SpaceOps Conferences
16-20 May 2016, Daejeon, Korea
SpaceOps 2016 Conference

AIAA 2016-2415

Voyager Interstellar Mission: Challenges of Flying a Very Old Spacecraft on a Very Long Mission

Sun Kang Matsumoto*
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, 91009

Two Voyager spacecraft were launched in 1977. After the successful flybys of Jupiter and Saturn by both Voyagers and Uranus and Neptune by Voyager 2, the mission has been extended for another 30 years in search of the transition region between the dominance of the solar energy and interstellar energy. The Voyager Interstellar Mission (VIM) started on January 1, 1990. It can be characterized by several factors including extremely long communication distances, aging hardware, reduced staffing levels and difficulty in obtaining Deep Space Network (DSN) resources necessitated by the increasing distance between the spacecraft and Earth. The mission was redesigned to compensate for such factors while maximizing the science return. After 25 years of VIM and several significant science discoveries, both Voyager spacecraft are still functioning well and the Voyager flight team is preparing for an even longer mission - until the year 2025 and beyond. In order to work around the challenges and to continue the mission even further, the team has been implementing numerous changes, mainly through flight software modifications and hardware reconfiguration. The major drivers for the changes are two-fold: resource constraints (such as decreasing power output and difficulty in obtaining the necessary DSN coverage) and anomalies due to the aging hardware. The majority of changes occur through flight software modifications so the state of the on-board responses is appropriate for the changing space environment and mission phase, and the flight software is compatible in allowing the maximum data gathering. The on-board flight software routines such as baseline sequence, fault protection routines, the High Gain Antenna POINTing to Earth (HPOINT) table, and long-term events table need to be maintained through flight software updates. The changes also occur through hardware reconfiguration such as selecting the backup Hybrid Buffer Interface Circuits (HYBIC) or attitude propulsion thrusters. This paper will describe the challenges of VIM and what has been done to overcome or mitigate those challenges. The primary focus will be the major flight software changes made during VIM and the changes that are in store for the near future in preparation for continuing the extended mission, from the originally projected year of 2020 out to the year 2025 and possibly beyond.

I. Introduction

Before the start of Voyager Interstellar Mission (VIM) on January 1st of 1990, both Voyager spacecraft had already completed more than twelve years of space operation and returned a vast wealth of scientific information. The primary mission was completed by Jupiter and Saturn encounters by both Voyager 1 (V1) and Voyager 2 (V2), and Uranus and Neptune encounters by V2. The mission has extended for another 30 years to explore the regions beyond our solar system and search for its termination shock and heliopause.

A. Spacecraft

The two spacecraft, V1 and V2, are identical. Figure 1 shows the spacecraft in its flight configuration.[1] Key spacecraft characteristics include the following.

1) Three-axis stabilized system uses celestial or gyro referenced attitude control to maintain pointing of the High-Gain Antennas (HGA) toward Earth.

---

* Voyager Fault Protection and CCS Flight Software Systems Engineer, Flight Electronics and Software Systems Section, 4800 Oak Grove Drive / Mail Stop 600-100.

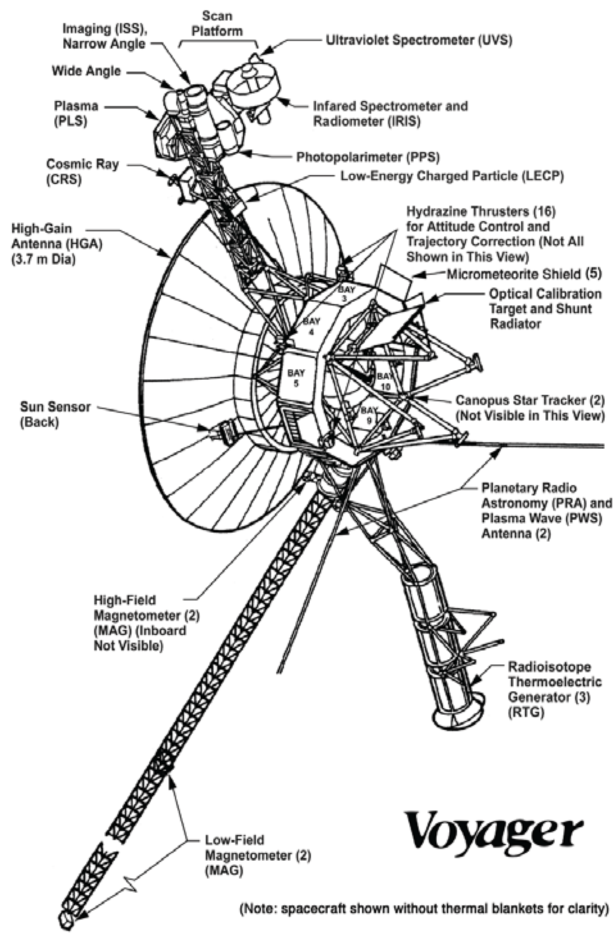

Figure 1. Voyager Spacecraft

2) Three on-board computers are reprogrammable.

