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Integration of Flight Dynamics Systems (FDS) with Integrated Trending and Plotting System (ITPS)

Jennifer Sager Cosgrove [1]
Honeywell Technology Solutions Inc., Greenbelt, MD 20771

Haim Brumer [2]
Honeywell Technology Solutions Inc., Greenbelt, MD 20771

and

Shubha Barriga [3]
Honeywell Technology Solutions Inc., Greenbelt, MD 20771

Abstract

This paper provides an overview of the development and integration of Flight Dynamics Systems (FDS) data with the Integrated Trending and Plotting System (ITPS) supporting Landsat-7, Lunar Reconnaissance Orbiter (LRO), Gamma-ray Large Area Space Telescope (GLAST), Solar Dynamics Observatory (SDO), Tropical Rainfall Measuring Mission (TRMM), and Earth Observing System (EOS). ITPS is a flexible and comprehensive trending and plotting system providing spacecraft controllers and scientists with tools for determining the health and performance of space-based assets. ITPS has been integrated with flight dynamics systems data to enable filtering of spacecraft telemetry data based on orbital events integrating orbit data with ITPS data extraction and plotting features. This paper discusses flight dynamics ITPS features; why these features are important; and how they impact mission science, mission planning, and flight operations.

I. Introduction

The ITPS is a comprehensive system for the storage, extraction, and analysis of spacecraft telemetry data, providing access to the complete mission telemetry data archive. ITPS has been integrated with flight dynamics systems to enable filtering of spacecraft telemetry data based on orbital events integrating orbit data with ITPS data extraction and plotting features, improving science and operations planning, as well as anomaly resolution.

In addition to the full-resolution telemetry archive, ITPS maintains a lifetime trend data archive of reduced-resolution telemetry compiled into data point mnemonic (or measurand) statistics. ITPS was designed specifically to meet the changing demands of multi-mission environments, providing critical trending support to flight operations teams managing modern spacecraft constellations. Using precise filtering, reporting, and plotting capabilities, ITPS analyzes data and provides it to users via the generation of telemetry plots, tables and reports. The ITPS secure remote web component supports external user requests and allows offsite operator access. By introducing functionality such as constellation support and comprehensive analysis tools, the ITPS has given flight operations teams and the science community a more meaningful view of mission housekeeping telemetry. ITPS has been used

[1] Systems Engineer, NASA Goddard Space Flight Center Flight Dynamics Facility, NASA GSFC Mailstop 452.4, AIAA Professional Member
[2] Systems Engineer, NASA Goddard Space Flight Center Flight Dynamics Facility, NASA GSFC Mailstop xxx.x, AIAA Professional Member
[3] Program Manager, NASA Goddard Space Flight Center Flight Dynamics Facility, NASA GSFC Mailstop 452.1, AIAA Professional Member

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operationally or is in development in numerous GSFC Mission Operations Centers (MOCs), at White Sands Complex (WSC), and in the DataLynx Facility in Columbia, Maryland, supporting various spacecraft including: Lunar Reconnaissance Orbiter (LRO), Solar Dynamics Observatory (SDO), the Tracking Data and Relay Satellite System (TDRSS) constellation, Solar and Heliospheric Observatory (SOHO), WIND, POLAR, Landsat-5, Landsat-7, Gamma-ray Large Area Space Telescope (GLAST), Tropical Rainfall Measuring Mission (TRMM), Earth-Observing-1 (EO-1), Earth Observing System (EOS), Space Environment Testbeds (SET-1) and the decommissioned Space Technology 5 (ST5) constellation.

Landsat-7 was the pioneer mission for integrating flight dynamics components with ITPS, with the first installation going operational in 1999. The first FDS ITPS installation integrated orbit nodal crossing data, sunlight information, and eclipse data with ITPS, which enabled filtering of spacecraft telemetry data by nodal, sunlight, and eclipse events. SDO and GLAST are also employing these ITPS FDS integration features, and these implementations are ongoing.

