target changes within requests in response to reference trajectory updates during the XM.

Covariance studies presented in section 3 show that the Enceladus ephemeris errors grow between flybys. The RSS 30-day prediction uncertainty, with radiometric data only, rises from 0.5 km at Enceladus-6 flyby (October 31, 2008) to 1.6 km at Enceladus-7 (November 2, 2009). This "runoff" can be to reduced to 1.3 km at E7 by the addition of pictures of Enceladus in this period. Thus approximately half (52) of the Enceladus pictures in the XM are concentrated in this period. Enceladus pictures are included between May 17, 2009 and October 23, 2009 to reduce ephemeris runoff. They peak between September 8, 2009 and October 2, 2009 in the period prior to E7 when the runoff peaks.

Enceladus-4 (August 11, 2008) is the first flyby of the XM and is one of the closest. The OD data-cutoff (DCO) for this flyby is on August 6, 2008. It is supported by seven pictures of Enceladus in the 20 days prior to the DCO. Five of these are in the 10 days before the event. The distribution of pictures is broken down by satellite in figures 3, 4, 5, and 6.

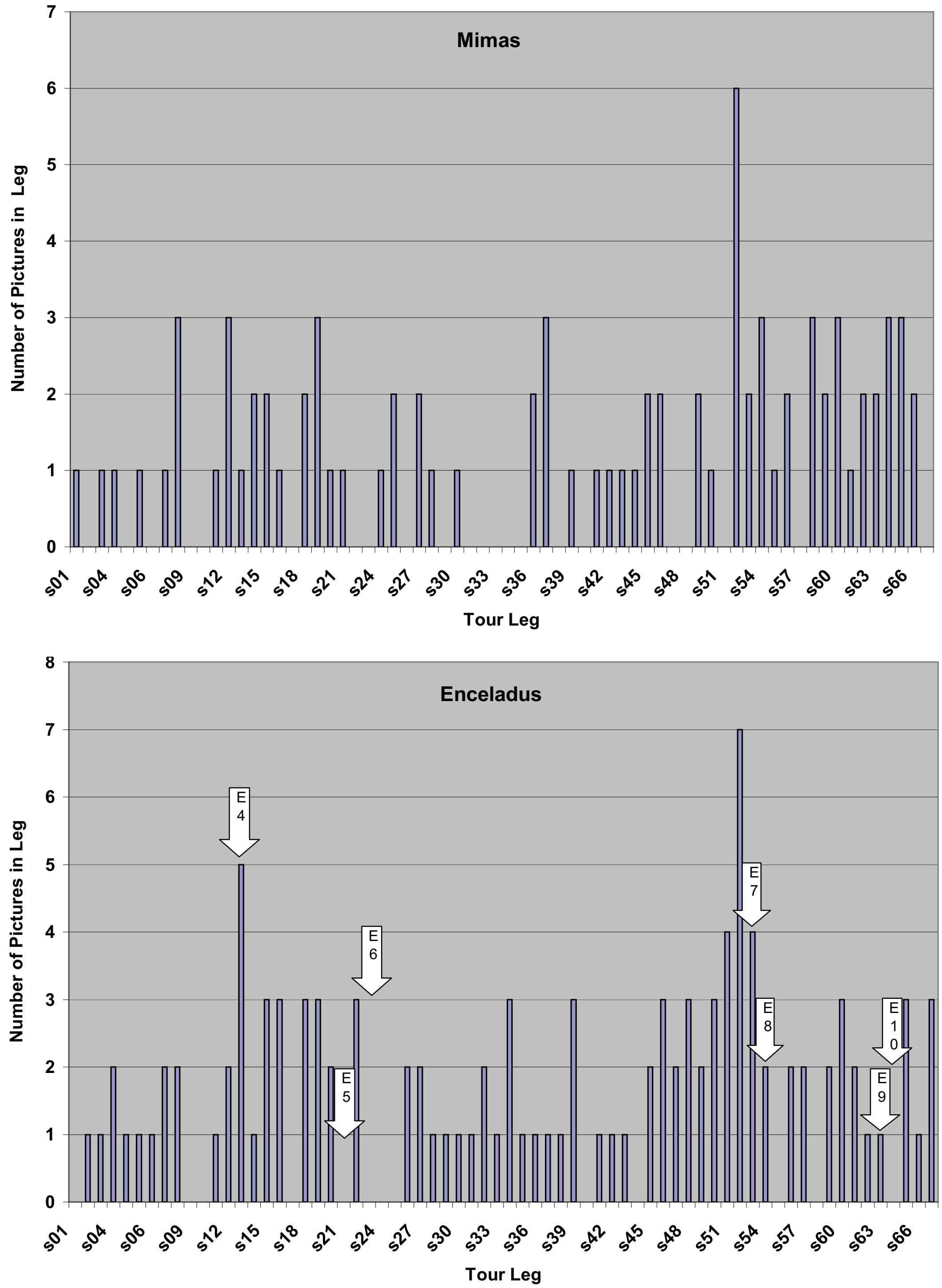

Figure 3 Distribution of Opnavs of Mimas and Enceladus.

