Highly automated on-orbit operations of the NuSTAR telescope

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ABSTRACT

UC Berkeley's Space Sciences Laboratory (SSL) currently operates a fleet of seven NASA satellites, which conduct research in the fields of space physics and astronomy. The newest addition to this fleet is a high-energy X-ray telescope called the Nuclear Spectroscopic Telescope Array (NuSTAR). Since 2012, SSL has conducted on-orbit operations for NuSTAR on behalf of the lead institution, principle investigator, and Science Operations Center at the California Institute of Technology. NuSTAR operations benefit from a truly multi-mission ground system architecture design focused on automation and autonomy that has been honed by over a decade of continual improvement and ground network expansion. This architecture has made flight operations possible with nominal 40 hours per week staffing, while not compromising mission safety. The remote NuSTAR Science Operation Center (SOC) and Mission Operations Center (MOC) are joined by a two-way electronic interface that allows the SOC to submit automatically validated telescope pointing requests, and also to receive raw data products that are automatically produced after downlink. Command loads are built and uploaded weekly, and a web-based timeline allows both the SOC and MOC to monitor the state of currently scheduled spacecraft activities. Network routing and the command and control system are fully automated by MOC's central scheduling system. A closed-loop data accounting system automatically detects and retransmits data gaps. All passes are monitored by two independent paging systems, which alert staff of pass support problems or anomalous telemetry. NuSTAR mission operations now require less than one attended pass support per workday.

Keywords: NuSTAR, NASA, flight operations, multi-mission operations, ground system, automation

1. INTRODUCTION

The Space Sciences Laboratory (SSL) at the University of California Berkeley (UCB) has been conducting on orbit operations of satellites on behalf of NASA continuously since receiving the outsourced flight operations of the Extreme Ultraviolet Explorer (EUVE) satellite[1] from the Goddard Space Flight Center (GSFC) in 1997. The current SSL mission operations center (MOC) was founded in 1998 in order to assume on-orbit operations of the Fast Auroral SnapshoT Explorer (FAST) satellite[2], similarly outsourced from GSFC. Subsequently, Space Science Lab has been awarded, developed, and operated three new missions of its own. The Reuven-Ramaty High Energy Solar Spectroscopic Imager (RHESSI)[3] was launched in 2002 and is still in operation. The Cosmic Hot Interstellar Plasma Spectrometer (CHIPS) satellite[4], planned for a half-year mission duration, was operational between 2003 and 2008. The five-satellite Time History of Events and Macroscale Interactions during Substorms (THEMIS) constellation-class mission[5,6,7], launched in 2007, is also still operational; two of the five THEMIS satellites have been maneuvered from earth to lunar orbits as part of the ARTEMIS mission extension[8]. The development of each new mission provided a significant opportunity to upgrade and extend the MOC architecture, and lessons learned during post-launch operations have lead to incremental improvement of heritage systems.

The SSL mission operations group joined the California Institute of Technology (Caltech)-led Nuclear Spectroscopic Telescope Array (NuSTAR) project[9] well before launch to provide operational support throughout development and testing, and has been conducting on-orbit operations since launch in 2012. NuSTAR is a high-energy (3–79 keV) X-ray telescope that is unique in its ability to focus high-energy photons, yielding spectral and spatial resolutions that are a two to three order of magnitude improvement over other instruments operating in this wavelength regime. NuSTAR also extends wavelength coverage of other lower-energy focusing X-ray telescopes such as NASA's Chandra X-ray Observatory and the European Space Agency's X-Ray Multi-mirror Mission (XMM-Newton), so coordinated observations between these assets are scientifically very valuable.

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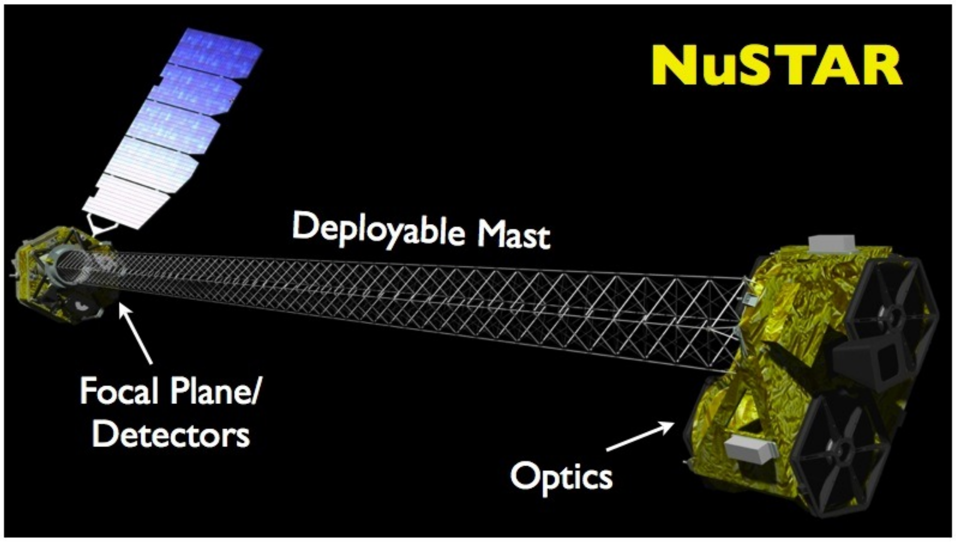


