OPERATIONAL COMPENSATION FOR EFFECT OF CLOSE TITAN FLYBY ON REMAINDER OF VOYAGER 1 SATURN NEAR ENCOUNTER

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ABSTRACT

Voyager 1's extremely close approach to Titan necessitated design and implementation of an extraordinary process to account for probable consequent changes in the pointing of science instruments. Originally conceived as a contingency plan, the so-called Satellite Pointing Update Process became a central activity in the Voyager 1 Saturn encounter operation.

Keywords: Operations Reaction, Contingency Plan, Science Instrument Pointing, Spacecraft Navigation, Voyager, Saturn

1. OVERVIEW

The Voyager missions have already provided a major portion of man's accumulated knowledge of the Jupiter and Saturn planetary systems, with still more data to be acquired and more analysis to be performed. The information acquired is the combined product of complex advance planning processes, a fast-paced final update process, and possible contingency (emergency) operations plans executed if there should be a late-appearing surprise of some form. This paper addresses a contingency plan devised for the Voyager 1 encounter with Saturn in November 1980. The surprise happened, and the plan was successfully executed.

Voyager is a three-axis stabilized spacecraft, on which are mounted ten scientific data gathering instruments. Six of these instruments are designed for fields and particles data acquisition and are by their nature tolerant to small trajectory, ephemeris and attitude uncertainities. Four of the instruments are pointable, mounted on a two axis articulated scan platform; they have narrow fields of view and their data acquisition is highly dependent upon precise knowledge of spacecraft trajectory, planet and satellite ephemeris, and scan platform pointing direction. Precise pointing of the scan platform is, in turn, dependent upon calibration of the platform actuators and predictability of the spacecraft attitude. Finally, the predictability of spacecraft attitude is dependent upon calibration of star and sun sensors (for celestial mode) and gyro stability (inertial mode).

For the Voyager 1 Saturn encounter, all of these factors were adequately understood--except for one. The mission design called for a very close flyby of Saturn's massive satellite Titan, closely followed by closest approaches to the satellites Rhea, Dione, Mimas and S-11. Uncertainties in the mass and time-variable location of Titan could easily affectthe spacecraft trajectory in a way that would propogate into unacceptable mispointing of the platform instruments.

The timing of the situation necessitated extraordinary action. Nearly all Voyager spacecraft activity is controlled by on-board computers. The effect of any surprise change from Titan's predicted characteristics would not be known until the two seqences (programs) controlling the Rhea, Dione, Mimas and S-11 observations were loaded on the spacecraft--one already executing.

The Voyager Flight Team developed and practiced a special contingency operations plan to accommodate this potential problem. The plan involved earlier sequencing of additional optical navigation images to refine both the spacecraft trajectories and satellite ephemeris, and a special 14-hour long intensive series of operational activities leading to command transmissions which would change the platform pointing during both the currently executing and already-loaded next sequence. During this short time period, not only would navigation parameters be updated using radiometric and optical data, but these parameters would be used to define new observation pointing, the spacecraft commands necessary to implement the pointing would be generated, the resultant modified sequences would be simulated, a modified operational sequence of events would be generated and printed, and the commands would be transmitted.

It is now history that the spacecraft flew about 330 Km closer to Titan than expected. The Rhea/Mimas/ Dione/ S-11 pointing update contingency plan was exercised and resulted in the acquisition of unique science data, including images that allow every man on Earth to share this new closeness of Saturn's satellites.

2. BACKGROUND

2.1 The Mission

The Voyager 1 spacecraft encountered Saturn on November 12, 1980, making its closest approach to the ringed planet at a distance of 124,000 kilometers from the planet's cloud tops. The flyby of Saturn, the third episode of the Voyager Mission to the outer planets, came 20 months after the spacecraft's meeting with Jupiter in March 1979, and 16 months after its twin, Voyager 2, made its Jovian encounter in July 1979. Voyager 1's intensive scientific examination of Saturn, its rings and satellites, is the spacecraft's final planetary encounter before it leaves the solar system about 1990. It's near-Saturn journey can be followed in Figure 1.

Saturn's satellite Titan, thought before last November to be the largest "moon" in the solar system but now known to be second in size to Jupiter's Ganymede, was a prime target for scientific study by Voyager 1. On November 11, the spacecraft sailed a course very close to Titan, 4,000 kilometers from the surface, the closest approach to any body in the Voyager missions. At this range, the gravit-ational influence on the subsequent trajectory is great.

The next day, November 12, marked the spacecraft's closest approach to Saturn and the satellites Tethys (415,320 kilometers), Mimas (108,400 kilometers), Enceladus (202,521 kilometers), Dione (161,131 kilometers), and Rhea (72,100 kilometers).

The Voyager 1 trajectory included occultations of the Earth and Sun by Titan, Saturn and the rings--time periods during which the Earth was obscured from the spacecraft's point of view by Titan, Saturn and the rings. Precise location and timing of these passages were important, since Voyager's radio signals were required to pass through the atmospheres of Saturn and Titan and through the rings toward Earth. The resultant changes in the radio signals would provide information on characteristics of the planet's and satellites's atmospheres, ionspheres and the size and density of ring particles.