- The Computer Command Subsystem (CCS) is responsible for sequencing and controlling functions. The CCS contains fixed routines such as command decoding and fault protection routines, HGA Pointing information (HPOINT), and spacecraft sequencing information.
- The Attitude and Articulation Control Subsystem (AACS) is responsible for controlling spacecraft orientation, maintaining the pointing between the HGA and Earth, and controlling attitude maneuvers.
- The Flight Data Subsystem (FDS) is responsible for configuring and operating science instruments. The FDS collects engineering and science data and formats the data for downlink transmission.

3) The eight track Digital Tape Recorder (DTR) is used as a data rate buffer to record and playback the primarily science data at data rate commensurate with Deep Space Network (DSN) resources and spacecraft capability. Currently, only the high-rate Plasma Wave Subsystem (PWS) science data on V1 are recorded and played back.

4) The radio communication system uses an S-band receiver for uplinking command and X-band transmitter for downlinking telemetry. The command rate is 16 bits per second (bps) and the downlink is at 160 bps normally and 1400 bps for playback of the recorded high-rate PWS data. All data are transmitted from and received at the spacecraft via the 3.7 meter (m) HGA.

5) Three Radioisotope Thermoelectric Generators (RTGs) supply the electrical power.

6) The scan platform on V2, including all the science instruments on the platform, was completely shut down in 1998. On V1, the instruments and heaters were powered off one by one to compensate for RTG power decay. The Ultra Violet Spectrometer (UVS) was the last instrument on the scan platform remained on; it was shut down in 2016.

B. Science

The science payload during the prime mission consisted of 10 instruments (11 experiments including radio science). Only five experiments are still funded. They are:

1) Magnetometer Subsystem experiment (MAG),
2) Low Energy Charged Particle Subsystem experiment (LECP),
3) Plasma Subsystem experiment (PLS) – V2 only,
4) Cosmic Ray Subsystem experiment (CRS),
5) Plasma Wave Subsystem experiment (PWS)

The V1 PLS instrument and its heater were permanently powered off in 2007 to conserve power for other activities because the instrument was not working properly. The Planetary Radio Astronomy (PRA) and UVS instruments were funded at the beginning of VIM but the funding was discontinued. Subsequently, they have been powered off (PRA in 2008 for V1 and V2, UVS in 2016 for V1 and 1998 for V2) to reduce the power consumption although the instruments were functional.

Both spacecraft, V1 and V2, are exploring the interaction of the heliosphere with the local interstellar medium. The goal of VIM is to make the first observations of the environment outside our heliosphere. V1 crossed the termination shock on December 15, 2004 at 94 Astronomical Unit (AU), and made the first in situ observations of the heliosheath, the region of shocked solar wind beyond the termination shock. V2 crossed termination shock on September 5, 2007 at 84 AU.[†]

In August 25, 2012, at 122 AU, V1 crossed a very sharp, totally unexpected boundary and entered interstellar space, the first spacecraft in history to do so. V2 is observing heliosheath characteristics very different from those observed at V1. It is unknown exactly when V2 will enter interstellar space but it is generally expected to occur within a few years. [2]

C. Mission

VIM was designed with a duration of 30-plus years in mind. Reference 3 provides detailed information of the mission in the beginning of VIM. The major characteristics of VIM, such as long Round Trip Light Time (RTLT), aging hardware, DSN resources, and reduced staffing, had to be factored into design and implementation of sequencing, Flight Software (FSW), HPOINT, and operations.

1) Sequencing

Unlike during the prime mission when a sequence was developed and sent frequently (typically, a couple of days to a week during a planetary encounter and every month between encounters), the sequencing strategy during VIM has to be compatible with minimum ground commanding. The repetitive nature of activities have been implemented in the baseline load which is an annual cyclic that automatically restarts itself every year. The baseline calls several subroutines, which are also cyclic in nature, and a subroutine, in turn, calls block routines. A block routine is a group of related activities such as powering gyros-on or PWS-RECording (PWSREC) activities. Regular Science data gathering and periodical calibrations are included in the baseline load. Non-repetitive, long-term activities are implemented in the separate entity called long-term events table and are activated based on the CCS internal timer called "HCLOCK."[4] Overlay loads and mini sequences augment the baseline load and long-term events table by providing a mechanism for the non-repetitive nature of short-term science and engineering activities. An overlay load typically covers activities for a quarter (three months) whereas a mini sequence spans a much shorter time usually to cover one activity, such as redoing a PWSREC Playback (PWSPB) to recover the lost data. The mission will continue even in the absence of any overlay load or mini sequence, albeit without any extra activities or enhancements.

2) FSW

Prior to the start of VIM, major FSW modifications were done in all the computers (AACS, CCS and FDS). All the non-essential routines, for example, related to video cameras or encounters, were deleted and some of the codes were relocated to make the memory more available and contiguous, so new functions for VIM could be added for a 30-year long-term mission.

All the Fault Protection Algorithm (FPA) functions were modified as well to configure the spacecraft for a long duration of the mission, and non-essential routines were deleted. In addition, several enhancements were implemented specifically for minimum ground commanding in the event of an FPA entry.

The Backup Mission Load (BML) is FSW that gets activated when the spacecraft can no longer receive any commands sent from the ground. It was first implemented on V2 after the loss of the backup receiver in 1978 and has been maintained since. When activated, it basically modifies the baseline load sequence to continue the mission in reduced scope. Due to the characteristics of the mission, BML has been implemented for V1 also in VIM. The BML has never been activated in either of the spacecraft.