Figure 1. In a representation of NuSTAR in orbit, the spacecraft bus is shown at left, and the focusing optics are held at the end of a 10 meter long deployable mast.

The NuSTAR instrument is compromised of two co-aligned telescopes that use grazing incidence mirrors at the end of a 10 meter long deployable mast to bring high-energy photons to a focus on an array of detectors, which record the time, location, and energy of each arriving photon. Ground-based science data processing remaps these photons onto the celestial sphere. A representation of NuSTAR in its operational state is shown in Figure 1.

NuSTAR was launched into a nearly circular 630 km orbit with an inclination of 6 degrees in order to avoid the high particle fluxes associated with the South Atlantic Anomaly (SAA). This inclination means the ground stations of NASA's Near-Earth Network (NEN) are out of view, so the mission selected the Malindi Ground Station, operated by the Italian Space Agency (ASI), in Malindi, Kenya. The Universal Space Network's (USN) two 13-meter antennas at South Point, Hawaii are used as backup, and the Kongsberg Satellite Services (KSAT) antenna in Singapore was added to the network after launch. NASA's Tracking and Data Relay Satellite System (TDRSS) provides low data rate coverage, and is occasionally used for state of health telemetry monitoring and command upload opportunities. Data from the spacecraft and instrument are stored on solid state virtual recorders which operate like ring buffers, with newest data overwriting the oldest. Data are brought down at 2000 kbps, nominally using four Malindi Ground Station passes per 24 hour period. More ground station passes may be added from auxiliary ground stations such as USN or KSAT in order to support observations of bright targets, which produce proportionally higher data volume.

The NuSTAR instrument is mounted to Orbital-ATK's LeoStar-2 spacecraft bus, which provides power, data handling, storage, and transmission, and attitude control functions. Observations are performed as the spacecraft bus's attitude control system (ACS) uses guidance information from three independent star trackers to keep the telescope boresight fixed in inertial space. The ACS slews the spacecraft between targets in maneuvers that are usually less than 30 minutes in duration. Commands for these slews and dwells, along with transmitter and data playback commands, are dispatched autonomously from an on-board absolute time sequence (ATS) table that is uploaded by the MOC.

The NuSTAR Science Operations Center (SOC) develops and maintains the observing schedule, and transmits it on a weekly basis to the MOC, to be converted into spacecraft pointing commands. The MOC merges the SOC's pointing requests with the ground station pass schedule in order to build and upload ATS tables. This process takes place at least once a week, but is often required more frequently because of ground station pass schedule changes or target pointing changes. Most sequencing occurs with about three days of lead time, but in cases of time-critical targets of opportunity (ToO's), the SOC and MOC have been able to schedule and upload pointing changes in as little as two hours.

2. EVOLUTION OF THE MISSION OPERATIONS CENTER

The mission operations center has been continuously and incrementally upgraded since its inception in 1998. MOC development is guided by a systems engineering approach that focuses on designing for automation from the outset, leveraging and extending heritage systems whenever appropriate, but implementing custom software solutions in-house when the need arises.

2.1 Standardized command and control software

The SSL mission operations group was first introduced to the *Integrated Test and Operations System* (ITOS) command and control software when taking on spacecraft operations responsibilities for the FAST satellite. ITOS is a "government off the shelf" (GOTS) software system developed by Goddard Space Flight Center that has been commercialized by The Hammers Company. SSL has used ITOS as the command and control system on all its subsequent missions, with the exception of CHIPS University Explorer class mission, thus ensuring that SSL systems engineers and controllers have continuous and ongoing familiarity with only one command control system. The operations group's "test as you fly" philosophy calls for using of ITOS in as flight-like a manner as possible during the earliest phases of pre-launch development, integration, and testing. This ensures that ITOS capabilities, page displays, command script development, and operator familiarity are all well established by the critical operational readiness test and launch and early orbit phases.