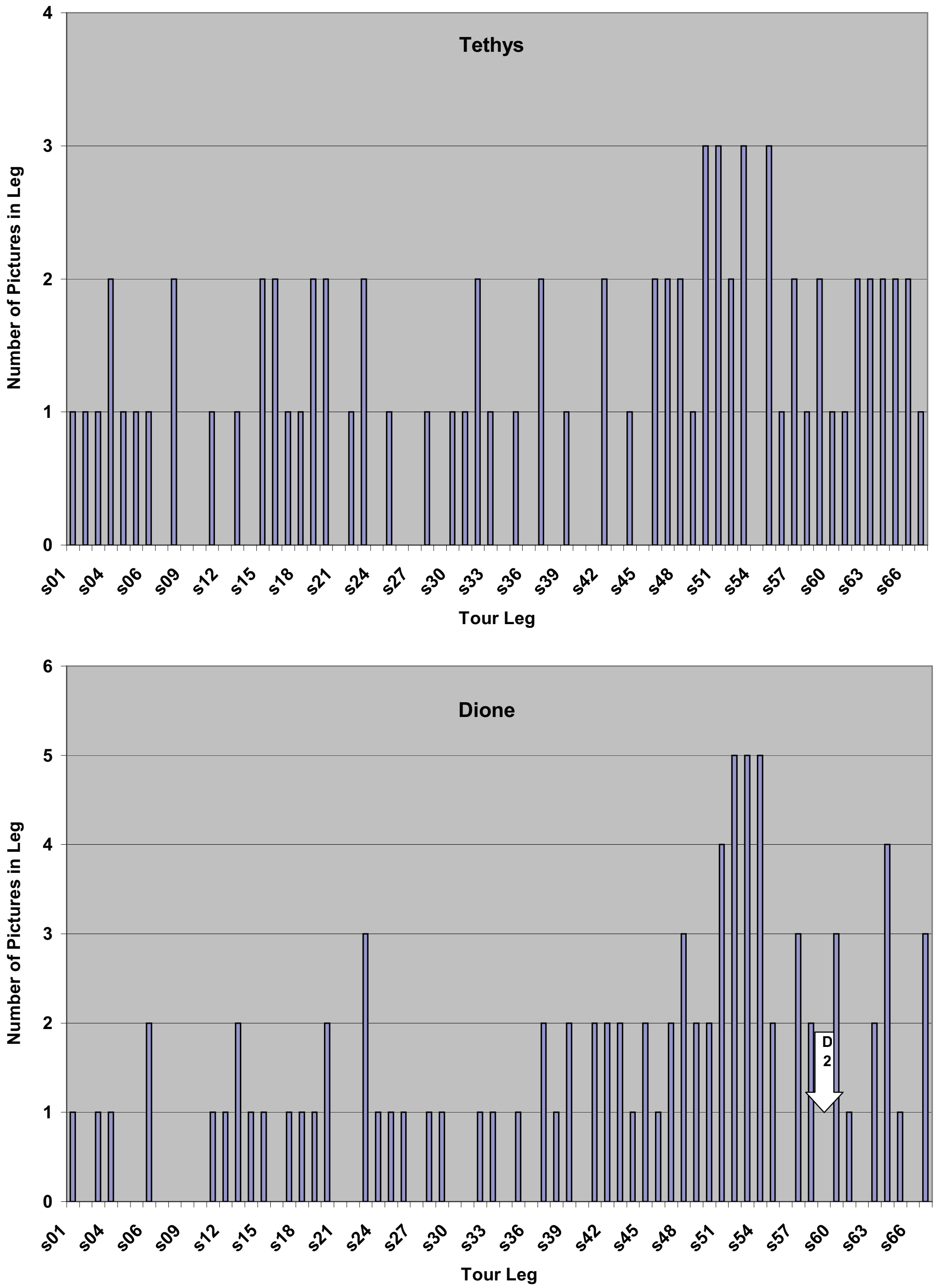

Figure 4 Distribution of Opnavs of Tethys and Dione.

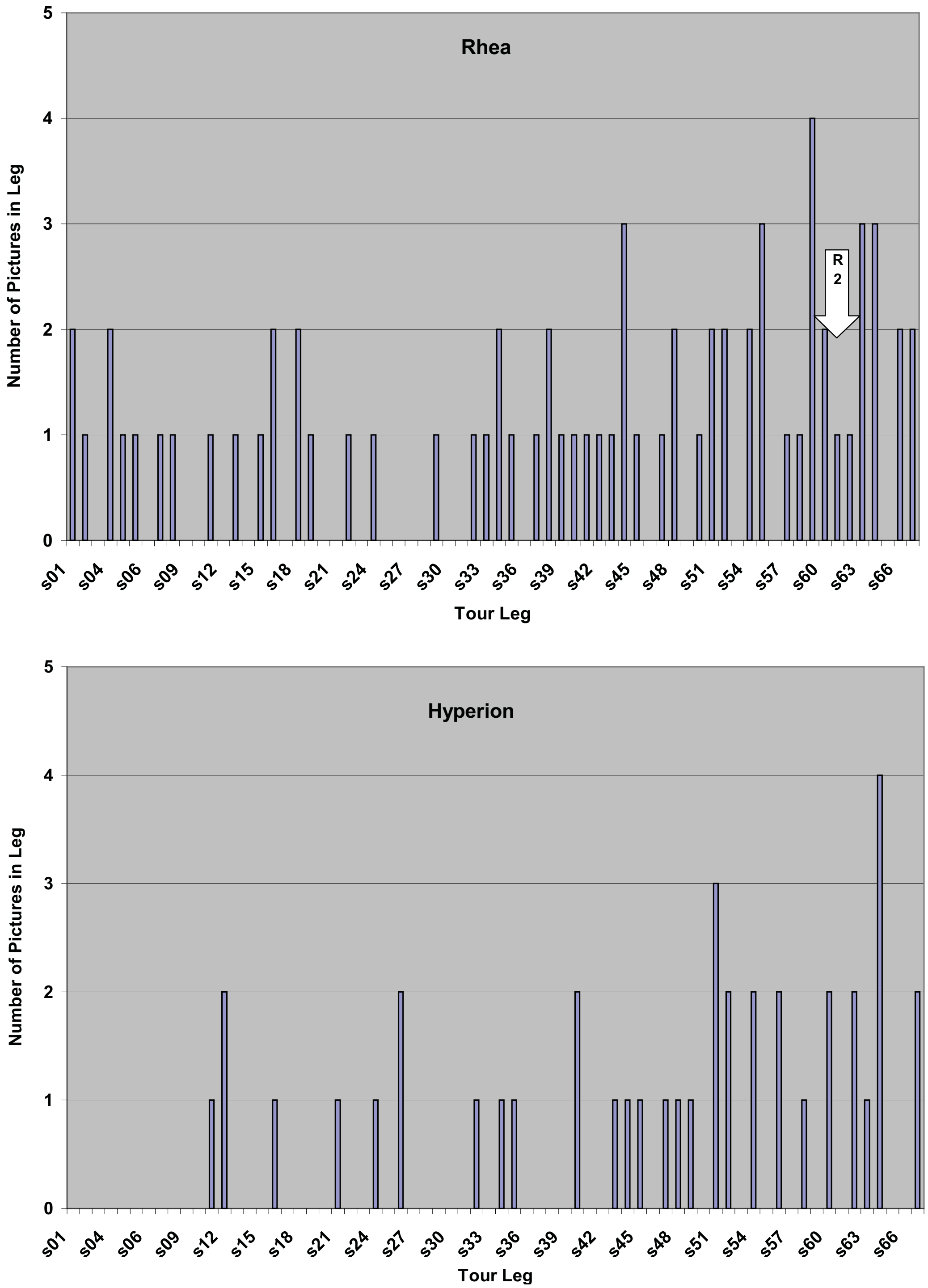

Figure 5 Distribution of Opnavs of Rhea and Hyperion.

