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THEMIS Mission Networks Expansion – Adding the Deep Space Network for the ARTEMIS Lunar Mission Phase

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THEMIS is a five-spacecraft constellation launched in 2007 to study magnetospheric phenomena leading to the aurora borealis. During the primary mission phase, completed in the fall of 2009, all five spacecraft collected science data in synchronized, highly elliptical Earth orbits. For an ambitious mission extension, the Project proposed to split the constellation into two parts – THEMIS-Low and ARTEMIS. THEMIS-Low includes the three spacecraft on the inner orbits with approximately one-day periods, continuing their study of the magnetosphere in a tighter formation. ARTEMIS involves transferring the outer two spacecraft from their Earth orbits with two and four-day periods into lunar orbits to conduct measurements of the interaction of the Moon with the solar wind and of crustal magnetic fields. This transfer was initiated on July 21, 2009 and follows low-energy trajectories with Earth and lunar gravity assists. The THEMIS mission is controlled from the highly automated multi-mission operations center at the University of California, Berkeley and was originally designed to be supported by 11-m class ground stations and NASA's Space Network. To increase the telemetry bandwidth for science data return at lunar distances, the mission network was expanded to also include the 34-m subnet of NASA's Deep Space Network (DSN). This paper discusses all aspects of the process to seamlessly integrate the new DSN interfaces into the THEMIS/ARTEMIS mission control network, and describes challenges and lessons learned with the implementation of real-time telemetry and command data transfer using the CCSDS Space Link Extension protocol. It also includes on-orbit characterization of the transponder ranging channels, orbit determination results using two-way Doppler and range data from a combination of conventional ground stations and DSN stations, as well as pass scheduling via the DSN Resource Allocation Planning Service and via automated, electronic data exchanges. All of these tasks were accomplished within a compressed schedule of one year, with very limited staffing resources, and on a tight budget.

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Nomenclature

BPSK	=	binary phase-shift keyed (suppressed carrier) modulation
c	=	vacuum speed of light
C_1, C_2	=	range components of sequential ranging code
dR/dt	=	measured range rate
f_T	=	transmit frequency
K	=	transponder coherent turn-around ratio
kbps	=	kilobits per second
M	=	range rate conversion factor
MB	=	megabytes
n	=	ambiguous range multiplier
N	=	cumulative two-way Doppler counts for range rate measurements
P_R/N_0	=	ranging power-to-noise spectral density ratio
PCM/PSK/PM	=	pulse code modulation / phase shift keying / phase modulation
Φ	=	round-trip count phase for range rate measurements
R	=	measured range
R_{amb}	=	ambiguous range resolving capability
R_{raw}	=	raw range measurement in decimal counts
R_{RU}	=	raw range measurement in Range Units
$R_{RU,stn}$	=	measurement of station internal range delay corrections in Range Units
RTLT	=	round-trip light time
T	=	time tag of range measurement
T_0, T_{-1}	=	time tags of present and previous two-way Doppler counts for range rate measurements
T_1, T_2	=	integration times for clock and ambiguity resolving range components

I. Introduction

SPACE Science Laboratory (SSL) at the University of California, Berkeley (UCB) has been performing mission-level flight operations since 1997, beginning with the *Extreme Ultraviolet Explorer (EUVE)* mission. The present Multi-mission Operations Center (MOC) at SSL was established in 1998 to provide mission operations support for the *Fast Auroral SnapshoT Explorer (FAST)*, outsourced from the Goddard Space Flight Center (GSFC) in 1999. The MOC also supports the *Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI)* mission, launched in 2002 and still operational, and the *Cosmic Hot Interstellar Plasma Spectrometer (CHIPS)* mission, launched in 2003. Support of the *Time History of Events and Macroscale Interactions during Substorms (THEMIS)* constellation-class mission started with its launch in 2007.[1]

For the *Acceleration, Reconnection, Turbulence and Electrodynamics of the Moon's Interaction with the Sun (ARTEMIS)* Project – a part of the extended THEMIS mission – two of the five spacecraft are transferred from Earth to lunar orbit.[2] Concurrent with on-orbit operations, the existing THEMIS ground station network was expanded to include antennas from NASA's Deep Space Network (DSN) in order to maintain communications with these spacecraft at distances far greater than those anticipated in the original mission design. This paper describes the interfaces, implementation, and results of this network expansion during the on-orbit phase of the mission.

II. THEMIS and ARTEMIS

A. THEMIS Prime Mission

THEMIS is a NASA-funded Medium-class Explorer (MIDEX) mission to study magnetospheric phenomena called *substorms* which suddenly and explosively release solar wind energy stored in the Earth's magnetospheric tail, causing dramatic intensification of the auroras. The space segment of the Project consists of a constellation of five spacecraft, called *probes*, each bearing identical suites of instruments to measure distributions of charged particles, as well as electric and magnetic fields. The spin-stabilized probes carry a monopropellant hydrazine reaction control system to allow ground-planned changes to the spacecraft attitude and orbit, and a coherent S-band transponder for Doppler tracking and ranging, remote commanding, and downlink of housekeeping and science telemetry data.

All five probes were launched into a common 31-hour period coast-phase orbit aboard a single Delta II rocket on February 17, 2007, and were subsequently maneuvered into a constellation of highly elliptical, low-inclination Earth orbits using their onboard propulsion systems.[3,4] The THEMIS mission design called for the five probes (THEMIS A-E) to be dispersed into orbits with periods of one, two, and four sidereal days, synchronized in such a way that all probes would line up in conjunction at apogee every four days inside the Earth's magnetospheric tail during the winter months of the northern hemisphere, the so called *tail observing season*. Resulting time-resolved *in situ* measurements from the five probes were correlated with measurements from ground-based magnetometers and all-sky cameras to build a comprehensive model of magnetospheric phenomena.

All aspects of THEMIS operations, including mission design, maneuver planning and execution, attitude determination, orbit determination via radiometric tracking, spacecraft commanding, health and safety monitoring, instrument configuration, science data recovery, and data processing are handled by the Operations and Ground Systems (OGS) group at UCB/SSL.[4,5]

Obtaining sufficient measurements from the instrument subsystems requires each THEMIS probe to collect and store approximately 100-140 MB of data per orbit, which translates to an average science data collection rate of 270-1500 bytes/s, depending on the orbit period. The S-band communications system allows downlink of these data at the highest two (524.288 and 1048.576 kbps) of ten available telemetry data rates near perigee, using a worldwide network of 11-m class ground stations, including the Berkeley Ground Station (BGS) located at UCB/SSL. To ensure the probes are never completely out of contact, the telemetry link was designed to operate at 4 kbps through these same 11-m class ground stations at the maximum apogee distance of 200,000 km. Two-way Doppler range rate measurements from multiple ground stations, conducted concurrently with both scheduled data playback and state-of-health monitoring pass supports, allow maintaining accurate orbit models for all five probes.