2.2 SatTrack Gateway Server – centralized automation

The SatTrack Suite[10], a "commercial off the shelf" (COTS) software system developed by Bester Tracking Systems, Inc, is a central and fundamental component of the SSL MOC's multi-mission automated ground system architecture. The *SatTrack Gateway Server* (SGS) component centralizes the crucial functions of ground station and ground system automation relative to a master schedule of ground station passes and predicted spacecraft events. The central SatTrack Gateway Server and its many client types reflect a service oriented architecture (SOA) design philosophy, and provide functionality such as automatically updating countdown clocks, regularly scheduled data product production and distribution, and autonomous configuration of all instances of the ITOS command and control software.

2.3 FrameRouter – network routing automation

In order to disentangle the complexity of routing data flows between many ground stations and many satellites, the *FrameRouter* application was developed as part of the SatTrack Suite of software prior to the THEMIS launch. The FrameRouter can be succinctly described as a Transmission Control Protocol/Internet Protocol (TCP/IP) socket equivalent of a telephone switchboard. Remote ground station complexes make telemetry and command socket connection to a single host – the FrameRouter server itself – to assigned, distinct TCP/IP server socket ports that are unique and constant for that ground station complex. Similarly, ITOS command and control workstations in the MOC connect to the FrameRouter host at port numbers that are unique and constant for that workstation instance. Prior to each scheduled pass support, the SatTrack Gateway Server directs the FrameRouter to establish the necessary server sockets, and write through telemetry and command data in both directions.

A *FrameRelay* application broadcasts a copy of telemetry out from the secure MOC network to be replicated by a FrameRouter running on an open network. In this manner, numerous ITOS workstations can monitor telemetry feeds securely, including at remote sites.

2.4 BTAPS – Berkeley Trending Analysis and Plotting System

The *Berkeley Trending Analysis and Plotting System*[11] (BTAPS) was developed from scratch as an in-house project, in advance of THEMIS pre-launch integration and test, and has been significantly expanded and improved over time. BTAPS receives and packetizes telemetry from real-time socket streams as well as post-pass archive files, and stores the raw packet data, with time-sorted indices, in the tables of a MySQL[12] database server. Telemetry data can be searched in random-access fashion, extracted from the database, and converted on the fly to make strip chart plots, using exactly the same telemetry format dictionary as ITOS.

BTAPS was originally envisioned and designed as a method of creating real-time and archival plotting, but over time, other applications that can benefit from fast and reliable random access to an entire mission's worth of housekeeping or science data have evolved.

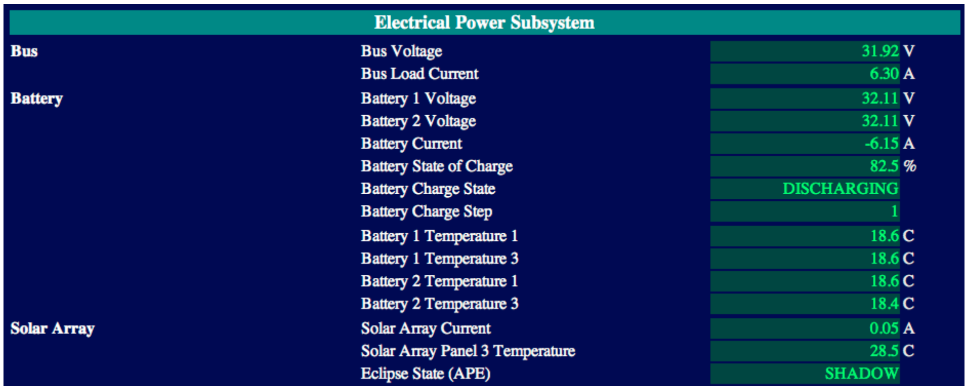
2.5 BEARS and SatStatus – anomaly paging systems

The MOC has two simultaneously active anomaly detection and paging systems, which alert operators of problems when the MOC is unattended. The first system, the *Berkeley Emergency and Anomaly Response System* (BEARS) receives limit violation alarms and special event messages from ITOS, as well as messages from other software systems, and broadcasts these to a configurable set of email addresses. Some email addresses are the email-to-Short Message Service (SMS) gateway addresses of on-duty operators' phones, which result in an audible page at all hours. Alerted users investigate the problem – usually by using remote monitoring tools, or sometimes returning to the control center – and respond to the BEARS system by email to indicate the problem has been accepted. If not, BEARS will continue to page an expanded list of email and pager addresses, until some action is taken. Typical BEARS alerts involve negative acquisitions ("negacqs"), but occasionally, alerts may be triggered by a more serious spacecraft problem. A backup paging system that is part of the Satellite Status monitoring tool of the SatTrack Suite also detects and sends one-shot notification limit violations, but it does not persistently page users. The two systems are implemented on different hardware to increase reliability.

2.6 Web-based monitoring

The MOC has created a large set of web-based tools which support remote monitoring and analysis of spacecraft and ground system status after hours. These web tools include:

- Spacecraft status summary web pages, which display a selection of the most useful telemetry mnemonics for each spacecraft. These update every 30 seconds during real-time passes, and maintain the most recently received values between pass supports. Out of limit conditions are displayed in yellow or red cells.