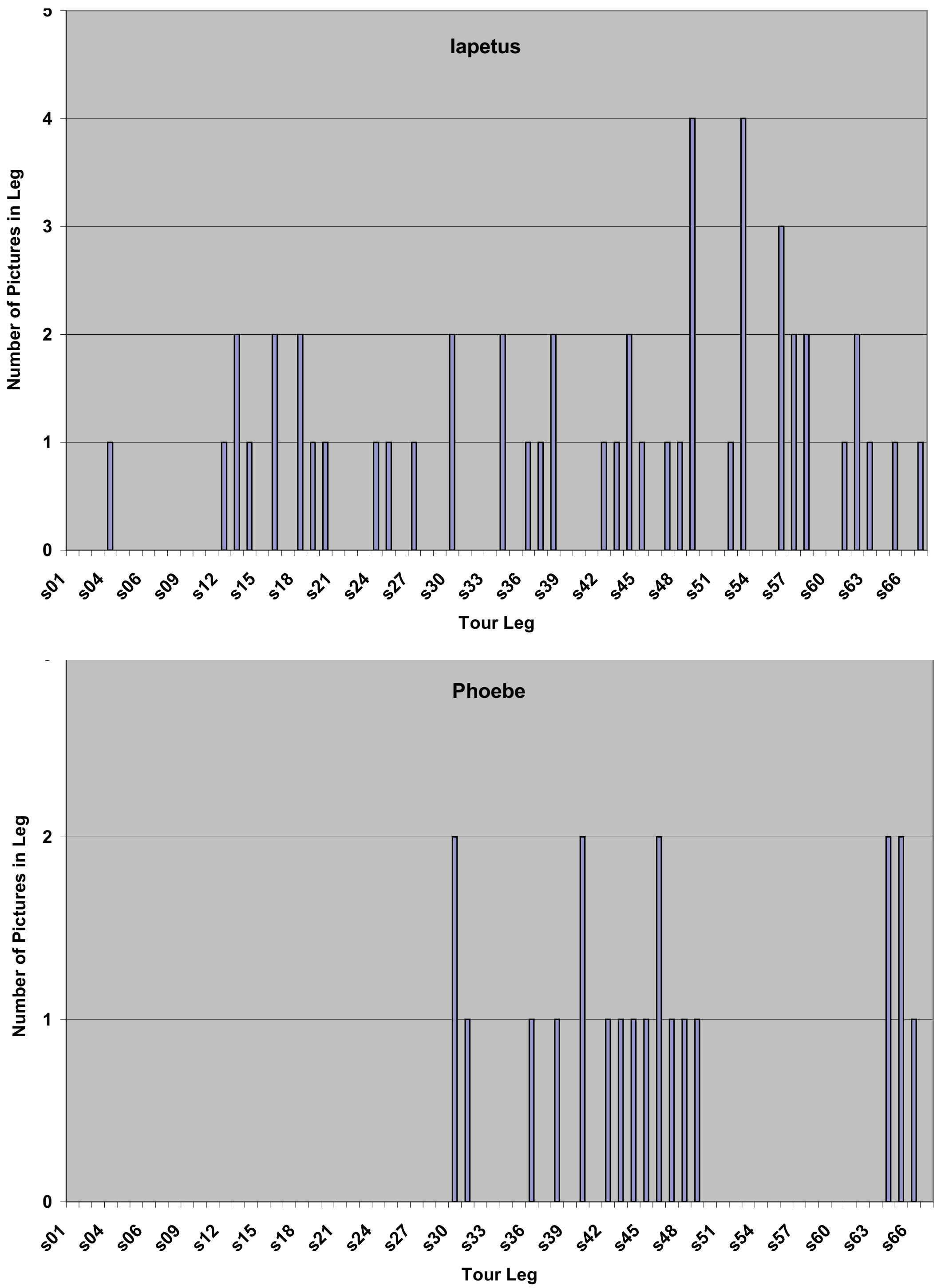

Figure 6 Distribution of Opnavs of Iapetus and Phoebe.

3. THE INFLUENCE OF THE OPNAVS ON THE EXPECTED OD UNCERTAINTIES

The magnitude of the B-plane uncertainties depends on the following factors:

1. Where there is only one flyby in the arc, the spacecraft ephemeris cannot be tied to a flyby early in the arc through the gravity signature on the Doppler data. For these arcs, the opnav data is especially helpful.
2. The presence of an apoapsis maneuver within two to three days of the data cutoff for the approach maneuver does not leave enough time in most cases, for the radiometric data to converge the OD solution. Opnavs after the apoapsis maneuver can reduce the out-of-plane components.
3. Flybys occurring during or immediately after a solar conjunction such as Titan-62 (October 12, 2009) are particularly affected by deweighting of the Doppler data or the deletion of all the data at small SEP angles.

The predicted uncertainties are good overall, and for the great majority of the flybys, the B-plane uncertainties at the DCO 2 days before the approach maneuver remain low (under 8 km) even when only radiometric data are used. However, optical data are necessary to prevent satellite covariance runoffs, to accelerate the convergence of some apoapsis maneuvers where the time until the approach maneuver is short, and as a backup data type, especially for the double flybys. The B-plane uncertainties for the Dione flyby are an exception, because they have high values with or without optical navigation pictures (11 km vs. 23 km). This flyby comes two days after T67, being part of a double flyby with Titan. The large B-plane uncertainties result from a significantly big apoapsis maneuver that sets up the flyby with Dione. Because the Dione and Titan flybys are only two days apart, the last control point for designing the approach maneuver and estimating B-plane uncertainties and pointing errors is at the approach maneuver 2 days before the Titan flyby. This double flyby emphasizes the importance of optical navigation pictures when the convergence time between an apoapsis maneuver and an approach maneuver is short. Larger ephemeris errors for the icy satellite also increase the spacecraft ephemeris errors.