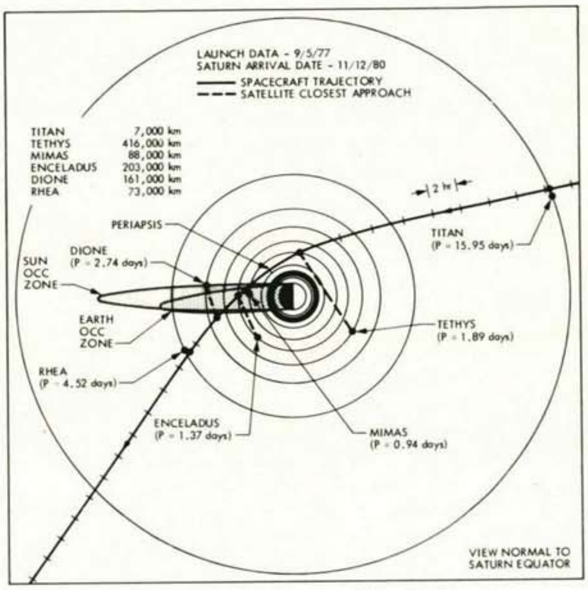

Figure 1. Voyager 1 Saturn Trajectory

2.2 Spacecraft Control Characteristics

A functional understanding of several Voyager spacecraft control characteristics is needed before proceeding. Three sets of redundant computers, six total, perform the on-board sequencing and contol functions. The two Command Control Subsystem (CCS) computers are used in a leap-frog fashion to perform the primary control functions, clocking out a series of on-board stored commands according to a pre-loaded program, henceforth referred to as a CCS Load (CCSL) or sequence. Real-time, immediate action commands, are also implemented by the CCS.

The second redundant computer pair, the Flight Data Subsystem (FDS), performs two functions:

(1) It clocks out and formats all engineering and science telemetry data into one of the format/data rate combinations available from its reprogrammable repertoire.

(2) It controls the variable states of certain science instruments (operational modes, sampling rates, filter settings, exposure times, and so on).

The FDS obtains its sequence-related information from the CCS.

The final redundant computer pair, the Attitude and Articulation Control Subsystem (AACS), performs the following functions under the master control of the CCS.

(1) It maintains the attitude of the spacecraft in a continuous closed-loop manner by firing tiny hydrazine thrusters mounted in pairs on each of three axes in response to error signals from either celestial sensors (sun/star), the normal mode, or inertial reference units (gyros), used when celestial reference usage is not possible or is risky. The attitude of the spacecraft is directly related to accurate pointing of the spacecraft antenna toward Earth, and to the accurate pointing of the four science instruments mounted on the controllable scan platform--imaging, the infrared interferometer spectrameter, the ultra-violet spectrometer, and the photopolarimeter--toward their observation targets. Three deadbands are available to control attitude within: $.5^{\circ}$, $.16^{\circ}$, and $.05^{\circ}$. As might be expected, narrow deadband usage results in greater gas consumption; therefore, the widest deadband possible within antenna and platform pointing accuracy constraints is always used.

(2) The AACS controls the pointing of the scan platform, aiming at targets of scientific interest. The actual scan platform position commands are issued to the AACS by the CCS at the time called for in the sequence or as immediate action commands. The translation of pointing requirements into scan platform position commands is done on the ground as part of the Spacecraft Sequence Generation activity, to be discussed later in Section 5.4.

(3) Finally, the AACS controls all maneuvering of the spacecraft, whether for engineering or science data acquisition purposes, and all propulsive thrusting for trajectory correction purposes.

2.3 Navigation

Precise predictions of where the spacecraft will be as a function of time in relation to the planet and its satellites is critical to sequencing the spacecraft, especially to pointing the scan platform. In Voyager's approach to this problem, traditional radio navigation is supplemented with the first planned use of optical navigation on a NASA deep space mission.

Accurate "two way" radio data types are obtained with a system that involves transmitting to the spacecraft an S-band carrier (approximately 2114.7 MHz) from any of NASA's Deep Space Network stations located in Spain, Australia or the Western U.S.A., and transmitting from the spacecraft an S-band carrier frequency that is 240/221 times the received carrier frequency, and an X-band carrier frequency that is 880/221 times the received carrier frequency. The resultant S- and X-band doppler provide spacecraft velocity information. Application of range modulation to the carriers and turning around range codes provides spacecraft range information. For Voyager, greater radio data-based accuracy is obtained through the use of more sophisticated multi-station data types.

Optical navigation takes engineering advantage of Voyager's imaging science instrument. Images of the planet and/or one or more of its satellites against a star background are sequenced, acquired by the spacecraft, and transmitted to Earth. There, the images are reconstructed in a special purpose computer system, and passed to another special purpose computer, the Optical Navigation Image Processing System (ONIPS), which aids in the identification of star and satellite targets and separates those targets from picture noise.

Radio and optical navigation are nicely complimentary. Radio navigation uses Earth-spacecraft relationships, and optical navigation uses target-spacecraft relationships. In the vicinity of a planetary encounterv the Earth-spacecraft line-of-sight range and velocity measurements indirectly provide the spacecraft-planet distance through observable dynamic effects, and the optical data effectively measure the instantaneous spacecraft-satellite cross line-of-sight position relative to a particular satellite. The radio and optical data were planned to allow determination of both the satellite orbits and the spacecraft trajectory relative to the planet.

It is important to recognize that star-satellite relationships useful for optical navigation are available only at discrete times, that almost 1-1/2 hr will pass between the transmission of an image and its receipt on Earth, and that several hours are required to reconstruct the image, extract the necessary optical data, perform an orbit determination with the new data, and analyze the results.