Electrical Power Subsystem

Bus	Bus Voltage	31.92	V
	Bus Load Current	6.30	A
Battery	Battery 1 Voltage	32.11	V
	Battery 2 Voltage	32.11	V
	Battery Current	-6.15	A
	Battery State of Charge	82.5	%
	Battery Charge State	DISCHARGING	
	Battery Charge Step	1	
	Battery 1 Temperature 1	18.6	C
	Battery 1 Temperature 3	18.6	C
	Battery 2 Temperature 1	18.6	C
	Battery 2 Temperature 3	18.4	C
Solar Array	Solar Array Current	0.05	A
	Solar Array Panel 3 Temperature	28.5	C
	Eclipse State (APE)	SHADOW	

Figure 2. A fragment of the NuSTAR Spacecraft Status summary page, showing a section of critical power subsystem telemetry values, all in a nominal (green) state.

- The *Berkeley Data Processing System* (BDPS) Schedule/File view displays all received post-pass telemetry files correlated to a scheduled pass support, displays data quality of each file, and sends alerts by BEARS if post-pass files have not been received in a timely fashion.
- The BDPS Data Gap Summary page shows the size and time span of data gaps in spacecraft and science telemetry channels. These are detected by data mining BTAPS database for packet sequence counter discontinuities, after all post-pass telemetry files have been processed and merged. The gaps are correlated back to a pass support for diagnostic purposes.

3. IMPLEMENTATION OF NuSTAR OPERATIONS

NuSTAR support was added to all the MOC software systems described in the previous section. SatTrack Gateway Server automation, FrameRouter telemetry distribution, BEARS paging and SatStatus webpages, BDPS file tracking, and BDPS gap checking were all expanded by creating NuSTAR-specific configurations or instances. Implementing ITOS and BTAPS support afforded the opportunity for some development and upgrades, though still at an incremental level. For instance, a web-based interface to BTAPS called webBTAPS was added to allow spacecraft vendor analysis of ground based tests, but it has been heavily used during on-orbit operations as well.

Nevertheless, all new missions give rise to unique ground system and flight operations requirements, and NuSTAR was no exception. Leveraging the high degree of heritage in the MOC freed up development resources to concentrate on these mission specific tools and software systems.

3.1 SOC/MOC Messaging System

NuSTAR observatory operations require the SOC at Caltech and the MOC at Berkeley to collaborate in the implementation of the observing schedule. Pointing requests from the SOC must be transmitted, constraint checked, converted to spacecraft commands, and then merged with ground station pass support related commands. To facilitate this, the MOC undertook the in-house development of the *Messaging System* to allow the secure, reliable, and validated exchange of pointing requests and instrument configuration information between the SOC and the MOC.

3.1.1 Message transmission

Messaging System exchanges are fundamentally revision control operations within a Subversion (SVN)[13] revision control system repository that is hosted on an open network at SSL, with clients at the SOC and in the secure MOC, as shown in Figure 3.

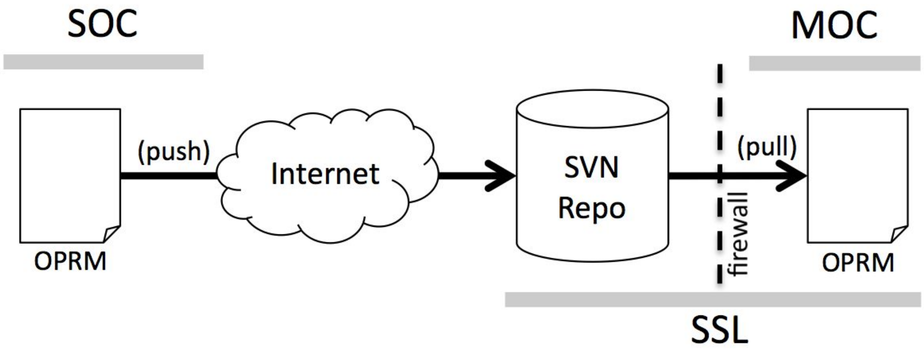


Figure 3. Messaging System are revision control operations by clients at the SOC and MOC.

The SOC delivers a pointing request by performing an SVN "commit" operation on a so called *Observatory Pointing Request Message* (OPRM) file. The SVN client at the SOC transmits this commit to the Message System repository at SSL via the open Internet through an encrypted secure shell (SSH) channel, ensuring that the message is both authorized and uncorrupted. The flow of an OPRM within the Messaging System is shown in Figure 4.