The contribution of the optical data can be evaluated by comparing B-plane plots of satellite targeting uncertainties obtained with the full and half optical navigation picture schedules to those obtained using only radiometric data only (RD). The covariance study shows that the inclusion of optical data does not, for many arcs, reduce the B-plane errors below those obtained from using radiometric data only. This is because the satellite ephemerides were very well determined during the PM and further opnavs cannot improve their precision.

The inclusion of optical navigation pictures produce significant reductions in the targeting errors in the arcs containing the T47 through T50 flybys, the T63 flyby after the solar conjuction, and the double flybys with the approach maneuver at two days prior to the first flyby. See figures 8, 9, 10, and 11. These show that for the T47–T50 arcs the errors in the semimajor axis of the B-plane at closest approach are reduced from 4–5 km to approx. 2 km. Figure 7 shows a smaller reduction to below 1 km is seen for T46. For the arc with T63 at the end, the errors drop from 3 km to 2 km due to the opnav just three days before the flyby. See figure 12.

Even when there is no difference in the magnitude of the B-plane uncertainties, the satellite ephemeris errors exhibit a runoff without opnavs but a reduced runoff with opnavs. Enceladus runoff is also reduced between flybys. This can be seen in figures 13 and 14.

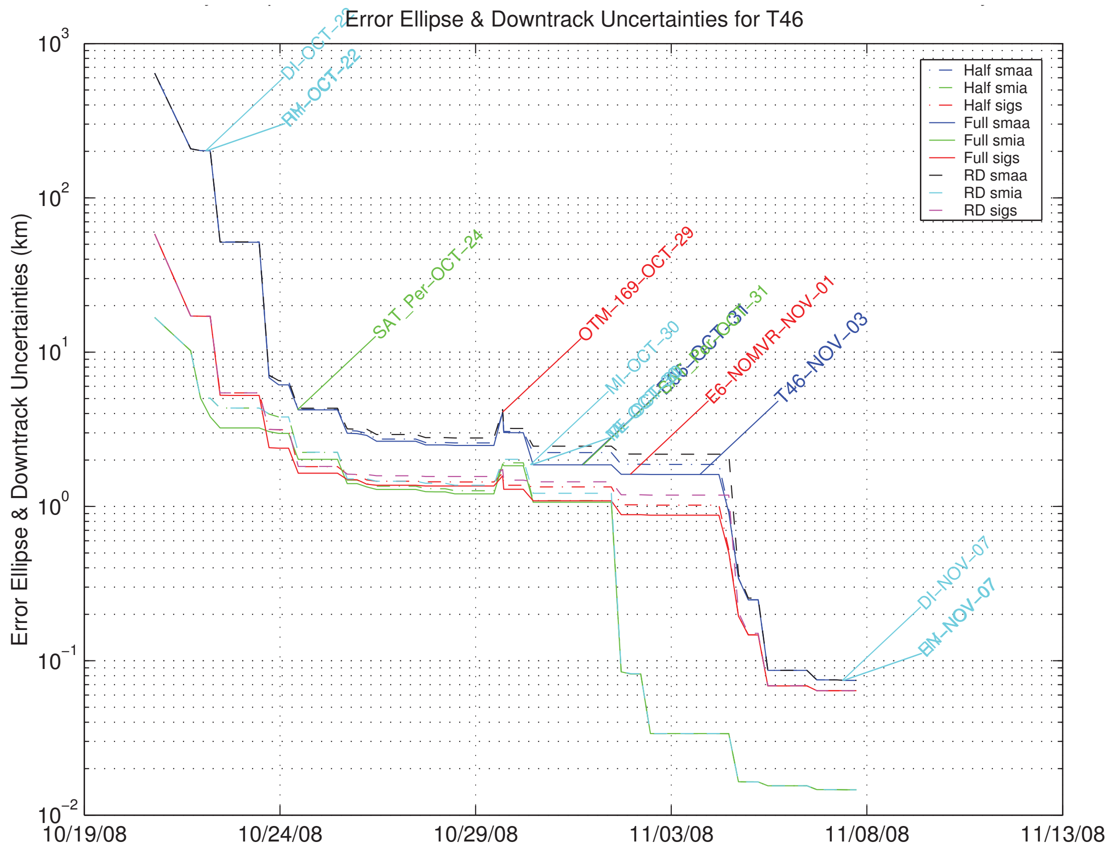

Figure 7 Spacecraft Targetting Errors between Enceladus-6 and Titan-46 Flybys Mapped to the T46 Flyby.