The prime THEMIS mission concluded in fall of 2009 after two successful observing seasons in the Earth's magnetospheric tail. The spacecraft bus and instrument suites of all five probes were still in excellent condition and the propulsion systems had sufficient fuel reserves to allow continued navigation operations.

B. ARTEMIS Lunar Mission Extension

For an ambitious mission extension, the Project proposed to NASA to split the constellation into two parts, called THEMIS-Low and ARTEMIS.[2] Three of the five probes, namely THEMIS A, D and E, that had been in near-sidereal day-long orbits during the prime mission, are now referred to as THEMIS-Low. These probes are maneuvered into sidereal orbits with even closer in-track proximity to each other, and continue their study of the Earth's magnetosphere. ARTEMIS involves transferring the two outermost probes, THEMIS B and C, from their two and four-day period, prime-mission Earth orbits into lunar orbits to conduct measurements of the interaction of the Moon with the solar wind, and of lunar crustal magnetic fields.

The capabilities of the THEMIS propulsion systems do not allow a rapid, direct transfer to lunar orbit. Instead, in collaboration with the Guidance, Navigation and Control (GNC) Division of the Jet Propulsion Laboratory (JPL) at the California Institute of Technology, and with the Navigation and Mission Design Branch (NMDB) at NASA's Goddard Space Flight Center (GSFC), the Project crafted an ARTEMIS mission design utilizing successive apogee raises, lunar gravity assists, Earth flybys, and deep-space maneuvers to deliver both probes to quasi-stable Earth-Moon libration orbits after approximately one year of transfer operations. The two probes are eventually transferred into stable, elliptical orbits about the Moon.[6]

During the Earth-Moon transfer phase, the probes travel as far as 1.6 million km away from Earth – eight times farther than the highest apogees of the prime mission phase.[7] Once in lunar orbit, ranges are approximately 400,000 km from Earth. Recovering stored scientific measurements collected at a cadency commensurate with the prime mission, but from lunar distances, can only be accomplished by utilizing much larger, more efficient ground antennas. Therefore, the Project obtained permission from NASA to add seven Deep Space Network (DSN) 34-m antennas (Deep Space Stations DSS-15, 24, 27, 34, 45, 54, and 65) to the existing set of ground stations already supporting the THEMIS mission. This effort required integrating new telemetry and telecommand interfaces, supporting new tracking and ranging data formats, and adopting new scheduling interfaces into the existing mission operations framework, but without disrupting ongoing constellation operations.

III. Ground System Overview

A. Ground System Architecture

The ground system architecture implemented at the Berkeley MOC is the result of a deliberate design philosophy to integrate commercial off-the-shelf (COTS), government off-the-shelf (GOTS), and in-house developed software packages with clean and consistent interfaces focused from the outset on true multi-mission support and highly automated operation.[5] With the exception of CHIPS, all missions supported by the MOC have used the *Integrated*

Test and Operations System (ITOS) for command and control that was originally developed at GSFC.[8] The *SatTrack Gateway Server (SGS)* orchestrates the processes of pass and event scheduling, flight dynamics product generation, ground station automation, telemetry and command flow management, and command and control system operation.[9]

B. Data Flow Management

Another crucial component of the SatTrack Suite is *FrameRouter*, which acts as the network equivalent of a matrix switch, providing Transmission Control Protocol (TCP) / Internet Protocol (IP) socket-based telemetry and telecommand data flows between remote ground stations and the active command and control software.[9,10] This scheme, shown in Fig. 1 for a pass support with the BGS 11-m antenna, greatly simplifies operations in a multi-ground station, multi-satellite environment, as all ground stations see a consistent virtual interface to the Berkeley MOC. Dedicated connect ports are assigned to each ground station for real-time telemetry and command data transfer. Likewise, from within the MOC, all ITOS command and control systems see a similarly consistent virtual interface to ground stations, with dedicated ports assigned for each spacecraft.

Routing connections facilitating data flows between the ground stations and ITOS are automatically configured by SGS according to the operational pass support schedule. Another SatTrack software application called *FrameRelay* transfers telemetry data out of the secure MOC and makes these available to another instance of FrameRouter running on the Open SSL Local Area Network (LAN), allowing engineers both inside and outside the MOC – including support personnel at remote contractor facilities – to monitor spacecraft telemetry in real-time during special operations. Fig. 1 shows the typical network flow configuration for a pass of THEMIS A at BGS.

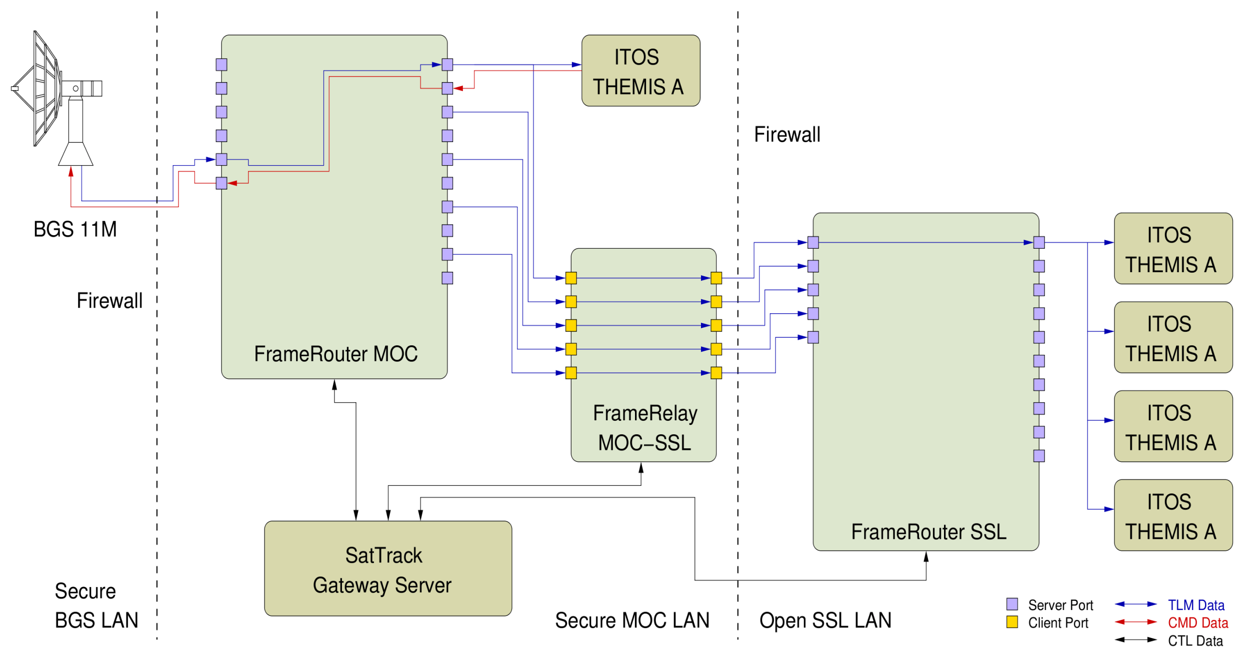

Figure 1. Network routing scheme for unidirectional telemetry and command socket connections. *Example shown for THEMIS A real-time telemetry and telecommand data flows between the Berkeley Ground Station and the primary ITOS command and control workstation. Telemetry data are also routed to additional ITOS workstations outside the MOC to allow remote monitoring of spacecraft state-of-health to support special operations.*