3) HPOINT

All the HPOINTs (the spacecraft orientation information) were stored in 1989 in a 'HPOINT Table.' The HPOINT table was implemented in a compressed method to save memory space. The HPOINT template stored in the CCS FSW takes the data from the table and converts them to several pointing commands. The HPOINTs were loaded with as much as the CCS memory was available at the start of VIM, i.e., up to 2020 for V1 and 2017 for V2. This was possible due to more memory being available in the CCS after deletion of some encounter-specific routines, but also by trading redundancy with memory space (some of functions are only in one of the CCS processors).

4) Operations

The staffing level, around 50 at the start of VIM including management functions,[3] has been reduced to about 12 full time equivalents. The reduced staffing levels require everyone to performs multiple functions.

[†] Voyager homepage: http://voyager.jpl.nasa.gov/index.html

During the prime mission and early VIM, Voyager had been using the JPL-developed software programs called SEQTRAN (to generate sequences) and COMSIM (to simulate sequences and CCS FSW changes). They ran on now-antiquated UNIVAC mainframe computers. Shortly after the start of VIM, these programs were converted over to more modern UNIX-based SEQTRAN and High Speed Simulator (HSSIM). They were rewritten to maintain the same functionality of the old SEQTRAN and COMSIM, and tailored for VIM. Rewriting and testing required significant effort from the developers and the project personnel; however, the end result is much improved speed and efficiency.

In the beginning of VIM, the ground-based telemetry and command systems began a transition from project dedicated hardware and software to multi-mission hardware and software called the Advanced MultiMission Operations System (AMMOS). Whenever there is a new version of AMMOS software delivered, it is necessary for the project to test the new version to ensure the compatibility with VIM.

The following are some examples of the Voyager-specific operations:

- Although there are multi-mission mission controllers available, Voyager uses project mission controllers who are also engineers experienced and well informed with specifics of the spacecraft and mission.
- Voyager Alarm Monitor Processor Including Remote Examination (VAMPIRE) is an operations tool that was developed to automatically process the broadcast telemetry data, and monitor the spacecraft whenever receiving downlink. VAMPIRE detects alarm conditions and contacts on-call personnel who, in turn, can remotely log onto the system and evaluate the data.
- Monitor/Analyzer of Real-time Voyager Engineering Link (MARVEL) is another tool that monitors the CCS telemetry and alerts the operators whenever the data deviate from simulated predictions. It also suggests possible problematic areas for troubleshooting.

II. Challenges

The challenges facing the Voyager Flight Team (FT) seem endless: the extremely long distance between the spacecraft and the Earth, hardware operating for nearly 40 years in space, decreasing RTG power, difficulty in obtaining DSN coverage, disappearing knowledge base, and many more.

A. Distance between the Spacecraft and the Earth

The biggest challenge by far is the distance between the spacecraft and Earth and its long RTLT. V1 distance is increasing by about 3.6 AU each year and V2 about 3.3 AU. On February 17, 1998, Voyager 1 passed Pioneer 10 to become the most distant human-made object in space [Voyager homepage]. Table 1 shows the distance in AU and RTLT, at each milestone.

Table 1. Distance and RTLT for V1 and V2

Milestone	V1		V2	
	AU	RTLT	AU	RTLT
Jupiter encounter Mar 79 (V1); Jul 79 (V2)	5.3	1 h 16 m	5.3	1 h 45 m
Saturn encounter Nov 80 (V1); Aug 81 (V2)	9.5	2 h 49 m	9.6	2 h 52 m
Uranus encounter Jan 86 (V2)			19.1	5 h 30 m
Neptune encounter Aug 89 (V2)			30.2	8 h 10 m
Start of VIM (Jan 1990)	39.9	11 h 14m	31.1	8h 54 m
Termination Shock Dec 2004 (V1); Sep 2007 (V2)	94.0	26 h 16 m	83.7	23 h 6 m
Heliopause Aug 2012 (V1)	121.6	33 h 40 m		
Currently (May 2016)	134.9	37 h 11 m	111.1	30 h 41 m
End of 2020	151.4	42 h 11 m	125.9	35 h 6 m
End of 2025	169.2	47 h 8 m	141.7	39 h 32 m

Such a great and increasing distance poses many challenges for mission operation and the available DSN coverage often occurs during the “off-shift” hours. Consequently, the FT tries to minimize real time commanding as much as possible. The majority of events are implemented in the baseline load, and the HPOINT Table is loaded as much as the memory allows. Command Loss (CMDLOS) timer, the timer that triggers CMDLOS FPA entry when it reaches to the pre-set value, is set for six weeks. It is still desirable to send the command to reset the timer every week but it is a best effort approach based on the DSN resources, usually without downlink coverage for command receipt verification. (The receipt of a command is verified indirectly by the CCS hourly status data when the telemetry is available.) The distance becomes an increasing hardship in time of an anomaly. Anomalies tend to occur when the spacecraft is not monitored which makes it much more difficult to diagnose the problem. By then, some of the signatures of that anomaly may have been overwritten. For example, when the V2 experienced a bit flip in the FDS in 2010, it took about two weeks to recover enough to receive the engineering data, and another two weeks to receive the science data. It took another four and one-half months to adjust the timing delay caused by the anomaly and resynchronize the CCS and FDS clocks. Realigning the baseline events to the regular schedule had to be delayed even longer due to other activities competing for the resources. In the meantime, adjustments had to be made in mission operations to compensate for this timing shift.