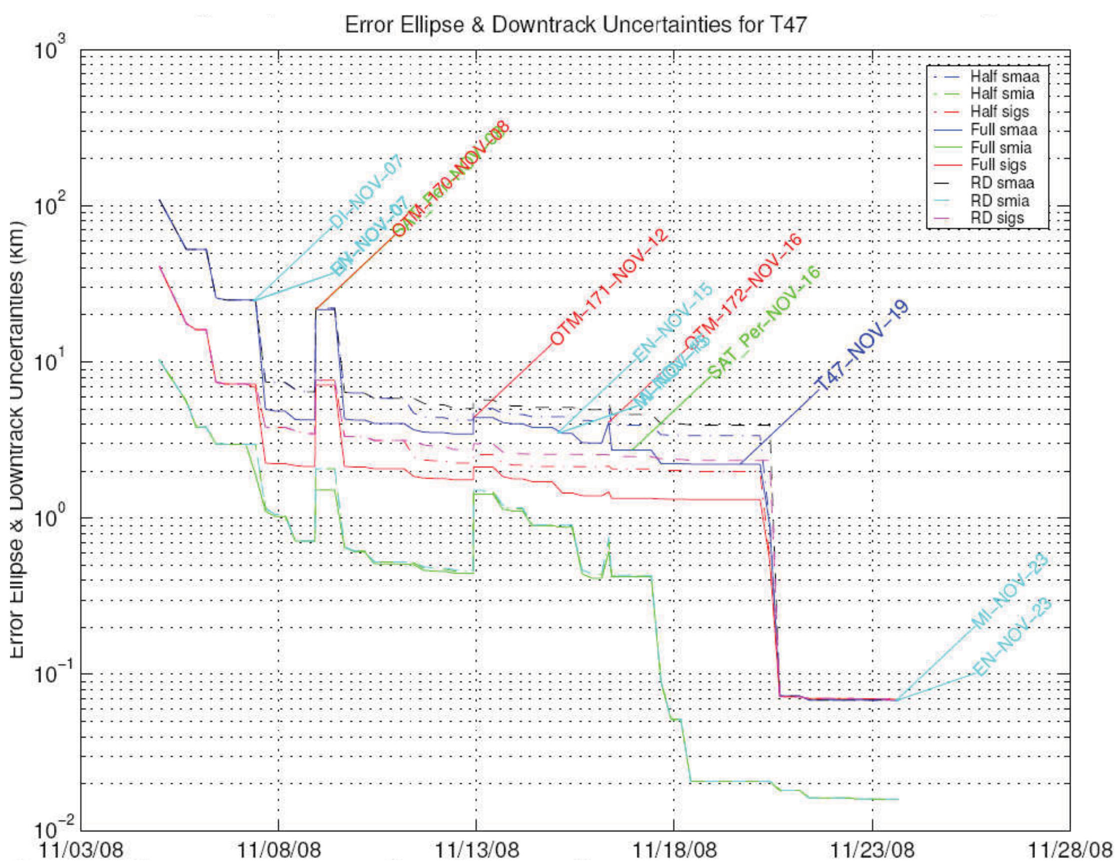

Figure 8 Spacecraft Targetting Errors Mapped to the Titan-47 Flyby.

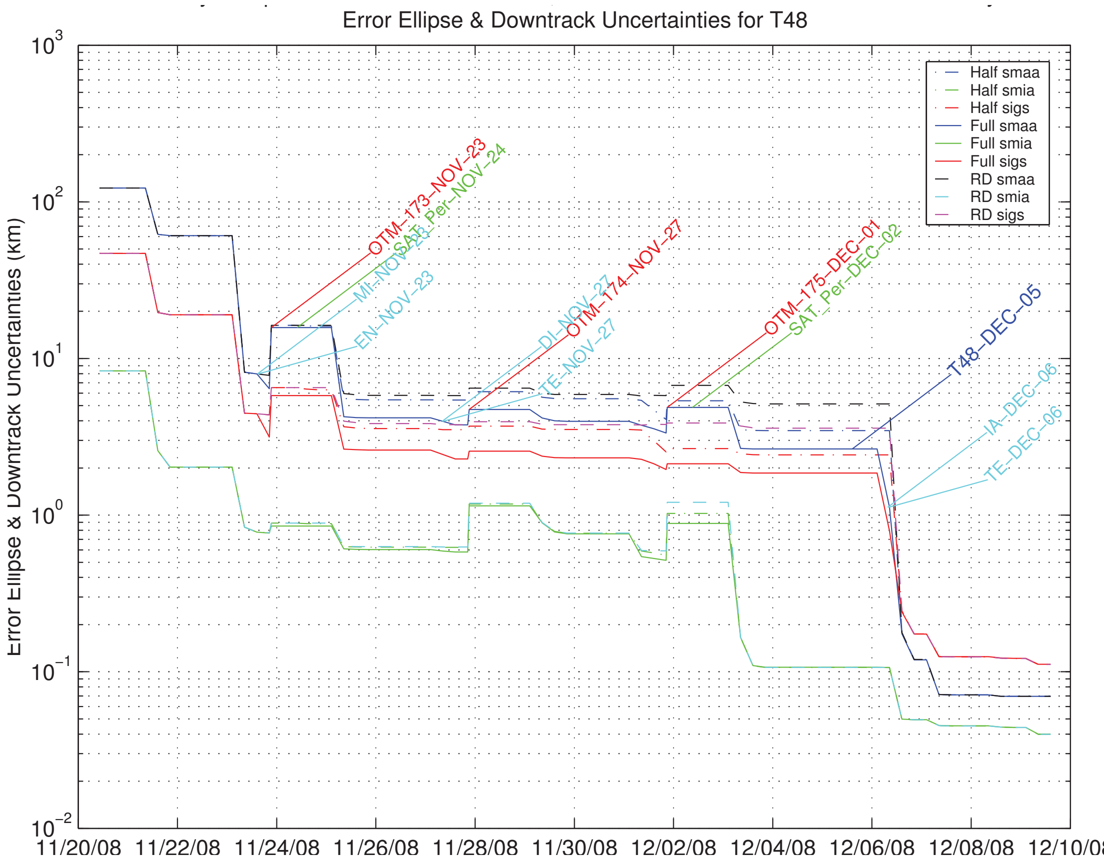

Figure 9 Spacecraft Targetting Errors Mapped to the Titan-48 Flyby.