C. Autopilot Command and Control

In-house developed custom software called *Autopilot* interfaces ITOS with the SatTrack Gateway Server. SGS maintains the operational pass support schedule and broadcasts a pre-pass message to connected clients 10 minutes prior to a planned Acquisition of Signal (AOS) event. Autopilot uses this message to pre-configure ITOS for telemetry and command with the appropriate spacecraft, to monitor for real-time telemetry at AOS, to send commands to turn the spacecraft transmitter on if telemetry is not detected, and to report a negative acquisition to the anomaly response system if these attempts fail. Once a reliable end-to-end two-way link is established, Autopilot commands the spacecraft to playback stored engineering and science data, provided the scheduled telemetry data rate for the current pass is high enough. This very reliable extension to ITOS allows the majority of THEMIS passes, even data playback events, to be conducted in an entirely hands-off manner. With the exception of critical maneuver events, passes are currently only staffed during normal working hours, and operations for the entire constellation are conducted in *lights-out* mode at all other times.

IV. DSN Network Interface Overview

A. Telemetry and Telecommand Formats

The THEMIS/ARTEMIS telemetry and telecommand formats are compatible with the Consultative Committee for Space Data Systems (CCSDS) Version 1 standard. Command Link Transmission Units (CLTUs) generated by the ITOS command subsystem are transferred to the ground stations with a prepended 24-byte command delivery header that is stripped off prior to radiating. Telemetry frames delivered from the ground stations to the MOC are identical in length and content to the Channel Data Access Units (CADUs) on the single physical channel and contain the standard 4-byte Attached Synchronization Marker (ASM), the telemetry transfer frame, and the Reed-Solomon (RS) codeblock, but are prepended with a 10-byte annotation header that primarily serves to record the ground receive time. RS codeblocks are used by the baseband processors at the ground stations to perform error correction and rejection (if uncorrectable) prior to real-time CADU transfer to the MOC and recording in local archive files for post-pass transfer. According to these formatting conventions, all software tools at the MOC that read telemetry data are designed to operate on annotated CADUs exactly as they are received from the ground stations in real-time or via post-pass file delivery.

B. Conventional Telemetry and Telecommand Flows

By convention, NASA's Ground Network (GN) stations, the Space Network (SN), and BGS utilize separate, unidirectional TCP/IP socket connections for transfer of command and telemetry data between the ground station and the MOC, as described in the previous section. In case of BGS, connectivity is established via a secure LAN, and with GN and SN via NASA's secure Internet Protocol Operational Network (IONet). For network security reasons, these connections are always initiated by the systems with the higher network security classification – typically the baseband processors at the ground stations – a few minutes prior to scheduled AOS. Since the sockets are unidirectional, these links provide no confirmation that a transferred command has been radiated, and there is no feedback to the ground station that the MOC has received all transferred telemetry data.

C. SLE Based Telemetry and Telecommand Flows

The interface between the MOC and the DSN ground stations is established via the Space Link Extension (SLE) protocol, a CCSDS recommended standard which extends existing CCSDS telemetry and telecommand space link protocols with a cross-support service model that governs data transport and management.[11,12,13]

In contrast to the unidirectional data flows that are commonly used for THEMIS with BGS, GN and SN, SLE telemetry and telecommand service providers and users communicate as *peers* connected by bidirectional TCP/IP sockets, constantly exchanging data, management, and heartbeat messages. The SLE recommendation presently provides service models for transporting all telemetry transfer frames on the master channel (Return All Frames – RAF), or frames from a single virtual channel (Return Channel Frames – RCF) from a ground station to the MOC, and for transporting CLTUs (Forward CLTU – FCLTU) from the MOC to the ground station.

CADUs received at a DSN station are encapsulated in SLE-mandated wrappers prior to delivery to the MOC, and cannot be directly recovered from the terrestrial network link without additional interface software. By DSN convention, the ASM is stripped off of received CADUs, and RS codeblocks are only left attached to CADUs containing uncorrectable RS errors. With the SLE protocol, the Earth receive time for each CADU is recorded in a protocol header of a different format than the header in standard use with other networks, as is explained further below.

The DSN RCF/RAF and FCLTU service providers passively wait for remote users to initiate inbound socket connections. Multiple, redundant and independent RCF/RAF and FCLTU providers are accessible to a given project at a range of project-specific host IP addresses and ports, and the address of the active server host may change within this range at any time.

V. DSN Network Interface Implementation

A. SLE Implementation

The integration of the SLE interface with DSN focused on five goals: supporting SLE itself, implementing MOC-DSN network connections, integrating SLE service instances with the internal MOC dataflow, interfacing SLE with existing pass automation systems, and reformatting SLE-received telemetry to match the existing THEMIS standard so that telemetry formats remain compatible across all supporting mission networks.

New ITOS software modules called *itos_sle_rcf* and *itos_sle_fcltu* support SLE RCF and FCLTU service instances, respectively. These modules had already been developed and tested in support of the Lunar Reconnaissance Orbiter (LRO) mission, and were inherited by the ARTEMIS Project. Since the telemetry data rates on the master channel from ARTEMIS in lunar orbit through DSN are never higher than 131.072 kbps, it is feasible from a network bandwidth perspective to return all frames through the terrestrial network link to the MOC in real-time. SSL therefore requested an additional module from the ITOS developers, *itos_sle_raf*, to support SLE RAF service instances in addition to RCF. These new software modules were easily incorporated into the version of ITOS that is currently used operationally for THEMIS.

B. Network Interfaces between MOC and DSN

The SatTrack FrameRouter system was originally designed to accept incoming, unidirectional client socket connections from external ground stations and from telemetry and telecommand systems, and to route real-time data between these, as shown in Fig. 1 above. A software upgrade now allows FrameRouter to also support bidirectional flows required by the peer-to-peer SLE service instance interface. The resulting, more complex connectivity and routing scheme is shown in Fig. 2.