3. THE PROBLEM

In August of 1979, 1-1/4 years before the actual Voyager 1 Saturn encounter would occur, a significant mission design problem was identified. During certain satellite encounter time periods, the possible navigation errors translated into target pointing errors which exceeded the fields of view of the pointable optical instruments, especially the narrow-angle imaging system. Furthermore, because of (1) competition for sequence time from the many other desired observations, (2) rapidly changing geometries, and (3) data rate limitations, it would not be prudent to sequence mosaics--multiple image, overlapped field of view coverge patterns of large areas. The near-Saturn observations of Mimas, Dione and Rhea were most seriously affected. The angular diameters of Mimas, Dione and Rhea at closest approach would be 6, 7 and 22 milliradians, respectively. The field of view of the narrow-angle imaging instrument is about 7 milliradian.

Two sigma pointing accuracy of 1.5 to 2.0 milliradians per axis was desired, with 3.5 milliradians barely adequate. Figure 2 shows the pointing uncertainity as a function of time for a typical problem observation, that of Rhea at Saturn plus 5 hours and 53 minutes. Note the effect of the close Titan encounter at about Saturn minus one day. This sample observation, along with most of the other problem observations, was in the A552 sequence, the second of two near-encounter sequences (CCS programs). The other problem observations were in the preceding A551 sequence. Figure 2 shows that the minimum pointing accuracy requirements could not be met at the required navigation data-taking cutoff times. These cutoff times are derived by working backward from the time that the sequence must be transmitted to the spacecraft (window open), allowing time for final generation and verification of the commands and prerequisite processing of the navigation data--a total of a little over three days under normal conditions.

4. ALTERNATIVE APPROACHES

Two alternative approaches were deemed worthy of investigation.

4.1 On-Board Pointing Improvement

The first alternative is conceptually simple, but complex to implement. A short time prior to the desired observation(s) the target (satellite) would be imaged using the wide-angle camera, which has a field of view approximately 9 times that of the narrow-angle camera, or possibly by the scan platform mounted photopolarimeter instrument. An on-board computer, probably the FDS, would be programmed to find the center of the target and relate it to the center of the field of view. A special algorithm in one of the on-board computers would convert the offset into scan platform incremental slew commands which would essentially bias the position specified in the executing sequence.

This approach results in two formidable operational problems: it would probably require interruption of the science

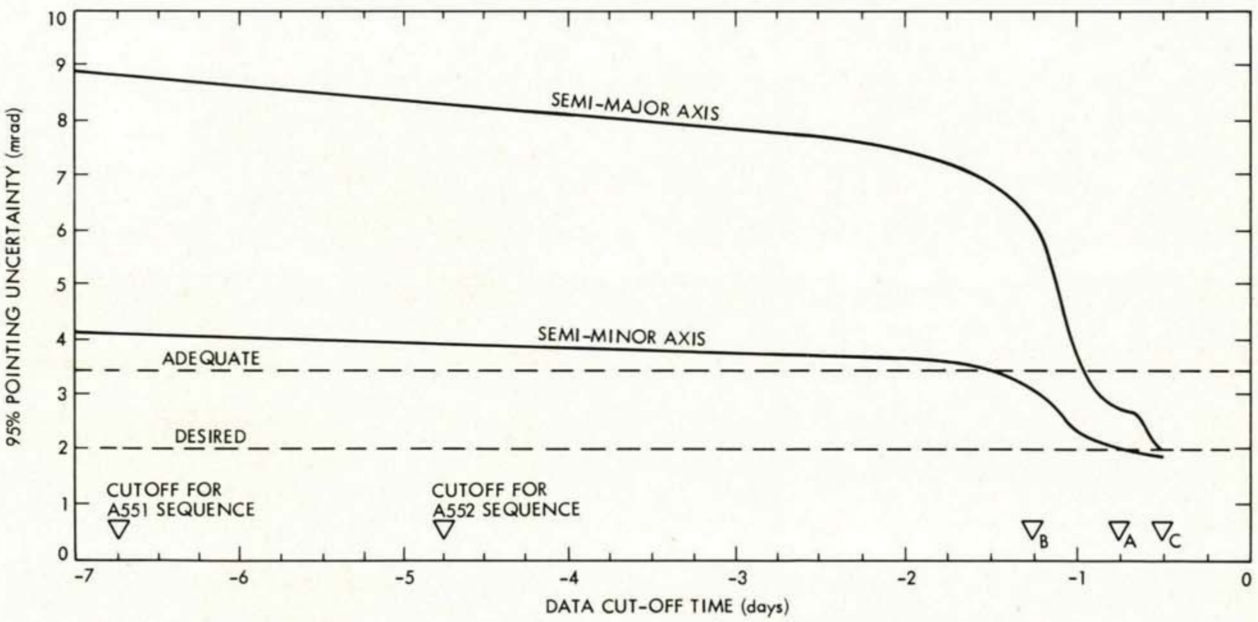

Figure 2. Time Projection of Rhea ($+5^h\ 53^m$) Pointing Uncertainty

telemetry flow to the Earth during the time that each center-finding was taking place, and it would require valuable computer memory space which would otherwise be used to control science data acquisition. These, combined with the risks associated with a complex in-flight computer software development activity, resulted in elimination of the on-board correction option.