LRO, TRMM, and EOS have decided to expand the current Flight Dynamics Systems (FDS) ITPS integration capabilities and are adding supplemental flight dynamics enhancements. LRO is integrating the beta angle (angle of the LRO lunar orbit plane and the sun) predictions with telemetry so users can display actual telemetry alongside predicted angles to analyze and improve the beta angle prediction model. LRO has also integrated lunar orbit terminator data with ITPS plotting so users can correlate the boundary between light and shadow on the lunar surface with spacecraft housekeeping telemetry. TRMM integrated the South Atlantic Anomaly (SAA) with ITPS so that users can correlate anomalous events to orbital events, which can often lead to resolving issues quickly and efficiently. For Low Earth Orbit (LEO) missions such as TRMM, correlating Single Event Upsets (SEUs) or other resets to the SAA using ITPS enables the trending system to report the reset and SAA region times within the same plot or report improving anomaly resolution by making the process quicker, more efficient, and automated. The EOS Terra, Aqua, and Aura missions are investigating vastly expanding the flight dynamics capabilities of ITPS by introducing over 25 new products and data types to be processed alongside spacecraft telemetry to be made available for analysis and trend determination.

This paper discusses the development and integration history of flight dynamics components with ITPS, originating with the USGS mission, Landsat-7, and then continuing with the current or future ITPS FDS enhancements in support of the NASA missions, LRO, TRMM, and EOS. The ITPS architecture and principle software components, which enable the FDS ITPS integration, are detailed and illustrated in this paper. The integrated flight dynamics ITPS features, why these elements are significant, and how they influence mission science, mission planning, and flight operations are also discussed.

This paper is organized into four sections. This section, Section I, Introduction, provides a general overview of the paper. Section II, Introduction to ITPS, presents an overview of ITPS, including a discussion detailing ITPS functions, architecture, and software components. Section III, ITPS FDS Integration, summarizes the ITPS FDS integration development history starting with Landsat-7 and continuing with LRO and TRMM FDS development, including a discussion of future ITPS FDS integration for the EOS missions, Terra, Aqua and Aura. Section III also enumerates why these ITPS FDS features are important, and how they impact mission science, mission planning and flight operations. The final section, Section IV, Conclusion, summarizes the ITPS FDS integration history and features, providing closing remarks and a look to the future of FDS ITPS integration.

II. Introduction to ITPS

This section of the paper, Section II, Introduction to ITPS, presents an overview of ITPS. This section includes discussions of ITPS features, architecture, and software components.

A. ITPS Features

ITPS was first envisioned in the planning stage of the Landsat-7 MOC in the late 1990s. The Flight Operations Team (FOT) was disappointed with existing technology used to ensure the health and safety of the Landsat-7 spacecraft – a critical asset of the US Geological Survey division of the US Department of Interior. The existing systems constrained the flight operations team to a limited number of spacecraft or instrument data collection points (also known as measurands or mnemonics), to a limited time frame for examination, or to both. ITPS introduced a solution which gave flight operations personnel and scientists access to all and any housekeeping telemetry points for the life of the mission.

A trade study was executed by the Landsat-7 FOT in the early planning stage of the Landsat-7 MOC architecture. This survey examined existing housekeeping telemetry systems and found that they had one or more of the following shortcomings:

1) Number of data points: The Landsat-7 spacecraft has about 4000 sensors, thermistors, relays, or other data generating points aboard distributed between the spacecraft and instruments. The technology that was available at the time the study was done often limited the spacecraft to a limited number of data points for collection, storage, and trending for housekeeping telemetry data. For example, one existing system limited the Landsat-7 FOT to any 3000 data points. Once that collection began, the FOT could not examine the remaining 1000 points. Since the nature of any spacecraft is such that it is impossible to predict which data points will be critical later in the mission, this was a severe handicap for planning and executing the FOT's mission of ensuring the health of the Landsat-7 spacecraft and nominal operations. A key point of the ITPS design was that it would provide no limit in the number of telemetry points available for examination, archive, and trending. If it was part of the spacecraft, it would be available in the ITPS.
2) Retention Time Span: Originally designed for a 5-year lifespan, the Landsat-7 mission, which launched in April 1999, has now been extended until at least 2013. When doing a survey of available archive and trending systems, the FOT found that existing systems limited the volume of on-hand data (measured in time span) that could be analyzed, with some systems limiting access to as little as 30 days of full-resolution telemetry access. On these systems, data older than 30 days had to be stored offline or near-line requiring time-consuming data restore procedures when examining historical data. Long-term trends of full-resolution telemetry required so much data swapping and restoration, that they were impractical and inefficient to perform. Thus one of the key ITPS design features was for it to make all mission data readily available without resorting to time-consuming data restoration.
3) Sustaining Cost: Telemetry archive and trending systems available to the Landsat-7 FOT were very costly to maintain. Primarily because they were hosted on expensive hardware with custom data storage solutions (such as robotic jukeboxes), these systems locked the mission into a hardware single vendor whose support costs were a burden to the mission looking at a long life span. In addition, the Landsat-7 FOT surveyed existing missions who reported that long-term sustaining costs would grow considerably as the mission matured due to the cost of paying to lengthen the life of outdated hardware. As a result, the ITPS was designed to run on a standard PC platform, ensuring ongoing support, access to inexpensive hardware, and a wide array of hardware vendors as the mission aged.
4) Limited Access: None of the available trending systems provided the ability to offer analysis and data access capabilities to users outside the immediate surrounding of the control center. This required that the FOT spend much of their time doing analyses and generating reports for remote users, experimenters, and members of the science community. In addition, the Honeywell led FOT had championed an automated "lights-out" control center where routine operations would be scripted and where appropriate personnel would be paged by the automation software upon detection of errors or anomalies. To support this functionality, remote users had to be able to access the suite of tools provided by the trending system. Consequently, the ITPS was integrated with a web server and web software to allow remote users to do their own analyses and to provide remote FOT with access to all mission housekeeping data.
5) Costly Manual Operations: The FOT found that in most control centers, much of the trending system operators time was spent doing routine operations such as preparing for data acquisition, data reduction, and generation of routine products. The Honeywell-led team had insisted that they would automate all routine operations, reducing staffing needs and dedicating staff to value-added functions. To further these goals, the ITPS was developed to eliminate entirely all routine operations, including data acquisition, data reduction, and routine product development.