Unlike the baseband processors at BGS, GN and SN, the RAF and FCLTU service providers at DSN do not initiate outbound socket connections to a Project MOC for a given pass support, and thus cannot directly interface with FrameRouter. Furthermore, the DSN service providers are hosted on NASA's Restricted IONet, whereas the SSL MOC is connected to the Open IONet. NASA Integrated Services Network (NISN) IONet Security Policy mandates that connections must be initiated by hosts on a network with a higher security classification, which disallows any connection directly from the MOC to the DSN service providers.[14]

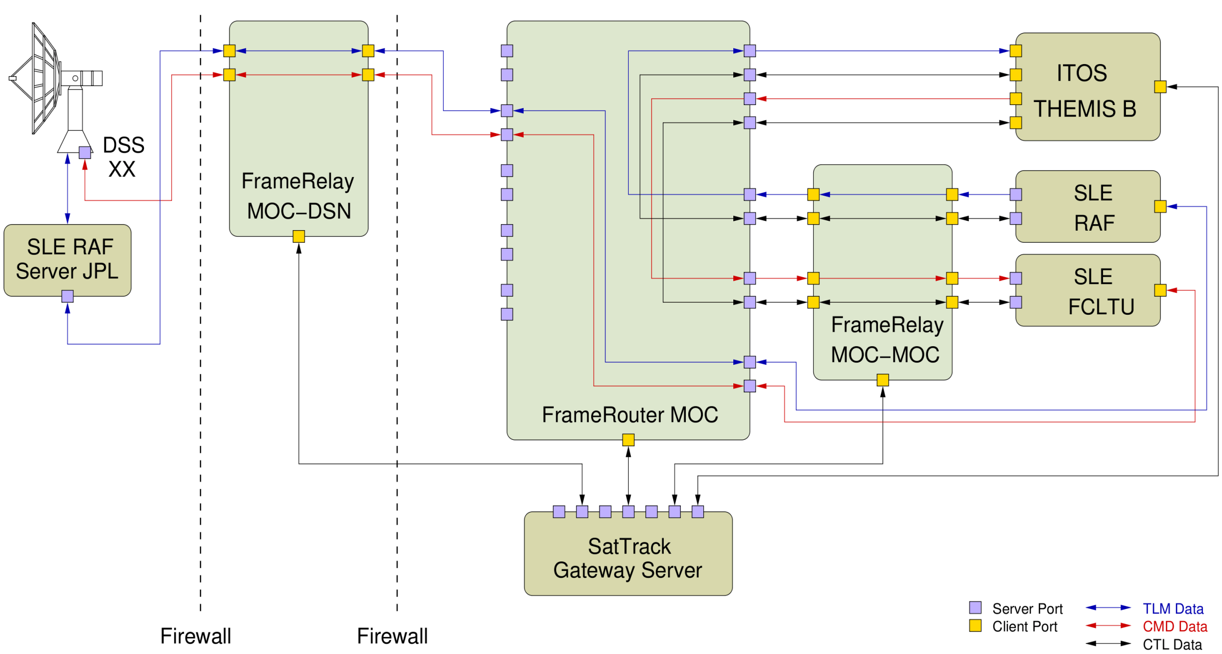

Figure 2. Network routing scheme for bidirectional telemetry and command flows across socket connections using the SLE protocol, shown in this example for THEMIS B. *The overall architecture allows concurrent passes with all five probes across all mission networks, with and without the SLE protocol.*

To solve this problem in a way that is compatible with the NISN IONet Security Policy, an instance of FrameRelay was installed on a Berkeley-owned workstation located at the secure Multi-mission MOC at GSFC. At program start-up, this software initiates and subsequently maintains a control socket connection to the SatTrack Gateway Server at the Berkeley MOC. FrameRelay *MOC-DSN*, shown in Fig. 2, then responds to remote configuration commands to initiate or remove bidirectional client socket connections between the DSN RAF and FCLTU service providers and FrameRouter *MOC*, all of which provide network server (listen) sockets to connect to. In this manner, FrameRelay acts as a secure Restricted-to-Open IONet bridge and as a network socket gender adaptor.

DSN supports ARTEMIS with four separate operational RAF service provider host addresses at JPL, and two operational FCLTU service provider host addresses per ground station. In preparation for establishing a RAF or FCLTU service instance, FrameRelay *MOC-DSN* attempts to connect to *all* predefined host addresses for the appropriate service provider. The first socket connection that succeeds becomes the active transport for the service instance, and all other connection attempts are terminated.

All instances of FrameRouter and FrameRelay send regular status messages back to the Gateway Server via the remote control connections shown in Fig. 2 (in black color) to provide visibility into each active network socket connection from a central location. A typical web page displaying the data transfer status of all active socket connections during a DSN pass with THEMIS C is shown in Fig. 3. The introduction of FrameRelay *MOC-MOC* is required to connect the SLE RAF and SLE FCLTU modules via FrameRouter *MOC* to the primary ITOS command and control system, and to simultaneously allow multiple instances of secondary ITOS systems and other telemetry processing software to receive the real-time telemetry stream in conventional, non-SLE format.

ROUTE STATUS ROUTER: MOC

ID	Route Point A				Flow	Route Point B			
1	TLM_THEMIS_C_SLE_FEED	11833	x.x.x.74	1002638 Bytes	->	TLM_THEMIS_C_ITOS_A	21033	x.x.x.116	1002638 Bytes
								x.x.x.120	1002638 Bytes
								x.x.x.119	1002638 Bytes
								x.x.x.74	1002638 Bytes
								x.x.x.113	1002638 Bytes
2	CMD_THEMIS_C_SLE_FEED	12833	x.x.x.74	266 Bytes	<-	CMD_THEMIS_C_ITOS_A	22033	x.x.x.113	266 Bytes
3	TLM_THEMIS_C_SLE_CTL	19133	x.x.x.74	11 0 Bytes	<->	TLM_THEMIS_C_ITOS_A_CTL	29133	x.x.x.113	28 0 Bytes
4	CMD_THEMIS_C_SLE_CTL	19233	x.x.x.74	28 0 Bytes	<->	CMD_THEMIS_C_ITOS_A_CTL	29233	x.x.x.113	28 0 Bytes
5	SLE_THEMIS_C_USER_RAF	27033	x.x.x.113	907717 6739 Bytes	<->	TLM_DSN_THEMIS_C_RAF	17033	x.x.x.217	907717 6739 Bytes
6	SLE_THEMIS_C_USER_FCLTU	28033	x.x.x.113	1277 90760 Bytes	<->	CMD_DSN_THEMIS_C_FCLTU	18033	x.x.x.217	1277 90760 Bytes