4.2 Ground Commanded Pointing Improvement

Figure 2 shows that adequate navigation data to confidently modify scan platform pointing would not be acquired until Saturn minus 1 day or later. At this time, the A551 sequence would be loaded on the spacecraft and have begun to execute, and the A552 sequence would have to be ready to transmit to the spacecraft. Thus, it would be impossible to modify the sequences prior to transmission. Two sub-alternatives remained: (a) modify the sequence before the event in question was executed (or preferably before the first event of the sequence was executed), or (b) follow the sequenced platform slews in question with a small correction slew implemented by means of an immediate action command.

Sub-alternative (b) would work for A551 if a small pause for each correction slew was placed in the sequence. In fact, because the time to generate an immediate action command is significantly less than the time to generate a sequence modification, alternative (b) would be less risky.

The opposite condition existed for the A552 sequence. For a major portion of the time that immediate-action commands would have to be transmitted, the spacecraft would be either maneuvered off of Earth-point or occulted from Earth view by the planet. The possibility of commanding through the spacecraft's low gain antenna, one less sensitive to precise Earth-point, was considered for some of the off-earth-point periods and was found to have a low probability of success. Thus, no ground commanding was possible. Fortunately, there appeared to be no major obstacle to implementing alternative (a).

After assuring to the first order that both adequate time was available to accomplish all required functions and that the required personnel could be scheduled in a way that they would not be exhausted while performing critical tasks, the ground commanded approach was decided upon, mixing sub-alternatives (a) and (b). It was named the Satellite Pointing Update Process.

5. THE SATELLITE POINTING UPDATE PROCESS

This chronological description of the Satellite Pointing Update Process is keyed to Figure 3. An a priori analysis of all Saturn near-encounter observations revealed seven which were particularly vulnerable to navigation uncertainties. These are listed in Table 1; the last two were nine and two position mosaics, respectively. Further analysis identified the maximum allowable pointing error, also shown in Table 1. This allowable error was used as the criterion for performing each update (see Section 5.6 and Figure 4).

TABLE 1

		Allowable Error (mrad)	
Sequence	Target Satellite	Δ AZ	Δ EL
A551	Rhea	±0.87	±0.87
A551	S-11	±2.79	±0.87
A551	Rhea	±1.05	±0.87
A551	Mimas	±1.05	±0.87
A552	Dione	±1.05	±0.87
A552	Rhea	±3.32	±0.87
		±3.14	±0.87
		±3.14	±0.87
		±2.97	±0.87
		±2.97	±0.87
		±2.79	±0.87
		±2.62	±0.87
		±2.44	±0.87
		±2.27	±0.87
A552	Rhea	±1.22	±0.87
		±0.87	±0.87

5.1 Deep Space Network Data Acquisition

Navigation radiometric data cutoff was designed to occur with a spacecraft-sequenced switch to the two-way non-coherent mode (TWNC ON) at 0649 (all times in GMT). The ground transmitter was turned off a light-time earlier. In this mode doppler data quality degrades because an on-board ultra-stable oscillator replaces the uplink carrier as a frequency reference. The switch was made for radio science experiment purposes, in preparation for the occultation of Earth by Titan, where two-way communication would obviously be impossible. This point in time, 18.4 hours prior to Saturn closest approach, is labeled A on Figure 2. It can be seen that the influence of Titan would be significant by this time, though use of some small amount of post-Titan data, from 0924 to 1000, labeled C on Figure 2, would provide even better accuracy. As insurance against operational problems, a fallback epoch, labeled B, was chosen at a point in time approximately 12 hours prior to the primary epoch.

The timeline to use the post-Titan radiometric data, plus two optical navigation images acquirable in the same time period, was considered too risky to be included as part of the nominal plan.