Thus the ITPS was developed based on a collection of the best features of existing NASA and USGS housekeeping archive and trending systems, while at the same time advancing the USGS requirement for reducing cost, enabling access to the entire mission housekeeping database, and securing remote access.

B. ITPS Architecture

ITPS is a PC based suite of applications for the storage, extraction, and analysis of spacecraft housekeeping data. Each ITPS system will be completely independent of the other for all functions, including data acquisition, analysis, and product generation.

Each ITPS system usually interfaces with a data source computer, such as a Telemetry and Command (T&C) computer (which may interface via TCP/IP or UDP port, or a shared directory where telemetry is deposited during a pass), and a flight dynamics computer, and may host optional web server software as shown in Figure 1.

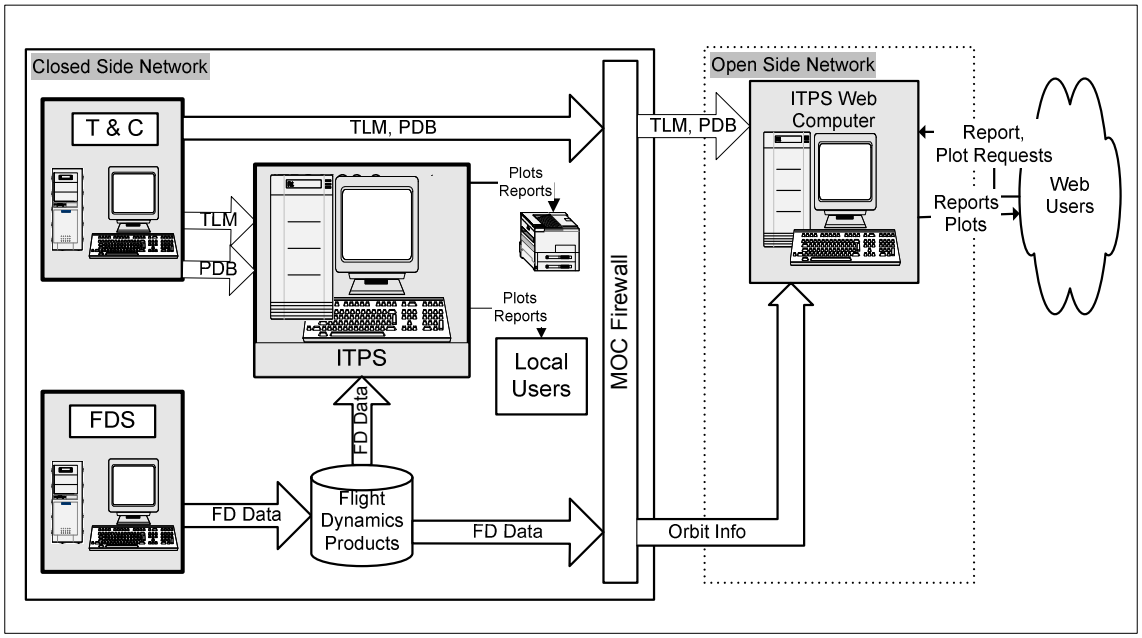


Figure 1. ITPS External Interface Diagram

1. T&C Computer:

ITPS continually receives spacecraft telemetry from the data source computer, usually a T&C system or a ground system data distribution system. ITPS has the ability to receive data via a direct socket connection, as well as reading data from transferred files. In all cases, the computer providing the data to ITPS initiates the transmission of data (a methodology that allows it to provide data to the web host computer where security restrictions would not allow bi-directional data access).