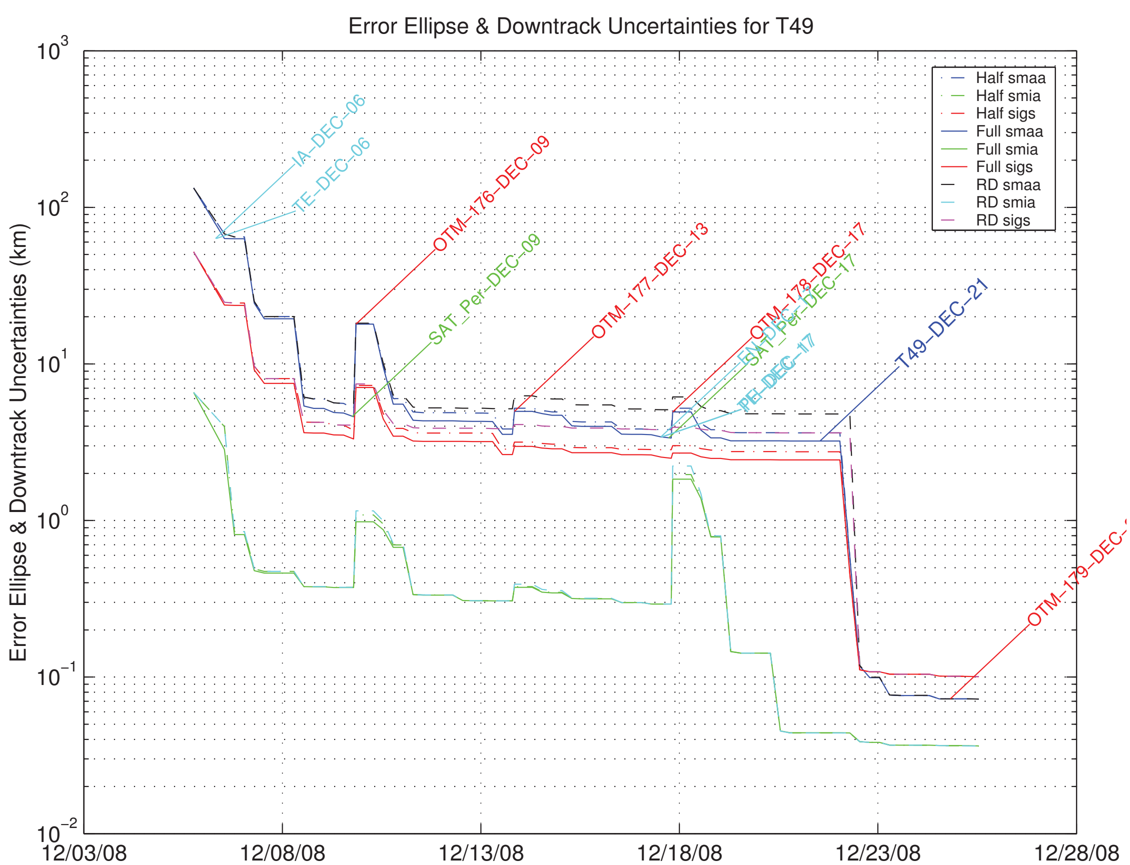

Figure 10 Spacecraft Targetting Errors Mapped to the Titan-49 Flyby.

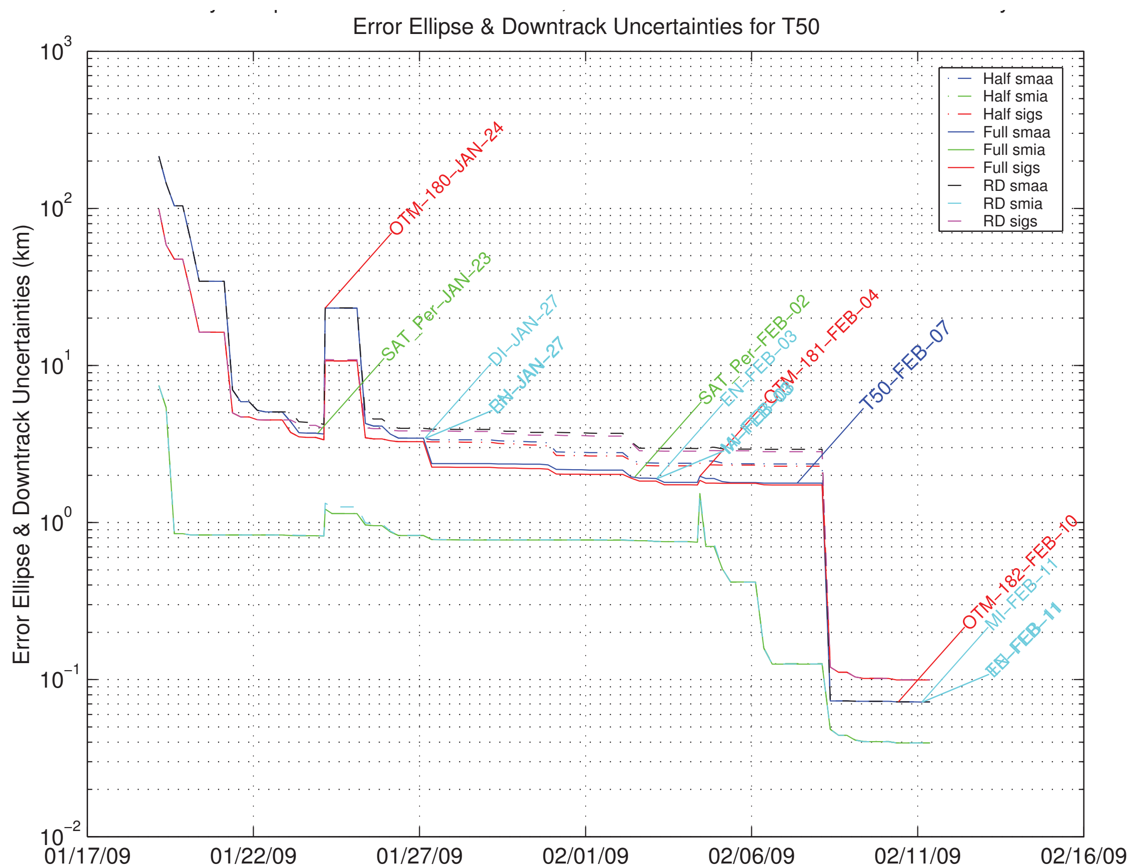

Figure 11 Spacecraft Targetting Errors Mapped to the Titan-50 Flyby.