B. Aging Hardware

After being in space for nearly 40 years and going through a harsh environment, it is only natural for Voyager spacecraft to experience various hardware degradations and failures.

1) V1

There is no backup X-band Traveling Wave Tube (TWT) amplifier available for V1 due to severe degradation of the backup unit. Conserving the X-TWT is so crucial to the mission that operating it in high power is allowed for critical operations only such as a playback, spacecraft maneuver, or in the event of an FPA entry.

The Hybrid Buffer Interface Circuits (HYBIC) on V1 was switched to the backup unit in 2002 due to a failing component inside the HYBIC Analog to Digital (A/D) converter.[‡] The star tracker on the original HYBIC was performing well at the time of the switch but each HYBIC has a unit (A/D converter, sun sensor, and star tracker) dedicated to the HYBIC. The star tracker on the current HYBIC is degrading rather rapidly and closely monitored; it is quite likely that a HYBIC switch back to the original is needed before the end of the mission. [§] However, there is a good possibility of the component healing itself while unpowered based on the experience from the Topex and Galileo spacecraft [T. Nguyen and B. Chrlan].

The CCS and/or FDS clock on V1 has been showing signs of degradation by shifting phase with one another more frequently in recent years, requiring more frequent CCS clock resets (resynchronizing the CCS clock to the FDS frame count) and CCS timing tests. The CCS and FDS clocks are generated from the same source and it is not known whether the CCS or FDS clock, or both, is degraded. The fix however always has been to synchronize the CCS to the FDS.[**]

The Ultra-Stable Oscillator (USO) failed in 1991. It was changed to an Auxiliary Oscillator (Aux Osc – the backup unit) by fault protection without any long-term effect on the spacecraft or mission.

2) V2

The power decoder relay matrix problem that first manifested in 1998 makes commanding of the spacecraft extremely difficult. Basically, the faulty decoder may cause an issuance of extraneous power commands in addition to the intended command.[††] The anomaly first occurred in 1998, after more than 20 years in operation, and issued the unintended S-band Exciter (Exc) off command, resulting in the total loss of communication for 2.5 days until the ground command was sent to turn the Exc back on. The problem has occurred two more times, during the HYBIC Switch Test in 2006 and Roll Branch Switch in 2011, issuing unintended power commands.

There is no backup receiver on the spacecraft and the Tracking Loop Capacitor (TLC) on the prime receiver failed in 1978, causing an extremely narrow receiver bandwidth subject to thermal variation. Performing the best lock frequency checks to determine the most probable uplink frequency for commanding at any given time is an on-

[‡] Hogle, T., JPL Internal memo, Voyager IOM SCT-02-009, “Report on S/C 31 HYBIC 1 Test and Permanent HYBIC Switch DOY 02-079 to 091,” JPL, 2002. The analysis on the failing component was done by JPL reliability engineers, Nguyen, T. and Charlan, B.

[§] Private communication with Weeks, T., Voyager AACS Hardware Engineer, February 2016.

[**] Private communication with Zottarelli, L., Voyager CCS/DTR/FDS Engineer, February 2016.

[††] Cunningham, G., JPL Internal memo, Voyager IOM SCT-07-017, “Spacecraft 32 Report on Extraneous Power Commands. ISA’s 8428, 8429 and 8430,” JPL, 2007.

going effort since the TLC failure during the prime mission. It is becoming more challenging as the distance between the spacecraft and Earth increases.

The HYBIC A/D converter on V2 is degrading similar to V1 and closely monitored; a switch to the backup unit may be necessary before the end of the mission [T. Weeks].

3) V1 and V2

All pitch/yaw and roll thrusters on both spacecraft are on the backup unit now, some swapped by fault protection and some ground commanded due to imminent failures or severe degradation.

The secondary FDS memory (one-half) on V1 and a block (256 words/block) of the FDS memory on V2 experienced a permanent failure during the prime mission and are not usable. Some other FDS memory locations have experienced unexplained changes but the FT was able to restore them back.

C. Resources

Decreasing RTG power output is the biggest limiting factor for the Voyager extended mission. The gradual power reduction throughout VIM is an on-going process to compensate for the RTG decay, currently about 4 Watts (W) per year. The total power output for V1 is 252 W and V2 is 254 W as the writing of this paper. It requires about 200 W for V1 and about 198 W for V2 to operate the spacecraft without any science instruments.[‡‡]

DSN usage, resulting mainly from the distance, is another big challenge. Sending a command to the spacecraft requires a 70 m antenna. Receiving telemetry from the spacecraft varies. Since 2010, a 70 m or an array of two 34 m antennas has been required for V1 to receive160 bps of cruise telemetry which is the nominal operating mode. V2 can still receive the 160 bps telemetry with one 34 m antenna until 2017, at which time the use of a 70 m or an array of two 34 m antennas will be required.[§§] The X-band TWT in low power, which is a nominal operating mode, is assumed in both cases. The highest data rate currently available for Voyager spacecraft is 1400 bps of playback on V1 and that requires an array of one 70 m and two 34 m antennas. In addition, only the Australian complex can communicate with V2 due to the location of the spacecraft.