The ITPS processes telemetry based on the mission Project Database (PDB). The project database is contained in files generated by the spacecraft and/or instrument engineers and is usually acquired from T&C system. These telemetry metadata files are required for ITPS and will be transferred to the ITPS computer whenever a new PDB version is created. Creation of new PDB versions is a rarity during mission operations, but is quite common during Integration and Test (I&T). The transfer of these data is initiated manually from the T&C system, on an as-needed basis.

2. Flight Dynamics Products

ITPS uses products generated by the FDS for determination of orbital events. These products describe predicted spacecraft orbit conditions which, alongside telemetry, are invaluable in giving flight operations personnel insight into the actual meaning of the data provided by housekeeping data points. Flight Dynamics (FD) products currently ingested into ITPS including nodal, eclipse, sunlight, SAA, beta angle, and lunar terminator data. Thirty other FD products are planned for integration with ITPS within the next year.

3. ITPS Web Host

ITPS computers can optionally host a web server and ITPS web server software. These computers can provide access for remote users to the entire mission housekeeping data archive and the entire suite of ITPS tools and capabilities. These computers have restricted access in accordance with NASA and USGS security requirements.

4. ITPS Components

The ITPS system comprises a number of software components, which interact to ingest incoming telemetry, process data and generate products, as shown in Figure 2. The main ITPS software components include:

- User Interface
- Product Automation
- Data Ingest (Telemetry and Flight Dynamics Data)

- Project Database Ingestion and Validation
- Request Processing and Job Production
- Events Logger
- Web Access Component
- Data Analysis
- Plot Generation/Data Visualization