Router Control Host: x.x.x.92 Router Status: ONLINE

RELAY STATUS RELAY: MOC-MOC

ID	Route Point A				Flow	Route Point B			
1	TLM_THEMIS_C_SLE_FEED	11833	x.x.x.92	1002638 Bytes	<-	TLM_THEMIS_C_SLE_FEED	8002	x.x.x.113	1002638 Bytes
2	TLM_THEMIS_C_SLE_CTL	19133	x.x.x.92	0 11 Bytes	<->	TLM_THEMIS_C_SLE_CTL	9002	x.x.x.113	0 11 Bytes
3	CMD_THEMIS_C_SLE_FEED	12833	x.x.x.92	266 Bytes	->	CMD_THEMIS_C_SLE_FEED	8004	x.x.x.113	266 Bytes
4	CMD_THEMIS_C_SLE_CTL	19233	x.x.x.92	0 28 Bytes	<->	CMD_THEMIS_C_SLE_CTL	9004	x.x.x.113	0 11 Bytes

Relay Control Host: x.x.x.74 Relay Status: ONLINE

RELAY STATUS RELAY: MOC-DSN

ID	Route Point A				Flow	Route Point B			
1	CMD_DSN_THEMIS_C_FCLTU	18033	x.x.x.92	1277 91672 Bytes	<->	CMD_DSN_THEMIS_FCLTU1	9900	x.x.x.15	1277 91672 Bytes
2	TLM_DSN_THEMIS_C_RAF	17033	x.x.x.92	910231 6739 Bytes	<->	TLM_DSN_THEMIS_RAF1	9800	x.x.x.93	910231 6739 Bytes

Relay Control Host: x.x.x.217 Relay Status: ONLINE

Figure 3. Monitoring network data flows via a web based interface. *Each row displays the status of a peer-to-peer network socket connection. A green background indicates an active flow with the number of bytes transferred in each direction. Note that four additional clients are connected simultaneously to route point TLM_THEMIS_C_ITOS_A (port 21033) to receive the telemetry stream converted to non-SLE format in parallel with the primary ITOS system. However, only one client – the primary ITOS command and control system for this spacecraft – is allowed to connect to route point CMD_THEMIS_C_ITOS_A (port 22033) to deliver CLTUs. For network security reasons, all IP addresses were purposely altered and masked in this figure, and port numbers were changed, and are shown for illustration only.*

C. Interfacing SLE with Pass Automation Software

The Autopilot software running on each primary ITOS command and control workstation acts in concert with the SatTrack Gateway Server to automatically configure ITOS prior to all pass supports. For DSN passes, Autopilot also initializes the SLE-related software modules and then issues operational directives through this software to establish the service connections, and to start telemetry and command data flows. ITOS opens archive files at the beginning of each pass to record all telemetry received. Since RAF data delivery transmits every non-idle frame received at the ground station, these local archives are sufficient to capture the entire telemetry stream, and there is no need to routinely arrange for post-pass telemetry delivery via offline requests.

THEMIS and ARTEMIS data playbacks are not initiated by stored spacecraft command, but rather started by ground command, once Autopilot has verified a solid two-way command and telemetry link. Consequently, no data are lost in the event of a late acquisition of signal or a failed pass support since all stored data remain onboard.

To minimize data loss in the event of a network link failure or an unanticipated protocol abort during an unattended pass support, an in-house developed program called *SleMonitor* continuously polls the Gateway Server for FrameRelay *MOC-DSN* status during a pass support and advises Autopilot if either the RAF or FCLTU connections have been broken. If the RAF connection breaks while the FCLTU connection is still operational, the spacecraft is first commanded in the blind to stop data playback, and then Autopilot attempts to re-establish the RAF service instance. If the FCLTU connection breaks, Autopilot promptly tries to re-establish this service instance.

D. Reformatting SLE Received Telemetry

As discussed earlier, the THEMIS mission utilizes a common NASA standard for delivering telemetry transfer frames from the ground stations to the MOC. In this standard, each telemetry transfer frame received at a ground station is prepended with a 10-byte annotation header that contains minimal processing information, namely the Earth receive time tag with an accuracy of 1 millisecond, and a number of data quality status bits. This annotation header is commonly referred to as the Small Explorer / Earth Observing System (EOS) Data and Operations System (SMEX/EDOS) header. Since the ITOS command and control system, the engineering telemetry archiving system, and also the science data processing systems already expect a common frame format consisting of annotated CADUs, the decision was made to convert all telemetry data received from DSN via SLE interfaces to also match the same standard.

In ITOS, the itos_sle_raf software module controls and manages the data transfer between the MOC and the RAF service provider on the DSN side, and broadcasts a stream of CADUs, albeit in a different format than has been standardized for use with other networks supporting THEMIS. A real-time socket-based application called *RafReformat* developed in-house at SSL intercepts the output stream from this module and performs a number of modifications on the fly before re-delivering the modified telemetry data to another port on FrameRouter *MOC*. The SLE-format ground segment header that prepends each delivered CADU is stripped off, but its Earth receive time field is used to create and populate the SMEX/EDOS header.

By convention, CADUs received and processed at a DSN station and found to be error-free after RS error correction are forwarded to the MOC with the RS codeblock stripped off. To maintain consistency with telemetry data formats across all supporting networks, RafReformat recalculates and reapplies the missing RS codeblock to these CADUs. The newly created RS codeblock does not provide any error correction capability, but this scheme has the advantage that downstream data processing systems that expect a fixed CADU length do not need to be modified. These systems include additional instances of ITOS (see Fig. 1), or engineering and science data archiving systems. RafReformat also attempts to correct any bit errors in cases where the original RS codeblock is still attached to a CADU. Post-delivery RS error correction is generally performed at the MOC on CADUs received from all networks with either real-time or post-pass file delivery to catch instances where a baseband processor may not be configured correctly to perform RS error correction, or to discard uncorrectable CADUs. A CADU is rejected at the MOC from further processing if it is determined to contain uncorrectable bit errors. The reformatted and cleaned-up telemetry stream is then provided to the primary, operational ITOS command and control console and all other telemetry processing clients.

VI. Tracking and Ranging

A. THEMIS Transponders

All five THEMIS probes are equipped with L3 Communications Telemetry-West Model CXS-610 transponders operating on the same S-band frequencies. A block diagram is shown in Fig. 4. The command uplink modulation mode is PCM/PSK/PM with a 16-kHz subcarrier at a modulation index of 1.0 rad, and with a data rate of 1 kbps. For telemetry downlink, ten different data rates are selectable between 1.024 and 1048.576 kbps. The transmitter can be operated in PCM/PSK/PM mode with a 1024-kHz subcarrier at the lowest six data rates up to 65.536 kbps, or in direct carrier (BPSK) modulation mode with all ten data rates. Depending upon the available receiving equipment at a given ground station, two-way Doppler measurements can be made either at the lowest six data rates in PCM/PSK/PM mode, or with all ten data rates in BPSK mode, using the coherent return channel.