Disappearing expertise, in personnel and documentation, is also something that makes the operations challenging. Many of the personnel who designed and built the spacecraft have passed on. Losing expertise is also a challenge for the science team not only in operating the instruments but also in reviewing and analyzing the data.

D. Other Challenges

In addition, the FT also has to work around a lack of a hardware test bed, the limited memory of on-board computers, and antiquated programming languages.

The Capability Demonstration Lab (CDL), the testbed used during the prime mission, could not be maintained and had to be abandoned at the start of VIM. The failures of the testbed were too often, even in pre-VIM, due to aging hardware and disappearing repair expertise. The project had to move to a new location in early VIM and the CDL did not survive the move. There are no simulators for the AACS or FDS and only the CCS has a simulator, i.e., HSSIM. As a result, any FSW changes other than something very simple have to be done in the CCS.

The CCS on each spacecraft has 4K memory in each processor, so 8K in total, but the majority of functions are in both processors for redundancy. To make the best use out of such limited memory spaces, different programmers used all kinds of tricks in maintaining and adding patches over the life of the mission, resulting in extremely unstructured code that is prone for mistakes. It is crucial to validate all the sequence products and any kind of FSW changes thoroughly in HSSIM.

Both the AACS and FDS use assembly language. The CCS uses assembly language and Voyager-unique pseudo code (interpreter). As a result, it is difficult to attract younger programmers to join the project.

III. Strategies for Meeting the Challenges

Despite all these challenges, both Voyager spacecraft have been working well and have returned a wealth of valuable science information since the start of VIM. The team has been continuously working around the anomalies and hardware failures and degradations, adapting to new space and ground environments, and implementing additional features to improve operations and to extend VIM for an even longer mission.

These changes are implemented, mainly through the CCS FSW modifications and hardware reconfigurations. In addition, reducing the power load to compensate for the RTG decay is a continuing effort.

[‡‡] Private communication with Medina, E., Voyager AACS FSW and Power Subsystem Engineer, February 2016.

[§§] Private communication with Ludwig, R., Voyager Telecom Engineer, March 2016.

A. FSW Modifications

Even though the FSW for all three on-board computers was extensively modified in the beginning of VIM with no major changes along the way in mind, it has become an ongoing process to modify the CCS FSW (system FPA routines are implemented in the CCS FSW) to ensure compatibility of the on-board responses to the external environment. Adding enhancements to the FPA routines whenever feasible is also a continuing effort to leave the spacecraft in the best configuration in case of a BML entry. In addition, anomalies, hardware degradation and failures, and decreasing power output make modifications unavoidable.

The following are some of significant CCS FSW modifications done in VIM.

1) Baseline Load Sequence/Long-Term Events Table

In planning and development of VIM, the activities in the baseline load were designed to be synchronized with the DSN view period. The painstaking details went into aligning the major activities to occur in the center of DSN passes. However, after many years in operation, the small differences in timing had accumulated enough that it was necessary to shift the timing of the baseline to better position the critical spacecraft activities to the center of DSN passes. This timing adjustment was made in 2006 for V1 and 2009 for V2

The science team requested more recording and playback of the PWS science instrument data in anticipation of the termination shock and heliophause. AHELIO, AHELI1, and AHELI2 routines were added to V1; BHELIO and BHELI1 routines were added to V2.

- A(B)HELIO: added to record rapid (every 9.5 hours) recording of PWSREC for two weeks,
- A(B)HELI1: added to record one extra frame of PWSREC midweek,
- AHELI2: added to record two extra frames of PWSREC midweek.

These PWSREC activities are in addition to the baseline PWSREC that occurs every week. The data have to be played back after 30 recordings as the DTR has limited space and the data will be overwritten. The playback data of V2 were found to be not usable due to the degraded instrument so its recording and playback of PWS were discontinued in 2007.

Several routines were added on-board to perform full Memory Read Out (MRO) - reading out all the locations of all three computers - in the 40 bps data rate. One 34 m antenna can receive 40 bps data until the end of the mission. For comparison, by 2014, it required an array of one 70 m and two 34 m antennas to receive V1's full MRO data in higher data rate (1200 bps) we were using at the time.

As more memory became available on V2 after discontinuing PWSREC and PWSPB, some major functions were added to the long-term events table. The added functions include 1) annual full MRO in 40 bps, 2) CCS timing test which checks the timing consistencies between the CCS and FDS, and also between the two CCS processors, and 3) reset of HCLOCK (the CCS internal hourly counter) so sequencing can be continued all the way out to 2030 and beyond, or as long as enough power exists.

On V2, one bit in the FDS had flipped in 2010 due to an anomaly. The frame interrupt to the CCS had not been processed during the anomaly and, as a result, the FDS frame start was delayed by 194 frames. One frame equals to 48 seconds so this is a delay of 2 h 35 m 12 s. This caused all the frame-driven events to occur 2 h 35 m 12 s later than initially scheduled. The flipped bit had to be reset in order for the FDS to function properly and the baseline load had to be realigned to the pre-anomaly timeline. It also required adjusting the frame count and resynchronizing the CCS clocks to the FDS frame count.