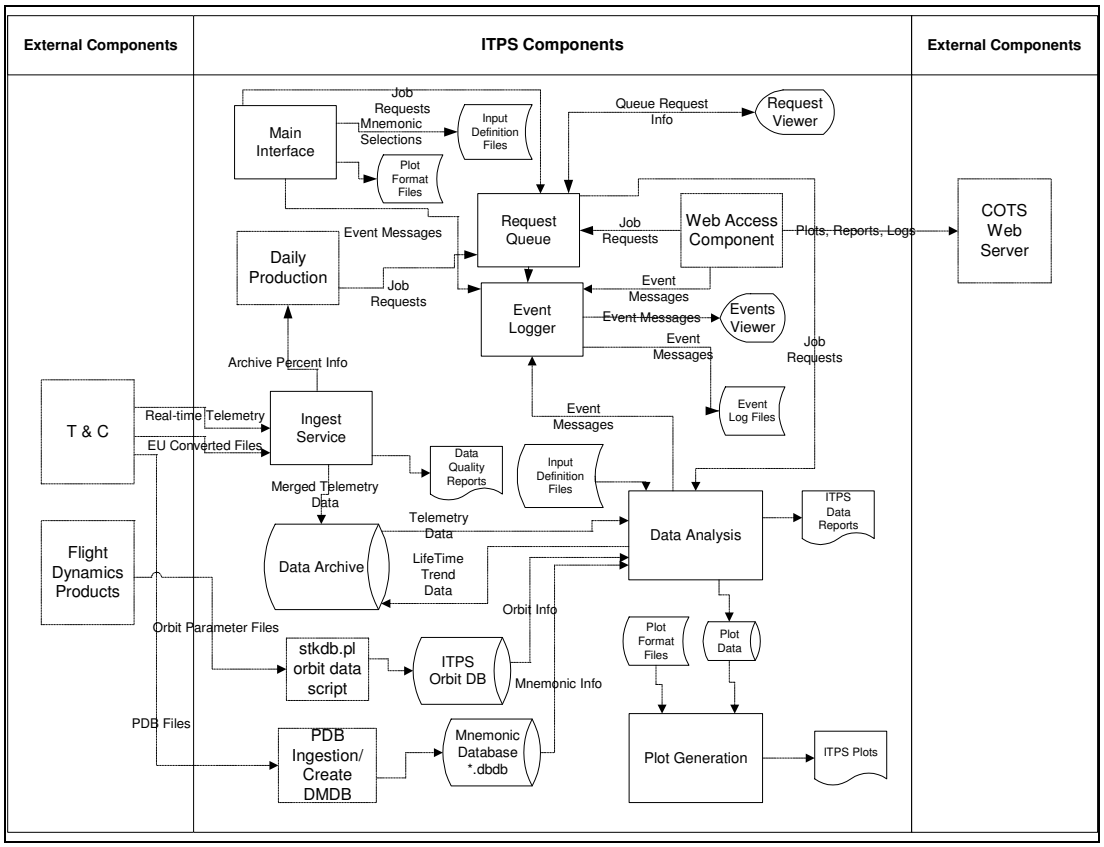


Figure 2. ITPS Internal Software Components

III. ITPS FDS Integration

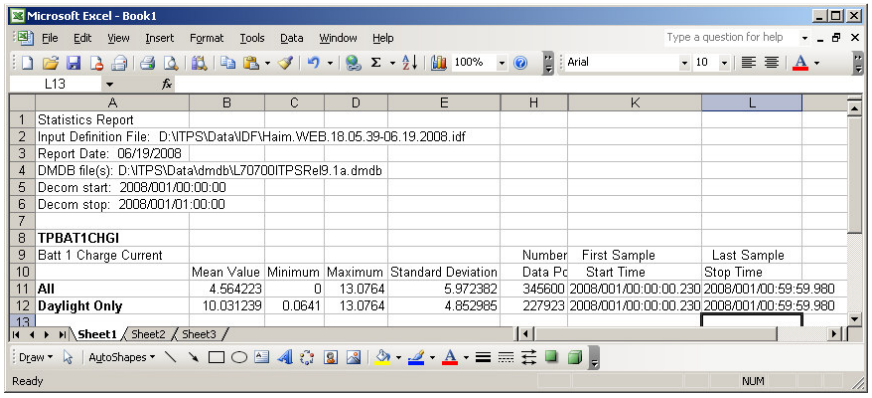
A. History

From the onset of ITPS, the Landsat 7 flight operations engineers insisted on having the key capability of integration with predicted spacecraft orbit data. This was to correct what was felt was a glaring omission of existing housekeeping telemetry analysis tools. The existing tools presented housekeeping telemetry in a vacuum – with no reference to spacecraft on-orbit events. This required the flight operations teams to manually research orbit conditions and correlate this data with spacecraft housekeeping data. Since this manual process was tedious, it was rarely being done, resulting in less-then-optimal data analysis.

B. Landsat 7 – The Pioneers in FDS ITPS Integration

As part of the responsibility of the flight operations team, members monitor function and status of all of the spacecraft components. Many of the systems being monitored are sensitive to sunlight (such as solar arrays) or heat (heaters, pressure sensitive components). To make sense of telemetry and to do effective analyses, it is critical to be able to easily correlate space environment conditions with housekeeping data. For example, the average temperature of a heat sensitive component would be skewed by the orbit shadow period. Similarly, examining battery current without the ability to distinguish between times when the batteries are charging or discharging and powering spacecraft components obscures important data from the observer. For example, Figure 3 illustrates a simple data

extraction for a battery current data point with statistics for daylight only versus all values, demonstrating the significant change in value when examining all points versus daylight only points. For a parameter regarding the battery charging current, this is a valuable distinction.



	A	B	C	D	E	H	K	L
1	Statistics Report							
2	Input Definition File: D:\ITPS\Data\IDF\Haim.WEB.18.05.39-06.19.2008.idf							
3	Report Date: 06/19/2008							
4	DMDB file(s): D:\ITPS\Data\dmdb\L70700ITPSRel9.1a.dmdb							
5	Decom start: 2008/001/00:00:00							
6	Decom stop: 2008/001/01:00:00							
7								
8	**TPBAT1CHGI**							
9	Batt 1 Charge Current					Number	First Sample	Last Sample
10		Mean Value	Minimum	Maximum	Standard Deviation	Data Pc	Start Time	Stop Time
11	**All**	4.564223	0	13.0764	5.972382	345600	2008/001/00:00:00.230	2008/001/00:59:59.980
12	**Daylight Only**	10.031239	0.0641	13.0764	4.852985	227923	2008/001/00:00:00.230	2008/001/00:59:59.980