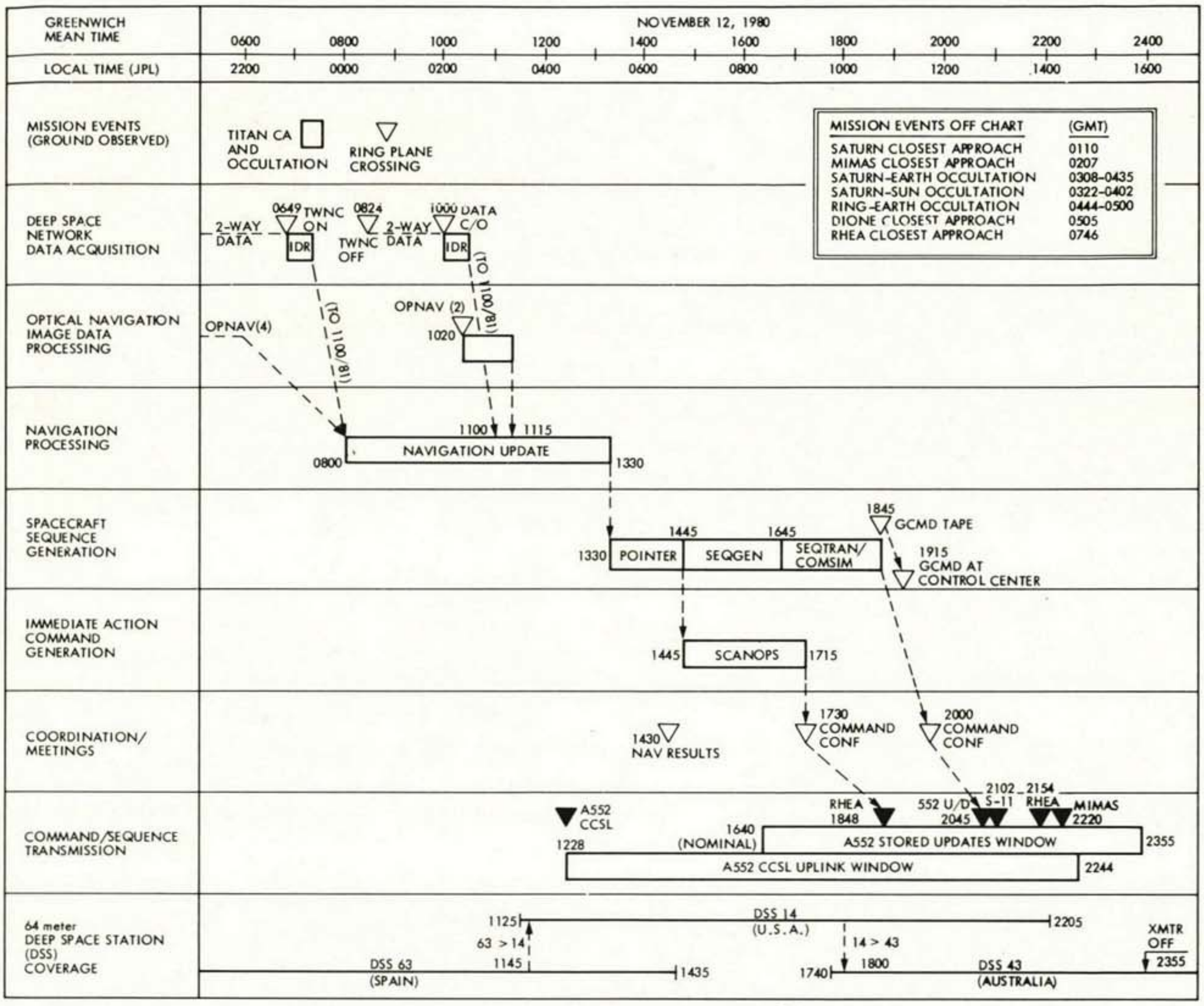

Figure 3. Satellite Pointing Update Timeline

Not wanting to forego the opportunity, a strategy was devised to include the data if operational status at the time the data was available indicated an acceptable risk.

After any data cutoff, about 30 minutes is required to produce a radiometric data IDR (intermediate data record)--the magnetic tape which is the input to the navigation processing performed on the very large Univac 1100/81 computer used for Voyagers non-real-time processing. The 1100/81 is located approximately two miles from the Voyager and Deep Space Network Control Centers, so an additional 30 minutes had to be allowed to physically transport the tape.

5.2 Optical Navigation Image Data Processing

Optical navigation information is extracted from telemetered images acquired by the spacecraft. Specialized processing separates real background stars from noise, and finds the limbs and centers of foreground satellites. The reduced data is electrically transmitted to the 1100/81.

Four critical optical navigation frames received approximately five hours prior to Titan closest approach were planned to be processed in this manner, as were the two post-Titan frames.

5.3 Navigation Processing

Compressing into 5-1/2 hours an activity that normally takes several days to accomplish, the Voyager Navigation plan called for use of a dedicated 1100/81 to assimilate the newly acquired radiometric and optical data, to update the spacecraft trajectory, to account for the now very pronounced effects of Titan's and Saturn's orbital parameters and mass, and to update the satellite ephemerides based upon the very accurate, new optical data. The updated trajectory and ephemerides would then be passed to Voyager sequence generation personnel in file form.

5.4 Spacecraft Sequence Generation

At 1330 the process called for the first of a series of sequence generation programs to begin execution under remote control from the Voyager control center, operating on the same 1100/81 computer just released by the Navigation activity. The POINTER program, a sophisticated geometry processor, combines inputs describing the spacecraft's trajectory, its attitude, target ephemerides, and scientists' targetting desires to produce requirements on scan platform pointing. 1-1/4 hours were allowed for this activity.

The second program of the sequence generation series, SEQGEN, controls another major program called SCANOPS Together, they convert spacecraft activity desires as a function of time into a sequence of actual on-board commands, and they validate that the commands do not ask the spacecraft to do something it cannot or should not do. Under the dedicated computer conditions, less than an hour would be required for this part of the process, but time for an aborted run followed by analysis and another full run brought the allocation up to two hours.

Knowledge that no spacecraft constraints would be violated was not a sufficient assurance that the very complex Voyager spacecraft would execute the generated commands in a way that would yield the desired results. Every sequence transmitted to Voyager goes through a detailed computer simulation. First the command/time pairs generated by SEQGEN are translated by a program called SEQTRAN into the bit patterns that are required by the ground command system. Then the massive spacecraft simulator called COMSIM is brought into action. It receives the bit stream and does everything with it that the spacecraft would do. The COMSIM output, a time-ordered listing of events executed by the spacecraft, is then compared with the requests. A match, or an acceptable explanation of differences , is required before transmission. Two hours were allowed for the SEQTRAN/COMSIM part of the process.

The output of SEQTRAN is called the Ground Command File (GCMD). It is the COMSIM input as well as the input to the ground command system. After COMSIM validation was complete, 30 minutes were allowed for the physical movement of the GCMD tape from the 1100/81 computer to the control center.

Since only small changes to scan platform pointing were being made in this final pass through the sequence software, problems were not expected. But experience had taught the Voyager Flight Team that, by definition, surprises occur when you least expect them.