2) Extension of HPOINT Table

At the start of VIM, the HPOINTs for the duration of VIM were loaded as much as the memory permits – up to 2020 for V1 and 2017 for V2. In 2009, with more CCS memory freed from the previous HPOINT calls clocking out and the thought of further extending VIM, HPOINT Tables for both V1 and V2 were extended and reloaded out to year 2030.

3) Modification of FPAs

AACS Power Code Processing (AACSIN) routine responds to the AACS anomalies by processing Power Code (PC) received from the AACS. The routine has been modified and several major patches have been added in VIM.

- There is not enough power to allow the use of gyros after the first quarter of 2017 for V1. The gyro use for nominal operations was stopped in March of 2016 for V2. Because it is critical to have gyros to recover the spacecraft from certain anomalies, a CCS FSW modification - Fault Protection use of Gyros (FPGYRO) patch - is being implemented to allow the use of gyros temporarily after there is no power margin available for such use. Prior to when a gyro is powered on, something has to be powered off to compensate for the power required for the use of gyros. After much debate on pros and cons of which load may be of less risk, the Bay 1 Heater was decided for that load. It is a complex patch that requires a big chunk of memory due to the way the CCS FSW has been written in the past; almost no flexibility had been planned for this part of the code since it was not envisioned to be modified in such ways. The patch is being implemented for V2 as the writing of this paper, and planned to be implemented in 2017 for V1.

- On V2, PC 10/20 Patch was added to mitigate the risks from the power decoder relay matrix problem. The patch issues dummy commands instead of power commands, thus avoiding issuance of potentially harmful power commands, and in turn, risking a PWRCHK undervoltage entry. As with the FPGYRO patch, it was complex due to the way this part of the CCS code had been implemented.
- The timer that takes the spacecraft to sun pointed attitude has been increased from 2 days to 30 days to accommodate the long RTLT, and operations response time due to the reduced staffing level and DSN requirements.

CCS Error routine provides the spacecraft a means of responding to certain anomalous CCS hardware and software conditions, placing the spacecraft in a quiescent state and wait for ground intervention. While this was ideal during the prime mission, it is not practical for VIM, considering aforementioned RTLT and resources constraints. A CCS FSW patch was developed and implemented in 1995, and linked on the spacecraft in 2006 for V1 and 2005 for V2 to automatically restart some of the critical functions in the event of an Error entry. This patch was exercised in flight in 2014, nearly 20 years after it was installed, when one of the CCS processors went into an error entry on V1; the patch worked as designed.

Command Loss (CMDLOS) routine provides a means for the spacecraft to automatically respond to an on-board failure resulting in the inability to receive ground commands. The routine alternates different hardware units that affect the commanding problems in an attempt to restore the commandability. CMDLOS had been modified extensively to configure the spacecraft to the lower power mode and the separation times between the commands have been extended to accommodate the long RTLT and FT response time. On V2, the routine has been modified to mitigate the risk from the faulty power decoder relay matrix.

Power Recovery (PWRCHK) routine configures itself to a safe, low-power operating mode following a power subsystem undervoltage condition, a main to standby inverter switch, or a CCS tolerance detector trip. Reviewing and modifying the routine is ongoing to reflect the changing environment such as incorporating the power reduction measures. For example, the S-band carrier only mode (radio signal without any telemetry) has been added as the last resort. The spacecraft will be placed in a mode that needs least power and telecom margin, and waits for the ground intervention. For V2, the routine has been modified to mitigate the risk from the faulty power decoder relay matrix.

Radio Frequency Power Loss (RFLOSS) routine provides the spacecraft a means of automatically recovering from a failure of an S-band or X-band exciter or transmitter. It was modified in response to spacecraft anomalies (USO failure on V1 and power decoder relay matrix anomaly on V2) and to incorporate the FT response time in the VIM environment. The S-band carrier only mode has been added as the last resort as well.

B. Hardware Reconfiguration

The major hardware failures and degradation have been presented in "Challenges" section. Table 2 summarizes the hardware reconfiguration in VIM for V1 and V2.

Table 2. Hardware Reconfiguration in VIM for V1 and V2

Hardware	V1		V2	
	Date	Switched By	Date	Switched By
HYBIC (A/D Converter, Sun Sensor, Star Tracker)	2002-087	Ground Commanding		
Thrusters Pitch/Yaw Roll	 2002-148 2004-125	 Ground Commanding Ground Commanding	 1999-244 2011-318	 Fault Protection Ground Commanding
USO to Aux Osc	1992-245	Fault Protection		
S-band Exc			1998-316	Fault Protection
X-band Exc			1998-316	Fault Protection
S-band TWT			1998-316	Fault Protection
X-band TWT			1998-316	Fault Protection

C. Power Reduction

Due to the decreasing RTG power output, it is necessary to permanently power down some loads as a part of nominal operation. This is normally done by commanding the specific load(s) to be powered off, and modifying the on-board routines in the CCS FSW so these loads will not be powered back on in the event of an FPA entry. Tables 3 and 4 show those loads that have been turned off in VIM for V1 and V2, respectively.