The original THEMIS concept of operations required only two-way Doppler tracking data, but no range data from all supporting ground stations to be used for orbit determination. However, the Project became interested in exploring the existing, but so far untested and unused ranging capabilities in light of the upcoming DSN integration for ARTEMIS.

The ranging channel can be used with the PCM/PSK/PM downlink modulation mode and has a bandwidth of 384 kHz with a modulation index of 0.5 rad on both uplink and downlink, and was originally planned to be used for a technology demonstration of a ranging scheme based on turning around pseudo-random number (PRN) sequences. While this non-essential demonstration was descoped prior to launch, the ranging channel in each transponder had already been tested and characterized by the manufacturer as part of the factory acceptance test procedure. The ranging channel was enabled on orbit for the first time on THEMIS C in August 2008 – 18 months after launch. Subsequent ranging tests were conducted in fall of 2008 when THEMIS probes A, D and E were utilized as a mission of opportunity to certify a new 18-m antenna at NASA's White Sands Complex in New Mexico, as well as four Universal Space Network (USN) ground stations in preparation for LRO mission support. Additional tests were also conducted with several NASA GN stations equipped with Spaceflight Tracking and Data Network (STDN) Ranging Equipment (SRE).[15] Valid range measurements were obtained with a 100 kHz major tone to ranges of approximately 70,000 km.

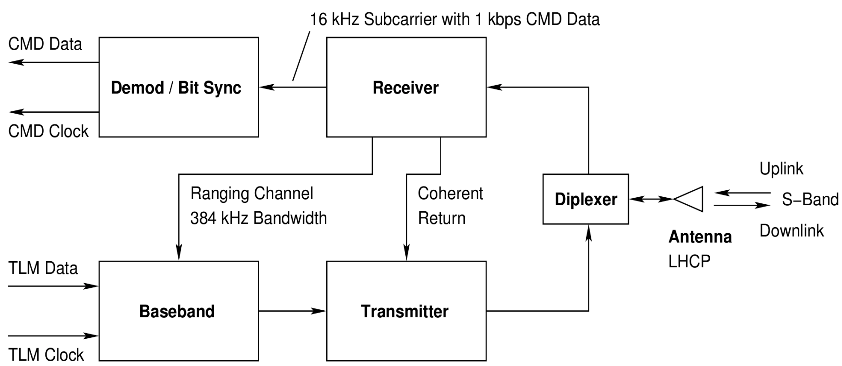

Figure 4. THEMIS S-band phase-locked transponder block diagram.

The first ranging tests with DSN were performed in December 2008, using the sequential ranging scheme.[16] With the bandwidth limitation of 384 kHz in the transponder ranging channel, the feasible range component numbers are 6-20, providing a one-way range ambiguity resolving capability R_{amb} of approximately 9,572 km. Range cycles are 131 s long, with integration times T_1 = 30 s for the clock component (6) and T_2 = 6 s for the ambiguity-resolving components (7-20). With this scheme, a ranging power-to-noise spectral density ratio P_R/N_0 of 20-30 dB-Hz was achieved with THEMIS B and both DSN 34-m High Efficiency (HEF) and Beam Waveguide (BWG) antennas (DSS-24, 45, 54, 65) at ranges of the order 1,000,000 km.

B. Processing of Radiometric Observations

A two-way Doppler measurement at a SRE compatible ground station is the cumulative cycle count of M times the Doppler frequency plus a 240-MHz bias frequency, and is time-tagged at the time of the cycle counter reading. Measurements are typically made with an integration time of 10 seconds and are saved as 75-byte binary records in Universal Tracking Data Format (UTDF).[15] The observed range rate is obtained from these data as follows:

$$dR/dt\,(T_0) \;=\; -c \,/\, (2\, f_T\, K\, M) \times [(N\,(T_0) - N\,(T_{-1}))\,/\,(T_0 - T_{-1}) - 2.4 \times 10^8] \tag{1}$$

$N\,(T_0)$ and $N\,(T_{-1})$ are the latched cycle counts at the current and previous read-out times, and f_T is the transmit frequency. At S-band, the coherent return ratio K is 240/221, and M = 1000.

The observed range measurement is the Round Trip Light Time (RTLT) in units of 1/256 ns and is time-tagged at receive time T. A range observation is converted from raw range counts R_{raw} to length units as follows:

$$R\,(T) \;=\; (c\,/\,512) \times 10^{-9}\, R_{raw}\,(T) \tag{2}$$

Tracking data from DSN stations are provided in a different standard, namely in TRK-2-34 format.[17] This file format is structured as Standard Formatted Data Units (SFDUs) and contains so-called Compressed Header Data Objects (CHDOs) for a number of different data types. Two-way Doppler data are found in CHDOs with Data Type 17 (DT17), and sequential range data in Data Type 7 (DT7). Additional information needed to process range rate data is extracted from the Uplink and Downlink Carrier Phase CHDOs (Data Types 0 and 1 – DT0 and DT1), and for range data from the Uplink and Downlink Sequential Range Phase CHDOs (Data Types 2 and 3 – DT2 and DT3).

Range rate information is extracted and processed for multiple, interleaved downlink channels, if present. The range rate is then derived as follows:

$$dR/dt\,(T_0) \;=\; c \,/\, 2 \times [1 - (\Phi\,(T_0) - \Phi\,(T_{-1}))\,/\,(f_T\,K \times (T_0 - T_{-1}))] \tag{3}$$

$\Phi\,(T_0)$ and $\Phi\,(T_{-1})$ are the round-trip count phases at the current and previous counter read-out times.

DSN range observations, R_{RU}, are provided in Range Units (RU) and are corrected for various station-internal range calibration offsets that are derived from CHDOs for DT2, DT3, and DT7, and are combined in $R_{RU,stn}$. The range ambiguity is resolved by using the predicted RTLT at the begin of a track, as provided in DT7 CHDOs, and adding multiples n of the range ambiguity resolving capability R_{amb}, as defined in the previous subsection, until the range measurement matches the predicted range within half of R_{amb}:

$$R\,(T) \;=\; 2\,c\,/\,f_T \times (R_{RU}\,(T) - R_{RU,stn}) + n\,R_{amb} \tag{4}$$

DSN range rate and range observations converted to metric units are subsequently written out in UTDF files to be compatible in format with radiometric observations made by SRE ground stations, as illustrated in Fig. 5. In this process, range rate and range observations are converted back to raw counts by inverting Eqs. (1) and (2). Several spare fields in the UTDF records are used to carry forward DSN specific parameters, as well as the transmit frequency with sufficient decimal places.