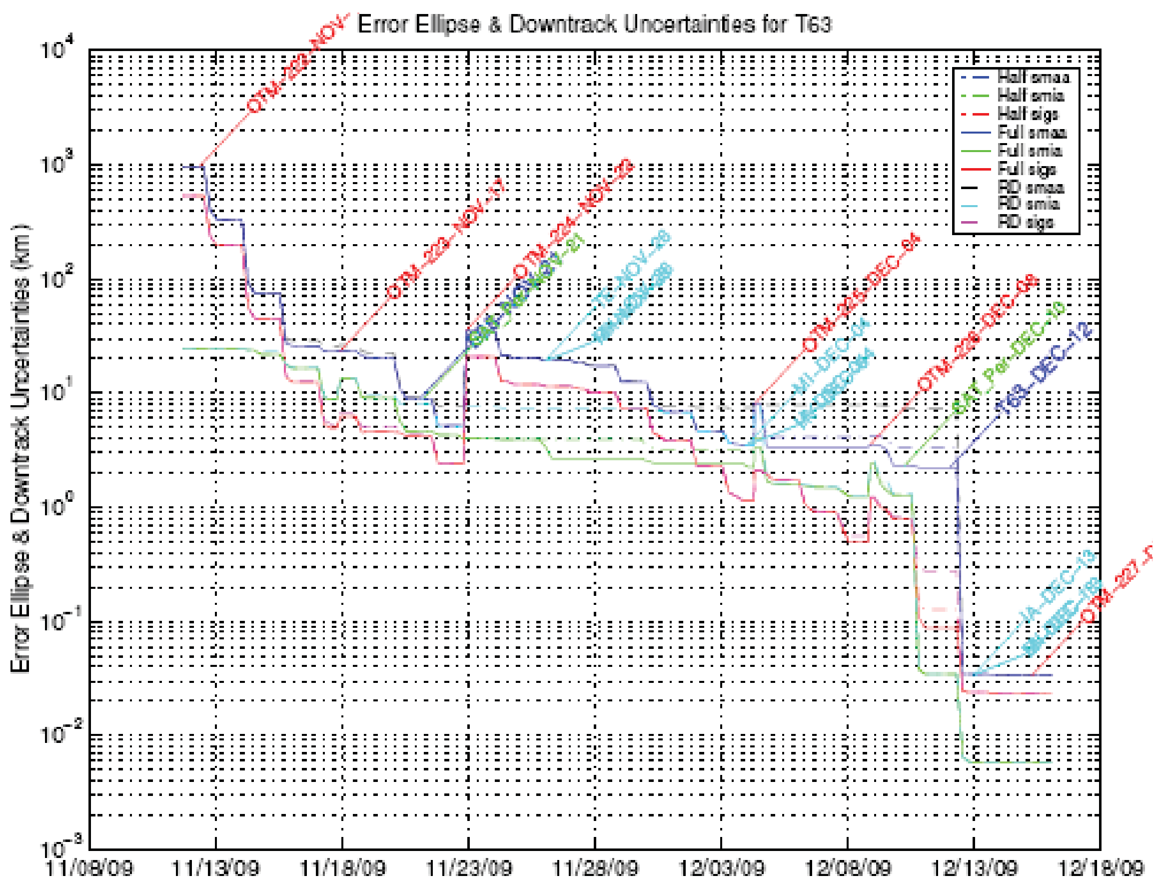

Figure 12 Spacecraft Targetting Errors Mapped to the Titan-63 Flyby.

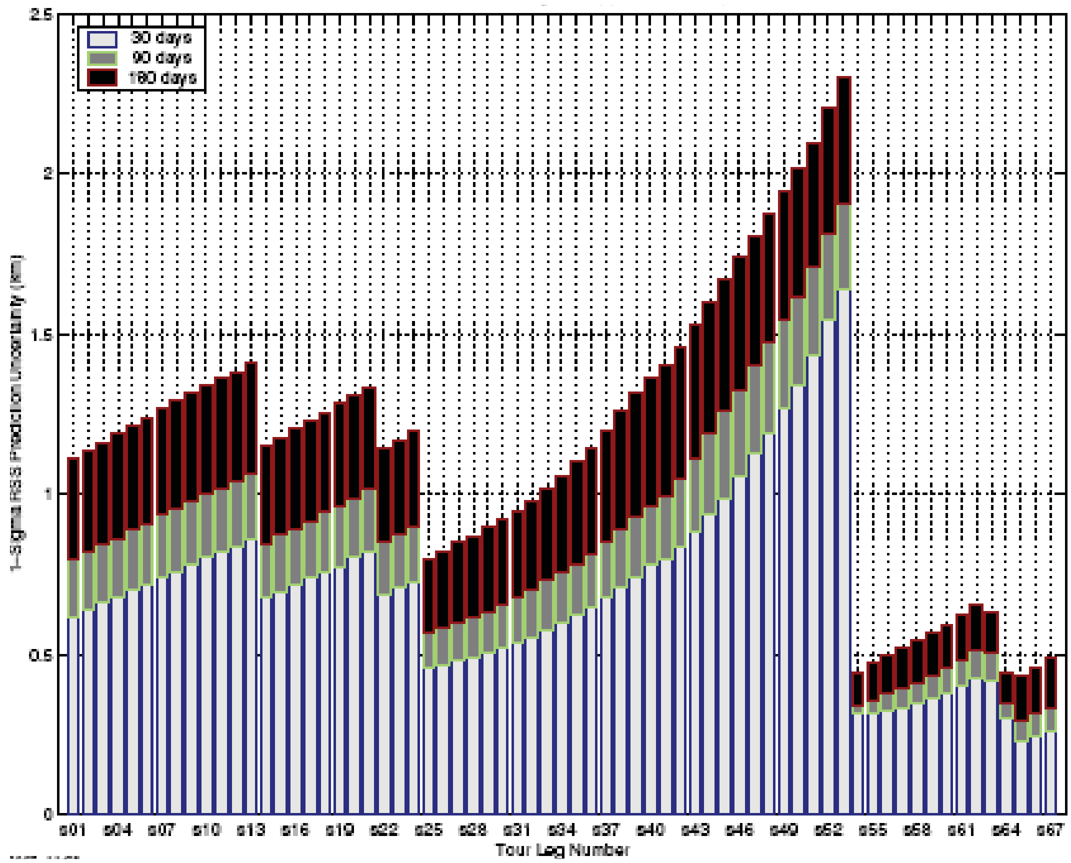

Figure 13 Ephemeris Errors for Enceladus with Radiomentris Data Only in the Orbit Determination.