Table 3. Power Reduction List for V1

Year	Load
1990	IRIS Flash-off Heater Off
	WA Camera Off
	NA Camera Off
1995	PPS Supplemental Heater Off
	NA Optics Heater Off
	IRIS Standby A Supply Off
1998	WA Vidicon Heater Off
	NA Vidicon Heater Off
	IRIS Science Instrument Off
2002	WA Electronics Replacement Heater Off
2003	Azimuth Actuator Supplemental Heater Off
	Azimuth Coil Heat Off
	Scan Platform Slewing Power Off
2005	NA Electronics Replacement Heater Off
2007	Pyro Instrumentation Power Off
	PLS Science Instrument Off
	PLS Replacement Heater Off
2008	PRA Science Instrument Off
2011	IRIS Replacement Heater Off
2014	Scan Platform Supplemental Heater Off
2015	UVS Replacement Heater Off
2016	UVS Off

Table 4. Power Reduction List for V2

Year	Load
1991	PPS Science Instrument
1994	NA Optics Heater Off
1996	WA Vidicon Heater Off
	NA Vidicon Heater Off
1998	WA Electronics Replacement Heater Off
	IRIS Replacement Heater Off
	NA Electronics Replacement Heater Off
	Azimuth Actuator Supplemental Heater Off
	UVS Science Instrument Off
	UVS Replacement Heater Off
	Azimuth Coil Heat Off
	Scan Platform Slewing Power Off
2006	Pyro Instrumentation Power Off
	TCM Chamber Press Transducers Off
2007	IRIS Science Instrument Off
	Termination of DTR operations
2008	PRA Science Instrument Off
2011	AP Branch 2 Backup Heater Off

D. Other Efforts

Considering the characteristics of VIM, it is easy to see why there are nearly 200 contingency files built, validated, and stored in the project database for ready use. The contingency files are valuable resources in time of an anomaly, such as FDS Bit Flip anomaly experienced in 2010.

Due to the reduced staffing going into VIM and further stream-lined funding afterward, the project does not have any thermal analyst on staff; the project has been relying on the expertise from the thermal section when the need arises. This worked in the beginning, but it has become increasingly difficult as the duration of VIM increases and the former experts disappear. It was decided to build a new desktop model to analyze the thermal effects of turning off subsystems in order to conserve spacecraft power and model the effects on the propellant lines. The model has been completed and is being validated by the project.

Since power is one of the most precious resources at this point in the mission, more accurate measurement of the power margin available on the spacecraft is crucial. Changes to the FDS and ground software were implemented to get more power data samples by utilizing the telemetry channels which had been discontinued during VIM. In addition, some flight tests are being conducted to better characterize the spikes in the power margin data seen in the telemetry. This required using some functions that have not been used since 1979.

Everyone on the FT multitasks, so cross-training may sound natural; however, personnel is another resource that can be stretched thin. It is a best effort approach to carve out any time for cross-training. In addition, the team employs some unusual approaches, such as keeping "ex-Voyagers" informed as much as possible and maintaining good rapport with retirees.

IV. Future

V2 is expected to enter the heliopause soon, although the exact date is unknown. It is hoped to occur while there is enough power to operate all the science instruments currently on, including PLS.

Beginning around year 2020, it will be necessary to start powering down the then-active science instruments and their heaters in responses to decreasing RTG power. The power down will consist of either turning instruments off sequentially or turning instruments off and on in a power sharing mode to maintain an adequate power margin. In general, the heater will be powered off before the instrument for CRS, LECP and PLS instruments. PWS and MAG do not have heaters. In nominal operation, the science team will monitor the instrument when its heater(s) are powered off, and make further decisions. For example, if an instrument fails by not having its heater on, then a decision will need to be made as to whether to give up the instrument or turn the heater back on (and turn off a heater of another instrument to compensate for the power). It will be a complicated process that requires human and DSN resources.

The DTR is required to stay on to prevent hydrazine lines from freezing. For V1, another 3.6 W is needed for DTR slews and recordings as long as the PWSREC and PWSPB activities are continued.

There will not be enough power to operate gyros after the first quarter of 2017 for V1. All the events that require the use of gyros, (i.e., antenna sun sensor calibrations, MAG roll maneuver, and LECP roll maneuver observations), will be stopped for nominal operations, and the baseline and BML will be modified to delete the gyro activities. The gyro use for nominal operations was stopped in March of 2016 for V2 and the FPGRYO patch has been loaded to allow temporary use of gyros for fault protection. The patch will be implemented on V1 in 2017 prior to terminating the use of gyros for nominal operation.

Another FSW modification that is being planned is a BML science instrument power down list for both spacecraft. There will be a date associated with each instrument or a heater according to their shutdown order, heaters before the instruments in general, based on the predicted RTG power output. Because of the interaction between this list and other on-board FSW routines, it will be necessary to include commands and instructions to modify the FSW to maintain the compatibility. The shutdown order or date may be updated based on the performance of the instruments and the RTG power output, as long as the commanding capability exists. Tables 5 and 6 list the planned shutdown order of the science instruments and heaters in BML for V1 and V2, respectively.

Table 5. Science Instrument Power Down Order in BML for V1

Activities (Power Off/On)
LECP Main Supplemental Heater Off
LECP LEPT Supplemental Heater Off
LECP Stepper Motor Off
CRS Replacement Heater Off
LECP Off
CRS Off
DTR Operation Stop/ PWS Low Rate
PWS Off
MAG Off/PWS On*
PWS Off

*PWS takes less power than MAG.