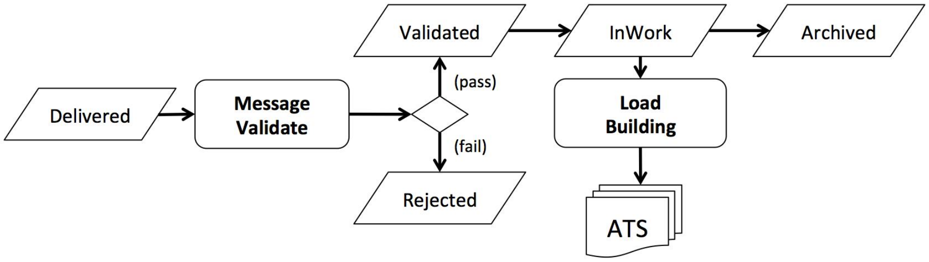


Figure 4. The flow of a delivered file within the Messaging System.

Upon completion of the commit, SVN hook scripts automatically perform software validations on the pointing requests contained in the OPRM. If any would violate instrument or spacecraft health and safety rules, the message is moved to a *Rejected* directory. If not, the file is moved to a *Validated* directory, indicating it is ready for further use. A spacecraft controller transitions the message into an *InWork* directory to make it available to the load building software. Critical message handling steps emit emails, so all team members are aware of the work-flow status of a message. Other message types exist to request specific absolute time command sequences, convey general instrument configuration requests, and alert MOC personel that a quick-action target of opportunity (ToO) has been triggered. All message types are transitioned to an *Archive* directory once processing has been completed.

3.1.2 Message validation and constraint checking

The observing sequence in a delivered OPRM is automatically checked by a program called *MessageValidate* once it arrives at the MOC. MessageValidate ensures that the schedule of slews between targets is properly timed, and satisfies spacecraft and instrument health and safety constraints such as:

- Availability of at least one unblocked star tracker throughout each pointing
- No more than 900 seconds of complete star tracker blockage by the earth, moon, or sun during slews
- Telescope boresight stays out of Sun and Moon "keep-out" cones
- The rotation about the instrument boresight places the Sun within an allowed sector that satisfies power and thermal limits
- The Sun doesn't move out of the above-mentioned allowed sector during very long pointings where the spacecraft stays inertially fixed while the Sun continues to move
- Each slew will have time to complete and settle before the next starts

A graphical representation of the telescope and star tracker boresight paths during slews that are checked by MessageValdidate is shown in Figure 5.

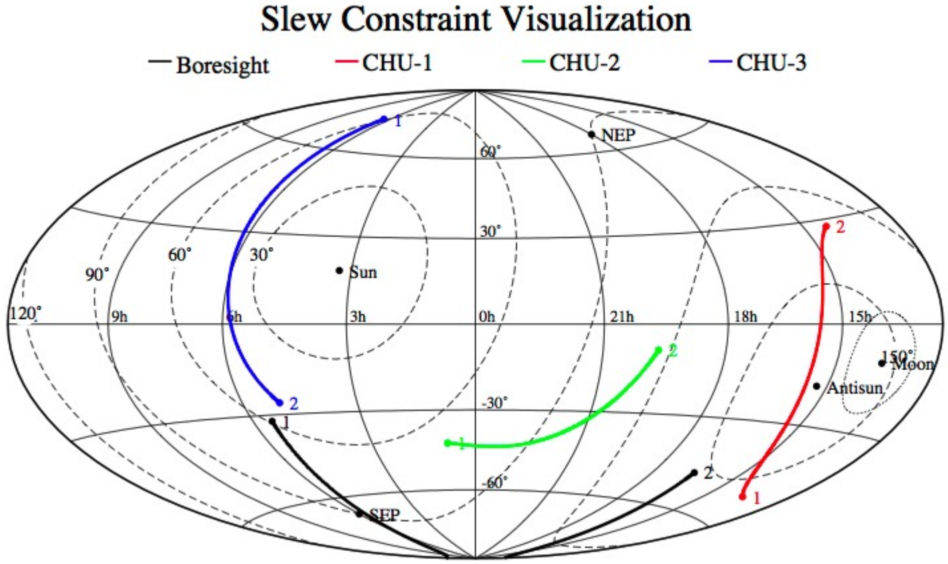
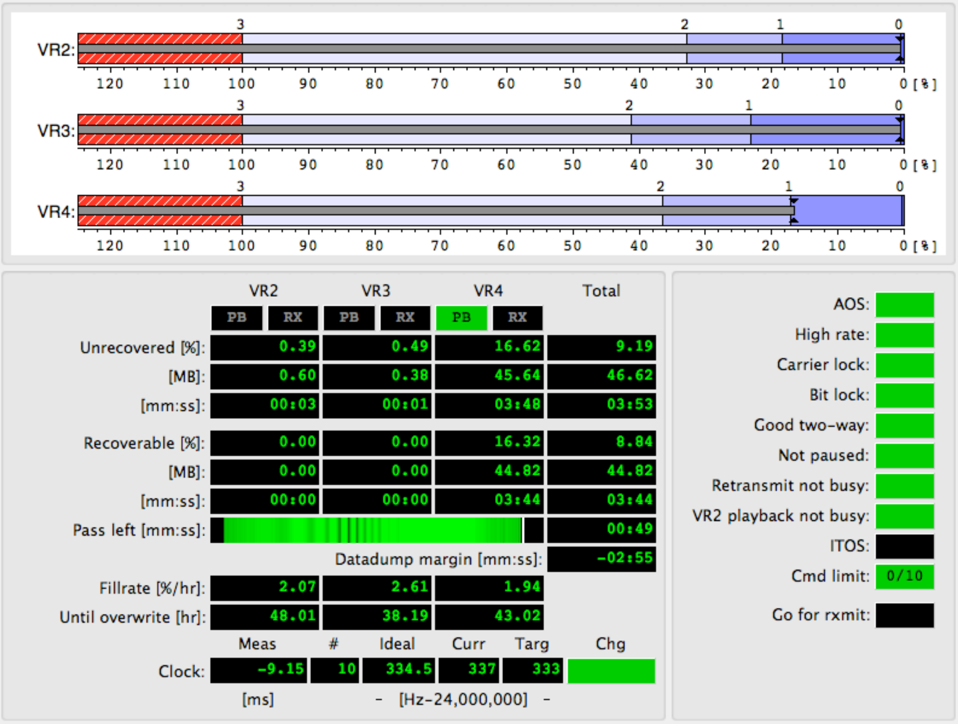