5.5 Immediate Action Command Generation

The SCANOPS program, used in a stand-alone mode, can be used to generate the actual spacecraft commands that come closest to satisfying pointing requirements. This approach was chosen for the A551 pointing updates. The POINTER output would be used to define the required platform position change to the stand-alone SCANOPS. Manual checks would be made to assure that no spacecraft constraints would be violated and that the immediate action commands would not interact with the on-going sequence in any unexpected way. With that assurance, the results of SCANOPS operation could be used to define the immediate action commands needed to be manually generated. 2-1/2 hours in parallel with the sequence update generation were allocated to this activity.

5.6 Coordination/Meetings

The Satellite Pointing Update Process described to this point involves performing on a precision timeline a series of activities normally performed with minimum time pressure and multiple crosschecks over a several days period. Normally, 1100/81 processing takes place in a multi-user environment with attendant thruput inefficencies for any one program. For this exercise, only one major program at a time would be allowed to operate, in order to optimize thruput time. A special coordinator position was established for the critical 14 hour period to assure the smooth flow of the activity, and to keep Project management appraised of status so that redirection could be promptly provided, if needed.

At 1430, Navigation personnel were scheduled to present the results of their activity (5.3 above) to appropriate elements of the Project. This would be the indicator to whether the rest of the activities were needed at all, and if so, how large the pointing errors might be. The form of their report was one diagram, like the one in Figure 4, for each observation to receive updated pointing. From the diagram, the need for an update would be made obvious and a means to double check the processes described in 5.4 and 5.5 above would be automatically provided.

Two formal command conferences were scheduled, one at 1730 for all of the immediate action command updates to the executing A551 sequence, the second at 2000 for the A552 sequence update. At these meetings, all necessary data and arguments would be presented to the Mission Director for his approval of command transmission.

5.7 Command/Sequence Transmission

The transmission of the immediate action commands to the spacecraft was

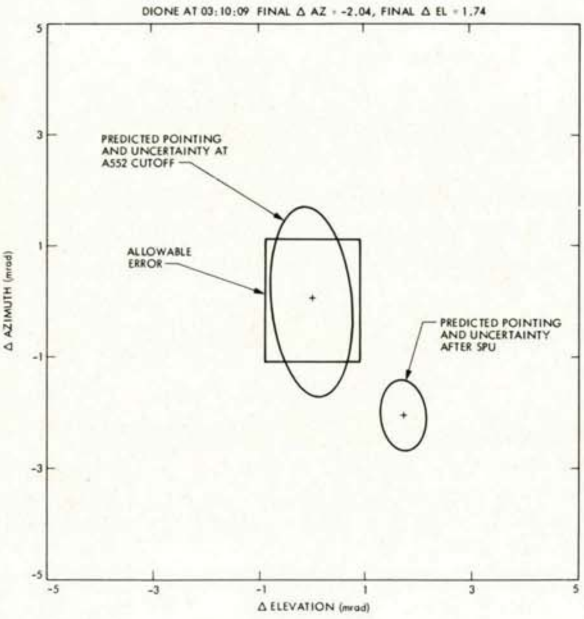

Figure 4. Typical Pointing Error Assessment Diagram

designed to follow routine procedures as much as possible, but some changes were made to improve reliability. The time between end of the sequenced platform slew and the observation ranged from 2 min:42 sec to 8 min:2 sec for the four A551 observations. To maximize the probability of success, each AZ-EL pair of update commands was to be transmitted such that the first bit of the first command would arrive at the spacecraft approximately 1 hr:25 min later at the predicted end of the second slew of the sequenced AZ-EL pair, and each update AZ-EL pair of commands would be transmitted twice.

A much larger window was available for the A552 sequence updates--basically extending from the time the A552 sequence was fully loaded to the time the ground transmitter would be turned off at 2355 in preparation for Saturn radio science activities.

6. PRACTICE

The Satellite Pointing Update process was practiced three times by the Voyager Flight Team, using simulated radiometric and optical data and essentially real sequences. In the first exercise many flaws in the procedure and timeline were uncovered, resulting in major revision to the timeline and institution of the coordinator role. The second exercise demonstrated that the revised procedure was sound, even when confronted with problems, such as a failed computer, which were intentionally introduced. The second exercise did result in a number of procedure and timeline refinements.

The final test was in conjunction with the Near-Encounter Test, the major readiness demonstration exercise during which the actual spacecraft is put through a sequence nearly identical to the most straining portion of the actual planned near-encounter. Only a few small refinements were needed. The Voyager Flight Team was ready.

7. RESULTS

As Voyager 1 approached Saturn, a set of trajectory correction maneuvers (TCMs) were performed to refine the spacecraft trajectory to meet a very stringent set of targetting constraints. The last of these maneuvers, TCMA9, was performed about 8-1/2 days prior to Saturn closest approach. The constraints were:

(1) The distance from the center of the zone theoretically swept clear by Dione of possible debris (R_{DCZ}) shall be no more than ± 1700 Km.

(2) The distance from diametric Titan occultation (D_{XTOCC}) shall be no more than ± 265 Km.

(3) The Saturn geocentric occultation exit time (T_{XTOCC}) by no more than ± 200 sec. from the time projected at TCMA9.

The Titan mean distance (R_T) was desired to be 7000 Km from the center of the satellite, but was allowed to float within reason since it could not be satisfied simultaneously with the above three constraints.