Figure 3. Example of All/Daylight Statistics

Integrating flight dynamics information with telemetry required reaching out to the FDS orbit component in the Landsat 7 control center. The Landat-7 MOC FDS uses Analytical Graphics Incorporated's (AGI) Satellite Tool Kit (STK) software to perform routine daily orbit determination and prediction, as well as to generate definitive and predictive flight dynamics products, which are then ingested by other MOC ground system components, network scheduling, and science teams for mission planning, building daily loads and contacts, imaging, scheduling, maneuver planning, and network long term planning. Since these orbit predicted products are routinely generated and refined as the Landsat-7 orbit changes daily, these orbit predicts are an essential source of flight dynamics information for integration with the trending system (since there was no real-time or on-board source of flight dynamics information available from the spacecraft or ground system). By using flight dynamics filtering with housekeeping data, engineers and spacecraft operations personnel can easily customize their findings to extract the information they need from among the mass of spacecraft telemetry. Figure 4 displays all the values of the solar array current parameter. These values are significantly skewed by the shadow portion of the orbit where the current drops down to zero. By filtering the data based on the orbit sunlight and shadow function, Figure 5 reflects the values when in sunlight only.

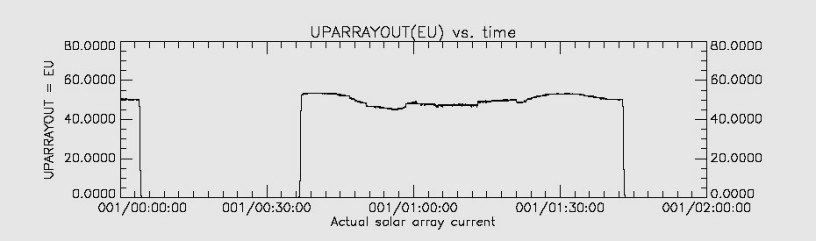


Figure 4. Sample Solar Array Current - All Values

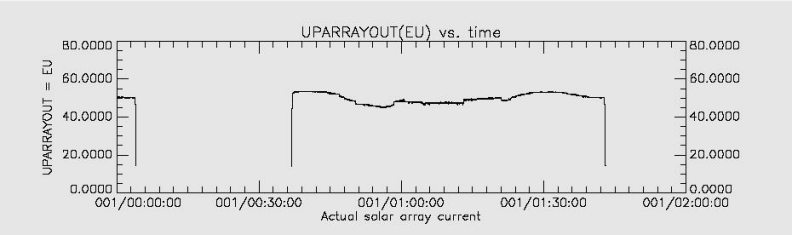


Figure 5. Sample Solar Array Current - Day Only

Another area where integration with flight dynamics was deemed valuable by Landsat 7 was the generation of products based on orbit boundaries. A standard product of most telemetry analysis systems is the generation of statistical data based on daily or hourly sampling. However, summarizing data based on daily and hourly boundaries is generally arbitrary (except for daily statistics for geostationary or geo-synchronous orbits for which a spacecraft's orbital period is essentially "daily") and does not reflect a spacecraft cycle. Orbits, on the other hand, are by definition a spacecraft cycle and a more appropriate choice for filtering and evaluating spacecraft telemetry. By integrating with ascending and descending nodal crossing data with ITPS, ITPS can create products "chunked" by orbit (one plot or report by orbit). It can also generate long-term trend data and extract statistics based on spacecraft orbit boundaries. These are much more meaningful than daily or hourly statistics and can be combined with light/shadow filtering to make the statistics on spacecraft telemetry very precise.

The integration of orbit data with telemetry in ITPS has also been valuable in providing the "back-story" for changes in telemetry by enabling analysis tools, which help troubleshoot and resolve spacecraft issues. For example, the Landsat-7 engineers noticed subtle unexpected jitter in some of the attitude control subsystem parameters from time to time. Upon examination of the eclipse and sunlight orbit integration data, the FOT was easily able to determine that the jitter was correlated with temperature changes related to the spacecraft going from light to shadow and back. Integration of orbit nodal, eclipse and sunlight data with housekeeping telemetry in ITPS has proved extremely useful for analysis related to batteries or power (voltage, max discharge current). Since batteries and power are affected primarily by light and shadow, it is critical to know the state of the spacecraft when investigating anomalies and irregularities in those components. This is especially true as spacecraft age and the power system components deteriorate. The integration of FD data with spacecraft telemetry in ITPS has proven very valuable when doing power and battery related analysis, which is critical to health and safety of the spacecraft.