Figure 5. A graphical representation of the color coded instrument and startracker (CHU) boresight paths during a slew, relative to Sun and Moon constraints.

3.2 Complete automation of NuSTAR passes

Like all other SSL missions, the SatTrack Gateway Server sends pre-pass directives to a client running on the NuSTAR primary workstation, and this client interacts with a mission specific set of *Autopilot* ITOS scripts to begin event logging, archive real-time telemetry, and establish two-way communication with the spacecraft after acquisition of signal (AOS). NuSTAR's onboard command sequence directs the spacecraft to start playing back stored data a short time after scheduled AOS, ensuring that data will be dumped even if there are problems with command uplink.

NuSTAR benefits from a new in-house developed program called *VR*[14] (short for "virtual recorder"), which leverages the real-time housekeeping telemetry decommutation of the BTAPS system to detect and determine the extent of transmission data loss if there are dropouts in telemetry. The VR program, the graphical user interface front end of which is shown in Figure 6, autonomously sends retransmission commands to the spacecraft on the fly, by way of the ITOS command and control system, so that missed data can be recovered even before the pass finishes.



	VR2	VR3	VR4	Total
Unrecovered [%]:	0.39	0.49	16.62	9.19
[MB]:	0.60	0.38	45.64	46.62
[mm:ss]:	00:03	00:01	03:48	03:53
Recoverable [%]:	0.00	0.00	16.32	8.84
[MB]:	0.00	0.00	44.82	44.82
[mm:ss]:	00:00	00:00	03:44	03:44
Pass left [mm:ss]:				00:49
Datadump margin [mm:ss]:				-02:55
Fillrate [%/hr]:	2.07	2.61	1.94	
Until overwrite [hr]:	48.01	38.19	43.02	

	Meas	#	Ideal	Curr	Targ	Chg
Clock:	-9.15	10	334.5	337	333	🟩
	[ms]		- [Hz-24,000,000] -			

AOS: 🟩
High rate: 🟩
Carrier lock: 🟩
Bit lock: 🟩
Good two-way: 🟩
Not paused: 🟩
Retransmit not busy: 🟩
VR2 playback not busy: 🟩
ITOS: ⬛
Cmd limit: 0/10
Go for rxmit: ⬛

Figure 6. The graphical user interface of VR showing data recovery and downlink process during a real time pass.