TABLE 2

Epoch	ΔR_{DCZ} (Km)	ΔD_{XTOCC} (Km)	ΔT_{XPOCC} (sec)	R_T (Km)	ΔR_T (Km)
TCMA9 Target (S-8½ days)	0	0	0	6860	0
A551 Cutoff (S-6¾ days)	-259.91	-12.25	-8.85	6829	31
A552 Cutoff (S-4¾ days)	-562.93	-15.35	-17.72	6800	60
S-3½ days	-785.51	-10.78	-21.47	6736	124
SPU Backup (S-1¼ days)	-1230.25	-25.96	-35.28	6599	261
Post-Titan SPU Final (S-16 hrs)	-1494.75	-20.11	-42.21	6523	337
Final Reconstruction (S+8 days)	-1479.25	-39.06	-45.84	6527	333
Constraint/ Desire	±1700	±265	±200	7000	float

The five columns of Table 2 show what happened. TCMA9 was able to be designed to satisfy the three constraints and to target within 140 Km of the desired Titan miss distance. However, as the days passed a pronounced drift close to Titan could be observed.(1) A near-violation of the Dione clear zone constraint could also be observed. The need for pointing updates was becoming obvious.

The well practiced Satellite Pointing Update process worked smoothly. Navigation personnel were able to incorporate the hoped for post-Titan radiometric and optical data. At the 1430 navigation results report, Figure 4 and a set of similar charts for other observations were presented. The forward projected effect of the drift evident in Table 2 upon the pointing for the update candidates is summarized in Table 3, which repeats Table 1 for easy comparison. Clearly, updates would be required.

TABLE 3

Sequence	Target Satellite	Allowable Error (mrad) ΔAZ	Allowable Error (mrad) ΔEL	Projected Error (mrad) ΔAZ	Projected Error (mrad) ΔEL
A551	Rhea	±0.87	±0.87	-2.09	+0.17
A551	S-11	±2.79	±0.87	+4.05	+4.33
A551	Rhea	±1.05	±0.87	-1.69	+0.47
A551	Mimas	±1.05	±0.87	-2.84	+1.41
A552	Dione	±1.05	±0.87	-2.04	+1.74
A552	Rhea	±3.32	±0.87	+16.72	+1.85
		±3.14	±0.87		
		±3.14	±0.87		
		±2.97	±0.87		
		±2.97	±0.87		
		±2.79	±0.87		
		±2.62	±0.87		
		±2.44	±0.87		
		±2.27	±0.87	↓	↓
A552	Rhea	±1.22	±0.87	+5.53	-1.24
		±0.87	±0.87	↓	↓

The sequence and immediate action command generation activities were well underway by this time, according to plan. Several other A552 observations, not originally thought to be in jeopardy, were found to be missing their mark. A decision was made to repair them also, since the added effort was small and the risk low.

All commands were transmitted on time. The entire process was executed with such ease that, except for the anxiety evident in key Flight Team personnel, an observer might have thought the operation to be routine.

(1) A thorough analysis of the cause of this drift is not yet complete, but preliminary results indicate that about 1/2 of it is due to errors in the Titan ephemeris, and about 1/4 each due to Saturn ephemeris and spacecraft ephemeris.

Did it work? Absolutely! The proof is in the pictures. Photo 1 is the Dione closest approach image, centered in the field of view with the first of the A552 sequence updates. Without update, an edge of Dione would have been clipped and, since color reconstructions are made from three or more successive images taken with different filters, a color picture with this resolution would have been nearly impossible. Dione is marked with many impact craters, the largest visible having a diameter of less than 100 Km. The sinuous valleys are probably formed by faults in the satellites icy crust.

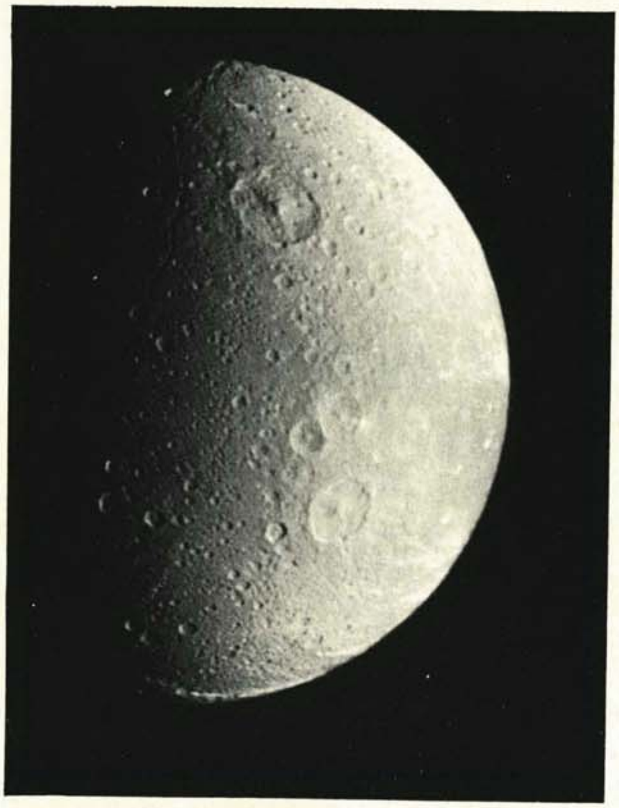

Photo 1.

Photo 2 is the Mimas closest aproach image, centered in the field of view by the last of the A551 immediate action command updates. Without the update, even more severe clipping than with Dione would have been experienced. The surface of the 385 Km diameter moon is heavily cratered, a record of bombardment occurring early in the solar system's history some 4 billion years ago. Craters as small as 2 Km across can be resolved.