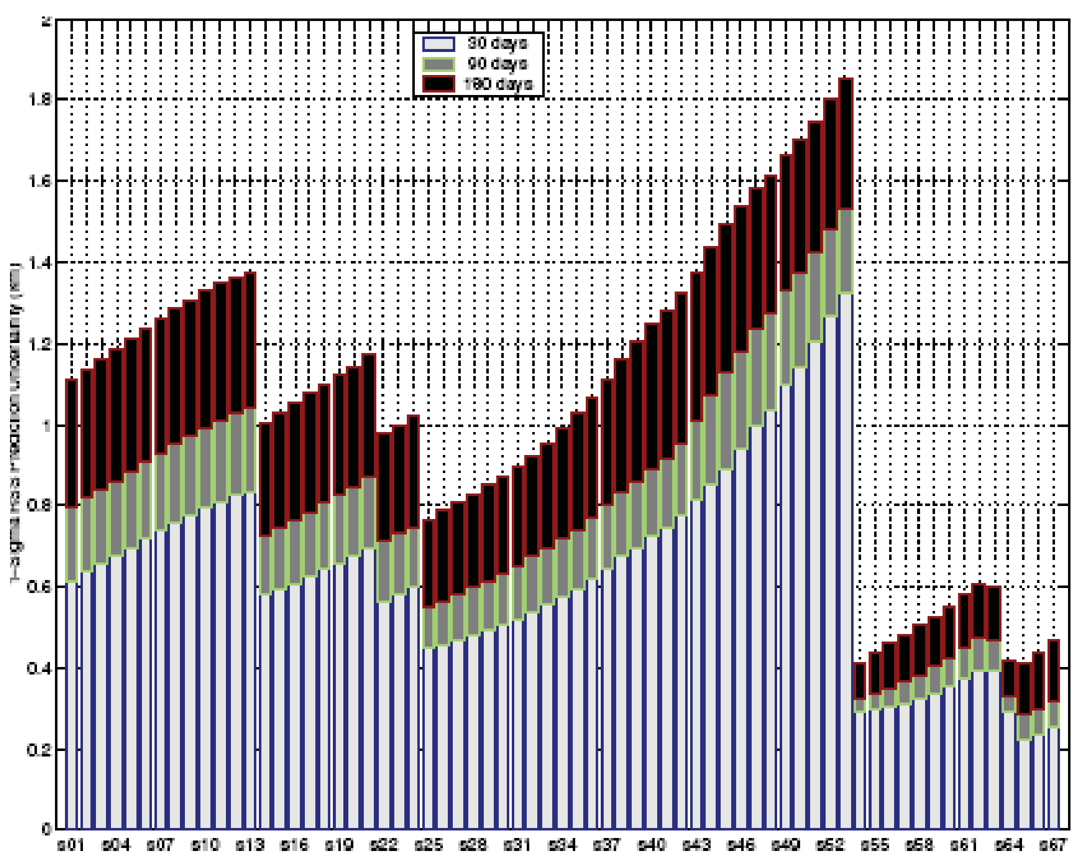

Figure 14 Ephemeris Errors for Enceladus with Radiomentris Data and the Full Picture Schedule in the Orbit Determination.

4. PROPELLANT SAVINGS FROM OPNAVS

Maneuver analysis showed that there was a cost on average, of approximately 5 m/s in ΔV (with a corresponding use of propellant) for each flyby. There are two to four maneuvers between Titan flybys, of which two may be deterministic and two may be statistical. (Deterministic maneuvers are required by the trajectory design; statistical maneuvers are those which are required only to correct trajectory errors. These may be due to underburns, overburns, pointing errors, OD errors due to mismodeling, or future ΔV events that deviate from their predictions.) The ΔV adds up, over the XM, to 224 m/s, at the 95% confidence level, when the expected statistical manoevers are included. As can be seen from figure 15 the total ΔV is reduced to 220 m/s with the inclusion of the full opnav picture schedule in the OD.

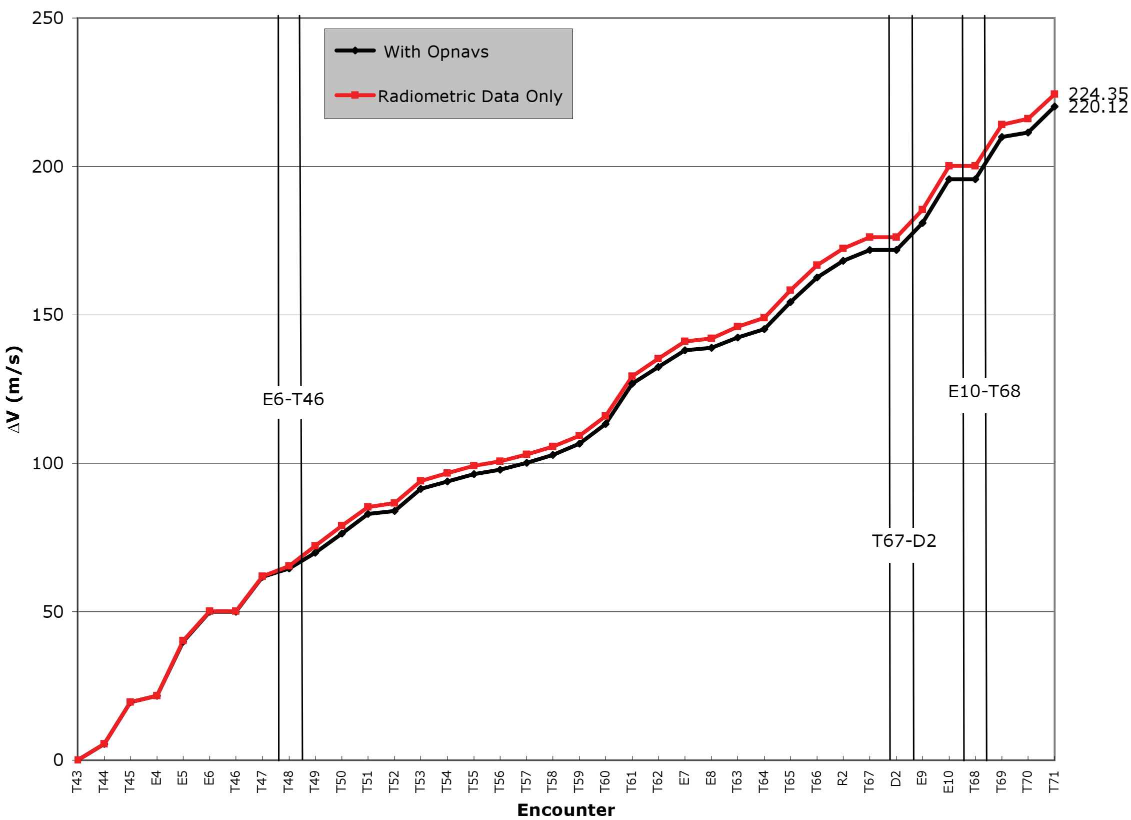

Figure 15 ΔV Savings From Including Optical Navigation Data in the Orbit Determination.

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