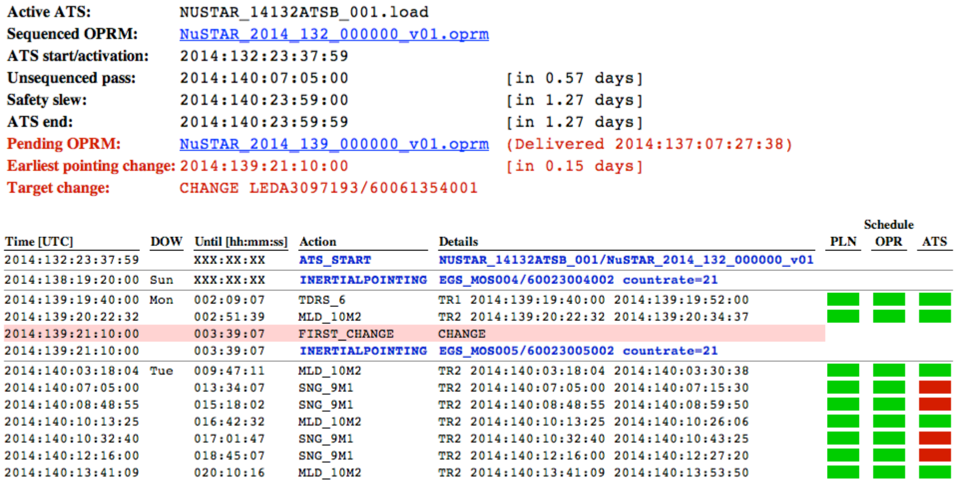
VR will also automatically recover from data lost due to issues with a previous pass, such as a negative acquisition ("negacq"). It also intelligently restarts data transmission where the previous pass left off, for instance if the data volume was too large to be completed in that pass. Consequently, short high-data rate observations that temporarily oversubscribe the downlink capability can be scheduled, and the data stored and replayed to completion at a later time, with no human management or attendance required.

VR calculates an overall recorder fill level by computing the fraction of downlinked data relative to the total virtual recorder size, and estimates how long it will take the oldest unrecovered data gap to be permanently overwritten on the spacecraft virtual recorders. These parameters are visible on the Satellite Status webpages. Occasionally, successive negacqs due to chronic remote ground station problems will require new downlink passes to be scheduled, and VR's time-until-overwrite predictions determine how promptly the passes must be scheduled. Read-only instances of VR are often run on controllers' personal workstations, as well as off-site from home and at the Caltech SOC, which allows detailed visibility into the data recovery progress outside the MOC.

During each high-data rate pass, VR correlates the spacecraft clock against true time by comparing spacecraft frame transmit times to ground station Earth receive times and subtracting out expected light-travel time delays. The NuSTAR LeoStar-2 bus's master oscillator has a variable divisor with a resolution of approximately one part in 24,000,000, and adjustments of < 10 ppm are made, no less than two days apart, to guide the spacecraft clock within a +/- 10 msec band of true time. The individual measurements are provided as a standard data product to the Caltech SOC, and allow *ex post facto* correction of system times to within 2 msec (2 sigma).

3.3 NuSTAR specific web-based monitoring

NuSTAR operations team members at both the MOC and the remote SOC need to be aware of and validate changes to both the pointing and ground station pass schedules, which often change independently of each other. Each change will require new ATS tables to be built and loaded. To make these differences easier to track, the MOC undertook an in-house development of a web-based system called the *Berkeley Mission Planning System* (BMPS) *Sequence View*. The web page shown in Figure 7 is dynamically generated from a database of pointing and pass schedule information. It shows a time ordered list of future timeline events that are extracted from an ATS table immediately after it is successfully loaded to the spacecraft.



Active ATS:	NUSTAR_14132ATSB_001.load	
Sequenced OPRM:	NuSTAR_2014_132_000000_v01.oprm	
ATS start/activation:	2014:132:23:37:59	
Unsequenced pass:	2014:140:07:05:00	[in 0.57 days]
Safety slew:	2014:140:23:59:00	[in 1.27 days]
ATS end:	2014:140:23:59:59	[in 1.27 days]
Pending OPRM:	NuSTAR_2014_139_000000_v01.oprm	(Delivered 2014:137:07:27:38)
Earliest pointing change:	2014:139:21:10:00	[in 0.15 days]
Target change:	CHANGE LEDA3097193/60061354001	