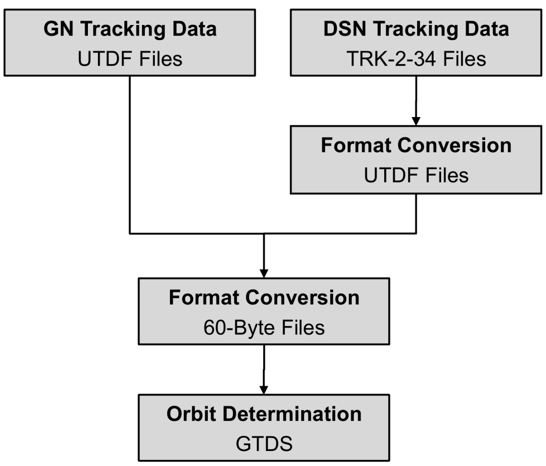

Figure 5. Pre-processing flow for radiometric range and range rate tracking data.

C. Orbit Determination

Once all DSN tracking data are converted from their native TRK-2-34 to UTDF format, an additional step is required to prepare range rate and range observations for ingest by the Goddard Trajectory Determination System (GTDS) which is used at the MOC for THEMIS and ARTEMIS orbit determination (OD).[18] Input data to GTDS are formatted in 60-byte binary records containing range rate and range observations in metric units. Various corrections such as frequency biases arising from a finite frequency resolution in the ground receivers, and transponder range delays are applied at this stage in the process of conversion from UTDF to 60-Byte file format.[19] Transponder round-trip delays for probes THEMIS A-E, as measured during factory acceptance testing, are 360.0, 430.7, 378.3, 348.3, and 408.2 m, respectively.

The GTDS FORTRAN code is called out of in-house developed Interactive Data Language (IDL) wrapper code, allowing OD runs to be performed interactively or in a fully automated fashion.[3,4,20] State vectors from converged orbit solutions are quality checked and appended to a separate state vector archive for each probe, and are in turn used as a seed for the next OD run. Radiometric observations for individual runs are selected based on time tags in UTDF files names that fall into the arc chosen for a particular orbit solution.

Converting DSN TRK-2-34 files to UTDF format has the large advantage that during the integration phase, observations from DSN station could be mixed in with those from other already certified THEMIS ground stations without changing and disturbing the operational, configuration controlled process. DSN tracking data were initially included in the OD runs to evaluate differences between calculated and observed range rates and ranges, but without using these observations in the differential corrector. This approach allowed the navigation team at UCB to develop and carefully test the new pre-processing code, to resolve various issues with range biases and to refine delivery and processing procedures.

D. Delivery of Acquisition Data to DSN

Short-term acquisition data in CCSDS Orbit Ephemeris Message (OEM) format are uploaded from the MOC to the DSN Service Processing Subsystem (SPS) at JPL for both THEMIS B and C on a weekly basis. Corresponding data files span 30 days and contain spacecraft position and velocity in one-minute steps in Cartesian coordinates in the EME2000 (J2000.0) reference frame, and with Earth as the central body.

VII. Pass Support Scheduling

A. MOC Scheduling Process

Since ARTEMIS is not a DSN-only mission, but is supported by several other networks, DSN passes are treated like any other passes for THEMIS or ARTEMIS. The scheduling system at the MOC ingests committed DSN schedules in plain-text 7-day format, and checks these against the local planning schedule with an extensive number of constraints. Details of this process are described elsewhere.[21] The selection of telemetry data rates is based on the prediction of a dynamically modeled link margin, calculated at the MOC and taking into account view periods, spacecraft antenna pattern, attitude, range and ground station specific figure of merit (G/T) for each antenna. These predictions are very reliable, and allow maximizing telemetry data volume and data quality.

B. DSN Scheduling Process

The DSN scheduling process currently requires utilizing a number of software interfaces, depending upon the stage of the process, beginning with users adding pass support requirements for their particular mission to a scheduling Wiki page at JPL many weeks in advance. Schedulers in the DSN community input these requirements into a scheduling engine to create a one-week long preliminary schedule that may or may not meet all requirements of participating missions. Users then access the preliminary schedule with the Telecommunications and Mission Operations Directorate (TMOD) Integrated Ground Resource Allocation System (TIGRAS) software program.[22]

Proposals for negotiating scheduling conflicts can be generated with TIGRAS and are submitted by electronic mail at which time the missions concerned with the proposal may submit counter proposals or continue negotiation via electronic mail or verbally in regularly scheduled weekly meetings. When all mission conflicts are closed for a given schedule, that schedule is then released to the JPL SPS web portal where users can login and download the finalized schedule in either standard plain-text 7-day scheduling format or in Extensible Markup Language (XML) format. Near-term and real-time changes to the finalized schedule can be submitted directly via TIGRAS and are reviewed by DSN schedulers for conflicts.

C. Scheduling Software Adoption

As TIGRAS is free and readily available from JPL, the Berkeley Flight Operations Team (FOT) decided to utilize this software as opposed to developing a custom interface to handle DSN schedule visualization and conflict negotiation. TIGRAS is the primary interface for JPL and many other missions in the DSN community, and has been in use for some time. Therefore the FOT was able to adopt the software quickly, compared to the time it would have taken to develop a custom interface. Accessing TIGRAS requires the additional use of Virtual Private Network (VPN) client software, which is also provided by JPL.

D. Scheduling Process Adoption

The scheduling process at the MOC involves interaction with multiple networks, including the local BGS, NASA GN and SN, USN, and now also DSN. Scheduling with DSN requires a shift in scheduling process timeframe as the current DSN scheduling system requires schedules to be de-conflicted by a minimum of eight weeks from the current operational week to accommodate missions that require sequence loads to be generated this far in advance. By contrast, requests for support through the other networks nominally occur only during the week prior to the operational week, and the MOC tries to only utilize those times that have not already been requested by other missions to minimize conflict resolution efforts. While critical events to be supported through these networks are planned out weeks in advance, utilizing the DSN required the Berkeley FOT to shift the process start time so as to participate in the DSN scheduling process even for nominal tracking supports.

VIII. Results and Lessons Learned

A. Overall Approach and Results

1. Overall Approach

Since ARTEMIS is not a new mission, but rather a significant extension to an already operating mission, and also involved two spacecraft that were still part of the THEMIS prime mission during the ARTEMIS integration phase, special care had to be taken to not disturb any of the operational interfaces or cause risk of science data loss to the prime mission. Therefore, the overall approach of integrating the DSN interfaces into the operational environment at the Berkeley MOC had to be carefully planned and executed. One key aspect of the integration strategy was to maintain flexibility and transparency so that any of the five THEMIS probes could be supported by any of the network assets, including GN, SN, DSN, USN and BGS, using both the non-SLE and SLE schemes for network connectivity. Another key decision was to continue to treat the two ARTEMIS probes for all operational purposes as members of the THEMIS constellation to avoid any issues resulting from changing names in numerous configuration files, automation scripts, file names of data products and written procedures. However, for programmatic purposes and for science planning, THEMIS B and C are usually referred to as ARTEMIS P1 and P2, respectively.