The integration of ascending/descending node, eclipse, and sunlight data with telemetry in ITPS has been carried over into other ITPS supported missions such as the recently launched GLAST spacecraft and the soon to be launched SDO mission.

C. LRO Enhancements

As a Government Off-the-Shelf (GOTS) product, one of the highlights of the way ITPS is developed is that new features developed for one customer or mission are rolled into the feature set for all other missions. Thus the government investment in ITPS is leveraged over many different projects, and ITPS enhancements made for and funded by one mission can be realized by all ITPS supported missions. LRO inherited the basic orbit integration capabilities from Landsat 7, including ITPS integration with ascending node, descending node, eclipse, and sunlight orbit conditions. LRO then chose to extend the FDS ITPS features by adding new flight dynamics data sources and products to enable improved spacecraft power management and improved image planning.

The first of the LRO FDS ITPS extensions was the addition of lunar terminator correlating functionality. The lunar terminator refers to the point at which the LRO spacecraft is orbiting directly above a transition from light to shadow or back on the lunar surface. This capability is useful when correlated with readings on imaging sensors and parameters that are affected by sunlight on the imaged surface. Figure 6 is an example of LRO telemetry (albeit very boring static simulated data) (in blue) with lunar terminator crossings overlaid in black.

Another LRO flight dynamics ITPS initiated enhancement is the introduction of predicted spacecraft beta angles. The predicted beta angles (where the beta angle is defined as the degrees of offset between the LRO lunar orbit plane and the sun such that when the sun is in the orbit plane, the value is 0 degrees angle, and when the sun and LRO lunar orbit plane are perpendicular to each other, the beta angle is 90 degrees) are generated by the mission's flight dynamics subsystem and ingested into the trending system to be made available alongside regular spacecraft telemetry. These predicted beta angles can then be compared with beta angles computed by the spacecraft's telemetry to enable improved beta angle constraint checking, which is critical to the spacecraft thermal system and the overall health of the orbiter. In this way, the model for generating the spacecraft beta angle values can be enhanced and the prediction process can be improved. Beta angle reporting in ITPS will allow the LRO Mission Operations Team (MOT) to perform automated power analysis. The beta angle is often linked to how much power is available per orbit, therefore, spacecraft engineers can run a definitive power analysis, but more importantly, run a predicted power analysis to determine if spacecraft configuration change is required.