					Schedule		
Time [UTC]	**DOW**	**Until [hh:mm:ss]**	**Action**	**Details**	**PLN**	**OPR**	**ATS**
2014:132:23:37:59		XXX:XX:XX	**ATS_START**	**NUSTAR_14132ATSB_001/NuSTAR_2014_132_000000_v01**			
2014:138:19:20:00	Sun	XXX:XX:XX	**INERTIALPOINTING**	**EGS_MOS004/60023004002 countrate=21**			
2014:139:19:40:00	Mon	002:09:07	TDRS_6	TR1 2014:139:19:40:00 2014:139:19:52:00	🟩	🟩	🟩
2014:139:20:22:32		002:51:39	MLD_10M2	TR2 2014:139:20:22:32 2014:139:20:34:37	🟩	🟩	🟩
2014:139:21:10:00		003:39:07	FIRST_CHANGE	CHANGE			
2014:139:21:10:00		003:39:07	**INERTIALPOINTING**	**EGS_MOS005/60023005002 countrate=21**			
2014:140:03:18:04	Tue	009:47:11	MLD_10M2	TR2 2014:140:03:18:04 2014:140:03:30:38	🟩	🟩	🟩
2014:140:07:05:00		013:34:07	SNG_9M1	TR2 2014:140:07:05:00 2014:140:07:15:30	🟩	🟩	🟥
2014:140:08:48:55		015:18:02	SNG_9M1	TR2 2014:140:08:48:55 2014:140:08:59:50	🟩	🟩	🟥
2014:140:10:13:25		016:42:32	MLD_10M2	TR2 2014:140:10:13:25 2014:140:10:26:06	🟩	🟩	🟩
2014:140:10:32:40		017:01:47	SNG_9M1	TR2 2014:140:10:32:40 2014:140:10:43:25	🟩	🟩	🟥
2014:140:12:16:00		018:45:07	SNG_9M1	TR2 2014:140:12:16:00 2014:140:12:27:20	🟩	🟩	🟥
2014:140:13:41:09		020:10:16	MLD_10M2	TR2 2014:140:13:41:09 2014:140:13:53:50	🟩	🟩	🟩

Figure 7. An example of the BMPS Sequence View showing pending target and schedule changes, which must be sequenced into an ATS table.

Each ground station pass row has three columns of status indicators: *PLN* indicates a pass schedule that is planned or requested, but not yet in the operational schedule. *OPR* denotes a pass support that is active in the SatTrack Gateway Server master schedule, meaning it will automate the ground system. *ATS* indicates a pass support for which the current on-board sequence table contains matching transmitter commands. Each status indicator will be red if the pass is missing, or green if the pass is properly sequenced.

Interspersed in blue text are the target name, ID, and count rate information for the current and future science target visits that are sequenced in the onboard ATS table. Delivery of a new OPRM automatically adds a pink highlighted row to the sequence view that shows earliest point at which the on-board pointing sequence differs from the newer pointing request.

The Sequence View page allows SOC and MOC team members to review that onboard pass and pointing commands are in sync with the expected schedules, without needing to explicitly communicate with each other. In the event differences arise, the Sequence View highlights the time remaining until a new ATS table must be uploaded.

3.4 Leveraging BTAPS for NuSTAR data production

Since the BTAPS MySQL database collects all packets generated by both the spacecraft and instrument, it is leveraged by the Berkeley Data Processing System to produce raw instrument data products for the remote SOC. After all post-pass data have been accumulated from remote sources, these raw packet data are cleaned, merged, sorted, and flushed to so-called *Level 0* (L0) files, which are made available to the SOC to retrieve via transfer over the open Internet. New file sets are automatically produced for any 24-hour UTC day that received new packet data, even if it was a result of a small data gap retransmission.

Because BTAPS was integral to the earliest phases of spacecraft integration and test campaign before launch, automated BDPS L0 data file generation was also put into use from the first day the instrument was integrated with the spacecraft during integration and test, and so was thoroughly tested before launch.

4. RESULTS

The MOC's focus on automation and system autonomy has allowed the NuSTAR observatory to be operated in a safe and reliable manner, with only approximately 3 full-time equivalents (FTE's), and almost exclusively work-week staffing. After a busy half-year period of post launch commissioning and system improvements, since the beginning of 2013, the NuSTAR MOC has met the following milestones:

- More than 2,800 pass supports have been taken, with complete network routing and ground system automation on every pass
- Only 286 of these pass supports – 10% – were attended by a controller (for instance, to load an ATS table)
- Only 19 of the attended pass supports were required after hours (that is, outside of 8AM-6PM, Monday-Friday)
- More than 145 GB of spacecraft data have been downlinked; 100.0% of spacecraft housekeeping data and 99.995% of science data were recovered; only 2 seconds of science data have been overwritten before transmission in the last 365 days
- No manual data retransmission commands were required, despite 39 pass supports that were missed due to ground station problems, and numerous instances of data dropouts.
- A new ground station in Singapore belonging to KSAT was added to the NuSTAR network after launch, but required minimal ground system reconfiguration thanks to the flexibility of the FrameRouter.
- All spacecraft anomalies – fortunately few, and all very minor – have been detected, reported, and responded to within hours of their occurrence, even when they occurred when the MOC was not staffed.

5. CONCLUSION

SSL's multi-mission MOC has benefitted over the last decade and a half from a history of incremental and deliberate upgrades, all focused on increasing ground systems autonomy and flight operations reliability. Each new mission has been able to leverage a high degree of well-proven system heritage. A high degree of automation allows existing missions to be run safely and efficiently while development and manpower resources are concentrated on pre-launch development of new missions, as in the case of the NuSTAR mission. Such development provides an increased set of capabilities for future missions, and will allow the safe and efficient operation of NuSTAR and all other SSL missions for years to come.

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