The HPOINT tables have been extended until 2030 for both V1 and V2. The CCS HCLOCK Reset has been added for V2 and is planned to be added for V1 to allow sequencing until 2030 and beyond, or as long as enough power exists. A full MRO and CCS timing test have been added to V2 to occur annually until 2030, and may be added to V1 when the memory is available after the gyro activities for nominal operations are terminated.

With the careful planning and monitoring, the mission will go on until 2025 and possibly beyond. It is our hope to celebrate the Voyagers 50th launch anniversary in 2027 with a few of the low power consumption instruments still on.

Table 6. Science Instrument Power Down Order in BML for V2

Activities (Power Off/On)
CRS Replacement Heater Off
LECP Main Supplemental Heater Off
LECP LEPT Supplemental Heater Off
LECP Stepper Motor Off
PLS Supplemental Heater Off
CRS Off
LECP Off
PWS Off
PLS Off
MAG Off/PWS On*
PWS Off

V. Conclusion

Flying a very old spacecraft for a very long mission presents a great number of challenges. However, it comes with even greater rewards. Being the only spacecraft in the interstellar region, the Voyagers deliver priceless scientific data no other spacecraft can. The 40th launch anniversary is next year in 2017. By then V1 will be nearly 140 AU away from Earth and V2 will be slightly more than 115 AU away. The RTLT will be close to 39 hours for V1 and 32 hours for V2. After four decades of space operation, there are numerous challenges. But the small Flight Team works hard and is constantly implementing changes and adapting to the new environment. The team is always on a lookout for enhancements to keep the spacecraft going strong, and extend this historic one-of-a-kind mission to 2025 and possibly even beyond.

Appendix

List of Acronyms

AACS	Attitude and Articulation Control Subsystem
AACSIN	AACS Power Code Processing Fault Protection Routine
A/D	Analog to Digital
AMMOS	Advanced Multi-Mission Operations System
AP	Attitude Propulsion
AU	Astronomical Unit
Aux Osc	Auxiliary Oscillator
BML	Backup Mission Load
bps	bits per second
CCS	Computer Command Subsystem
CDL	Capability Demonstration Lab
CMDLOS	Command Loss Fault Protection Routine
CRS	Cosmic Ray Subsystem
DOY	Day Of Year
DSN	Deep Space Network
DTR	Digital Tape Recorder
Exc	Exciter
FDS	Flight Data Subsystem
FPA	Fault Protection Algorithm
FPGYRO	Fault Protection Use of Gyros Patch
FSW	Flight Software
FT	Flight Team
HCLOCK	Hourly Clock (CCS internal)
HGA	High-Gain Antenna
HPOINT	HGA pointing information to maintain the spacecraft pointing to Earth
HSSIM	High Speed Simulator
HYBIC	Hybrid Buffer Interface Circuits
IRIS	Infrared Interferometer Spectrometer and Radiometer Subsystem
JPL	Jet Propulsion Laboratory
K	Kilobytes
LECP	Low Energy Charged Particles Subsystem
MAG	Magnetometer Subsystem Experiment
MARVEL	Monitor/Analyzer of Real-Time Voyager Engineering Link
m	meter
MRO	Memory Read Out
NA	Narrow Angle
NASA	National Aeronautics and Space Administration
PC	Power Code
PLS	Plasma Science Subsystem
PPS	Photopolarimeter Subsystem
PRA	Planetary Radio Astronomy Subsystem
PWRCHK	Power Recovery Fault Protection Routine
PWS	Plasma Wave Subsystem
PWSPB	PWS Playback
PWSREC	PWS Recording
RFLOSS	Radio Frequency Power Loss Fault Protection Routine
RTG	Radioisotope Thermoelectric Generator
RTLT	Round Trip Light Time
TCM	Trajectory Correction Maneuver
TLC	Tracking Loop Capacitor
TWT	Traveling Wave Tube
USO	Ultra-Stable Oscillator
UVS	Ultra-Violet Spectrometer Subsystem

V1	Voyager 1
V2	Voyager 2
VAMPIRE	Voyager Alarm Monitor Processor Including Remote Examination
VIM	Voyager Interstellar Mission
W	Watts
WA	Wide Angle

Acknowledgments

The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Author thanks all of the members of the Voyager project flight team for their hard work and dedication. Special thanks to Larry Zottarelli, Suzy Dodd, Enrique Medina, Roger Ludwig, Fernando Peralta, and Jeff Hall for reviewing the paper.

References

[1]Heacock, R. L., "The Voyager Spacecraft," *Proceedings of the Institution of Mechanical Engineers*, Volume 194 No. 28, 1980.

[2]Stone, E., Richardson, J. and Dodd, S., "Voyager Interstellar Mission Proposal to Senior Review 2015 of the Mission Operations and Data Analysis Program for the Heliophysics Operating Missions", March 2015, pp 1-2, 23-25.

[3]Rudd, R., Hall, J. and Spradlin, G., "The Voyager Interstellar Mission," *47th International Astronautical Conference*, IAA-96-IAA.4.1.03, 1996/Beijing, China, October 7-11.

[4] JPL Project Document 618-235, Vol. I. Rev. L, *Voyager CCS Flight Software Design Description*, February 2014.