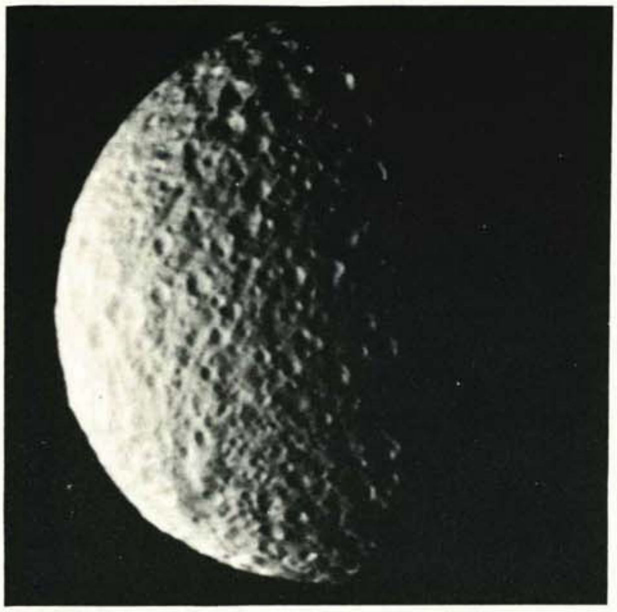

Photo 2.

Photo 3 is the nine-image Rhea mosaic updated in A552. The missing coverage is a small example of what was being avoided--gores in mosaics and clipped single images. But the update process did not fail us here--it saved us. Without update, the camera would have been aimed 18 milliradians away, and there would only be nine terrific pictures of black sky to admire and analyze.

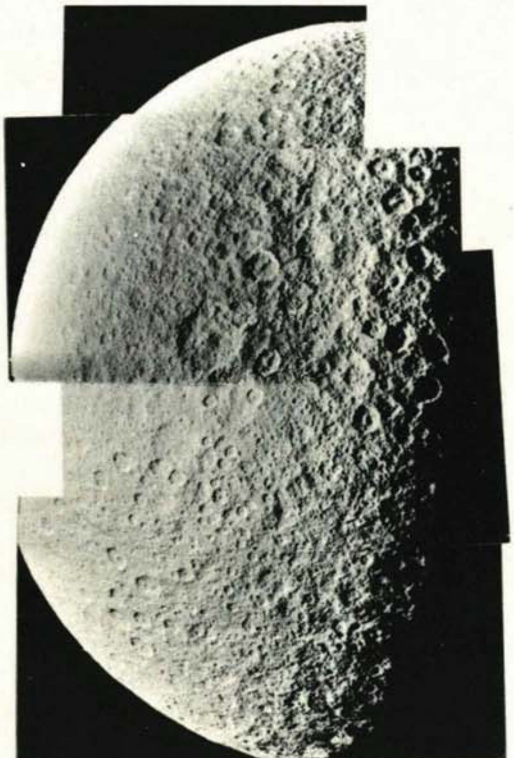

Photo 3.

Finally, in Photo 4 we see six successive (a through f) frames taken of yet unnamed S-11. The tiny pock-marked moon is an irregular 135 by 70 Km in size. Note the progressive shadow of Saturn's exotic F-ring across the face of the satellite. The timing was a stroke of luck, but it would have taken the same luck to have seen S-11 at all without the updates.

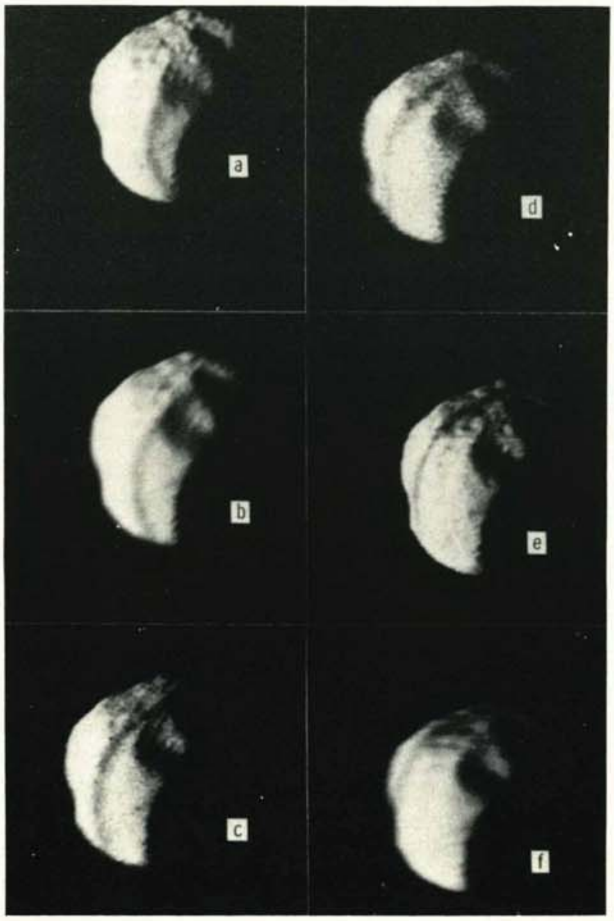

Photo 4.

It was definitely worth the effort. A similar activity is planned for the Voyager 2 encounter with Saturn on 26 August 1981.

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