2. Implementation Milestones

The THEMIS-Low/ARTEMIS mission extension proposal was submitted to NASA in February 2008, and ARTEMIS was provisionally approved in May 2008. Meetings and telephone conferences between UCB, JPL and GSFC to plan the DSN integration began in June 2008. The first successful two-way Doppler and range track of a THEMIS probe with a DSN 34-m antenna was achieved in December 2008. The first attempted and immediately successful DSN telemetry and command passes with both THEMIS B and C using the SLE protocol occurred on July 10, 2009, just 11 days prior to the initiation of the Earth departure sequence of THEMIS B. Up to this point, DSN had already supported 109 two-way Doppler and ranging-only passes, allowing the UCB flight dynamics team to include DSN tracking data along with those from BGS, GN and USN in the orbit determination process.

DSN became officially certified for ARTEMIS in fall of 2009, after already having supported maneuver operations as well as post-maneuver tracks for both THEMIS B and C Earth departure sequences for several months. Until the end of March 2010, DSN supported 472 passes for THEMIS B and C combined, including continuous tracks during the two lunar flybys of THEMIS B on January 31 and February 13, 2010, respectively, and during the lunar flyby of THEMIS C on March 28, 2010. Overall, it took approximately two years from initial ARTEMIS proposal submission to achieving the lunar flybys with both spacecraft.[7]

B. Telemetry and Command Interfaces

1. SLE Implementation

It appears that the implementation of SLE-based interfaces at the MOC represents a large investment in the short term, but with the expectation of benefits to materialize in the long term. Implementation and test efforts should not be underestimated, and should be planned with ample schedule reserves.

2. Reliability of Network Connections

The network routing scheme described in this paper is based entirely on Berkeley Sockets.[23] However, the application program interfaces (APIs) in the Berkeley Sockets library do not allow direct access to all low-level status information in the TCP header that is used by the SLE service provider employing the System V Transport Layer Interface.[23] This potential incompatibility raised concerns initially regarding the ability to cleanly connect, disconnect or reconnect to/from the SLE service provider. However, it was demonstrated that the implemented scheme described in this paper is very reliable. While there were a number of instances when connectivity between the MOC and DSN was lost, no proof was found to indicate the root cause might be related to the slight difference in communications protocols. Mechanisms were implemented at the MOC to detect disconnects and to automatically reconnect, rebind and restart telemetry or command flows with the SLE service provider to minimize service loss. These procedures are far more complex than those required to recover from a drop-out of a conventional telemetry or command network socket connection because of several logic layers that are associated with the SLE protocol.

C. Tracking and Ranging

1. Transponder Performance

All five transponders have been performing exceptionally well for more than three years on orbit. Operation of the ranging channel has been successfully exercised with DSN out to a range of more than 1,000,000 km (THEMIS B) to date. Offering the THEMIS constellation as a mission of opportunity to the LRO Project in order to certify the White Sands (WS1) and USN ground stations also provided an invaluable, early start with testing the ranging channels on orbit, prior to the first DSN pass of THEMIS B or C.

2. Orbit Determination

Orbit determination runs including radiometric observations from multiple networks (GN, DSN, USN, BGS) have been very successful. Usage of tracking data from multiple networks were very valuable during the DSN integration phase to refine processing of the DSN TRK-2-34 data files at UCB. DSN range observations will be particularly important for accurate orbit determination during certain parts of the ARTEMIS lunar transfer trajectories, such as near the Earth-Sun Lagrange points where range rates do not vary much.

3. Acquisition Data Delivery

Providing both short-term and long-term acquisition data in CCSDS Orbit Ephemeris Message (OEM) format to JPL/DSN is a clean and reliable approach, and has been working very well. A large advantage is that no conversion to SPICE Kernel (SPK) format is required on the Project side prior to data delivery.

D. Scheduling Interfaces and Processes

1. Schedule Negotiation Process

Most schedulers in the DSN community are responsible for multiple missions. ARTEMIS is one of the few cases in which the schedulers solely responsible for ARTEMIS are also members of the FOT. While this approach requires these three FOT members to perform duties in addition to their normal console activities, it also continues to provide a significant advantage for THEMIS. Scheduling activities across all five probes in a multi-mission environment allows the FOT as a whole to respond to conflicts or mission updates as quickly and efficiently as possible. This aspect was of particular importance as the work of integrating DSN began while the THEMIS mission was well into its operational phase.

Since the ARTEMIS trajectories were designed for an operational mission and on a relatively short schedule concurrent with DSN integration, major mission events could not be planned far in advance and moved to avoid already scheduled DSN asset downtimes or major events of other missions. FOT members with a detailed understanding of the mission trajectory and in immediate contact with mission operations management and the navigation team were able to rapidly respond to scheduling and navigation challenges as they developed.

Additionally, with multiple networks supporting the THEMIS and ARTEMIS missions, it is advantageous for the schedulers to work across all networks, providing them with an intimate knowledge of the whole scheduling picture, and allowing them to avoid potential conflicts within the mission, across all THEMIS probes, and across all networks. Although the timeframe for scheduling and negotiation with DSN is different from all other networks, knowledge of which networks may support a particularly important orbit event allows the FOT to appropriately balance the support load for the mission. The result is increased flexibility in negotiating scheduling conflicts with other DSN missions, and also a reduction in risk and cost.

2. Future Changes

Introduction of the Berkeley FOT to the DSN scheduling system occurs at a time when the DSN is developing a completely web-based interface to manage all aspects of scheduling, called the Service Scheduling Subsystem (SSS).[24] These aspects include requirement submission, automated schedule build, real-time chat-based conflict negotiation, user activated scheduling change-proposal creation and submission, and schedule product formatting. Not all features have been implemented and most are in the testing phase, but the release of such a scheduling interface will help streamline the DSN scheduling process for Berkeley scheduling operations, as the current set-up requires the use of multiple software tools across differing operating systems and platforms. The FOT is currently participating in review and testing of SSS.

IX. Conclusion

The ARTEMIS mission is a significant step-up from THEMIS in terms of complexity of network communications and navigation. Integrating the Deep Space Network into the already extensive THEMIS mission network was a difficult task that had to be carefully planned and accomplished on a relatively short schedule, in parallel with ongoing on-orbit operations. All challenges were successfully met, and the DSN integration and transition from GN to DSN as the primary ARTEMIS network were completed seamlessly and at low risk to the operating mission prior to the first set of critical lunar flybys. The Deep Space Network now allows the operations team to continue to communicate with the two probes along their lunar transfer trajectories, and will be instrumental for providing critical radiometric tracking data to support the upcoming navigation operations, and for eventually returning exciting new science data from the lunar environment.

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