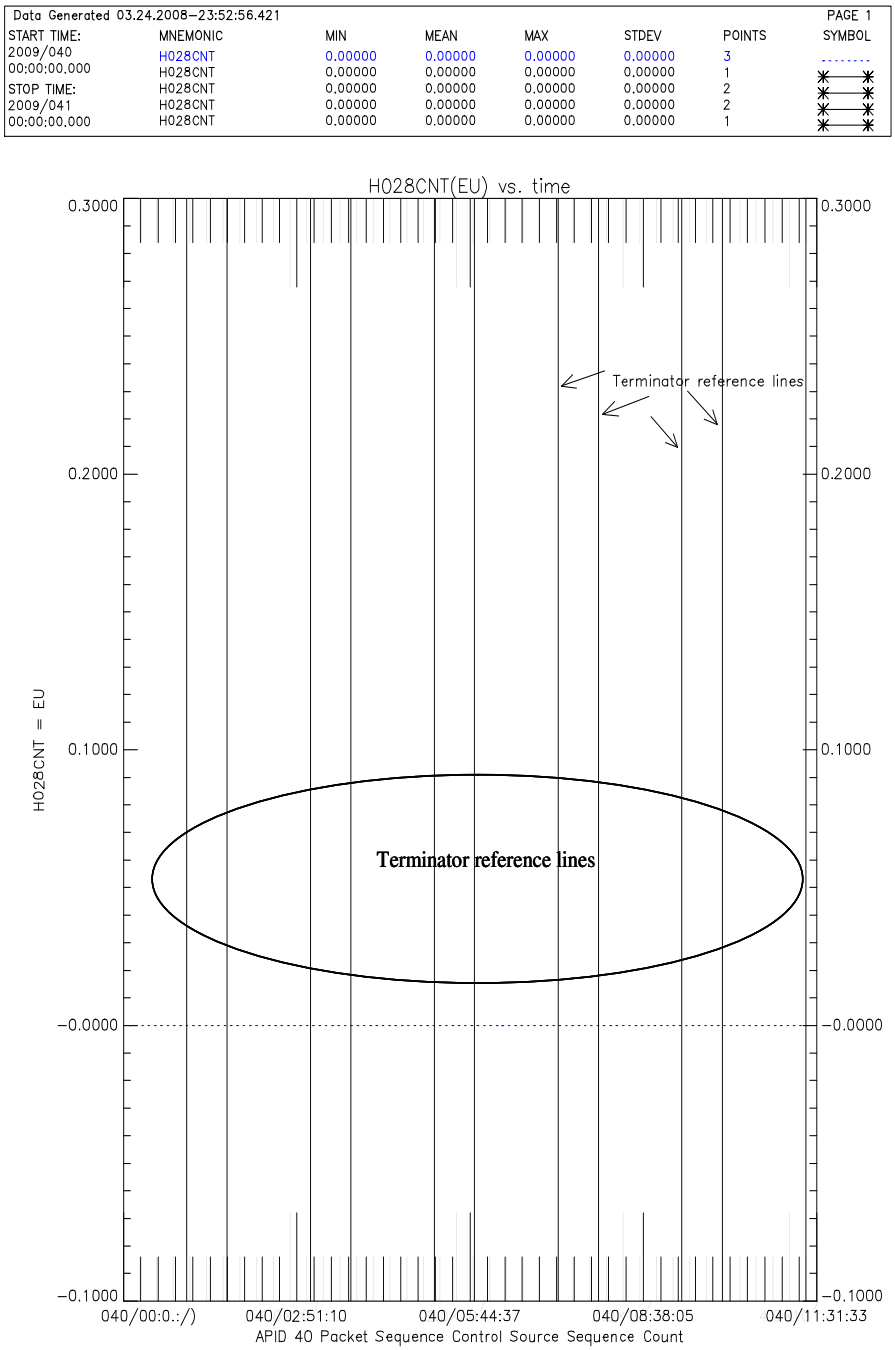


Figure 6. Sample Lunar Terminator Plot (static data – dotted blue) with Overlaid Terminator Crossings (solid vertical black lines)

D. TRMM Enhancements

The introduction of flight dynamics data alongside telemetry has proven so successful and useful that missions currently using ITPS are requesting more flight dynamics data be integrated with the trending system. The TRMM mission has recently required ITPS to process predicted SAA times, which the TRMM FOT can then use to filter telemetry data and link anomalous events to orbital events, thereby improving problem resolution. The SAA is a high radiation zone, which often can cause Single-Event Upsets (SEUs) or resets with on-board computers, instruments, and sensors. By filtering telemetry data based on SAA, the TRMM FOT can correlate problems such as SEUs or resets noted in spacecraft telemetry data with spacecraft's passage through the SAA. Once implemented, this feature will be available to other missions using ITPS, including other LEO missions impacted by the SAA. For LEO missions, correlating SEU or other resets to the SAA using ITPS enables the trending system to report the reset and SAA region times within the same plot or report improving anomaly resolution by making the process quicker, more efficient, and automated.

E. EOS Future Enhancements

The EOS Terra, Aqua, and Aura missions are investigating greatly expanding the flight dynamics capabilities of ITPS by introducing a large number of new products and data types that are to be processed alongside spacecraft telemetry and made available for analysis and trend determination. Table 1 enumerates the EOS flight dynamics products (over 25 in all) planned for integration with ITPS within the next year.

Table 1. EOS Flight Dynamics Products for Integration with ITPS

Day/Night Durations
Ground Station Line of Sight contact Times
HGA Gimbal Angles
HGA to TDRSS Line of Sight Viewing Times
HGA-TDRSS S-band Viewing Times
HGA-TDRSS TONS-based Viewing Times
Instrument Solar Azimuth /Elevation
Local Oscillator Frequency Report
Lunar Azimuth/Elevation angles
Lunar Beta Angles
Mass and Center of Mass Location Estimates
Nadir Omni to TDRS viewing times,
OMIS Data via X-band Dumps
Omni – Ground Station Viewing Times
Predicted EOS Brouwer-Lyddane Elements
Predicted Orbit Period
Predicted Orbit Number Times
Predicted S/C Attitude
Predicted S/C Ranging Data
Predicted Solar Array Angle
Simulated EOS Brouwer-Lyddane Elements
Solar Azimuth Elevation Angles
Solar Beta Angles
Sub Satellite Point Latitude and Longitude
TDRSS Contact Times via Zenith Omni
TES mirror Pitch/Roll Angles

By introducing this broad array of flight dynamics data into the trending system, flight dynamics becomes an integral part of the housekeeping data archive, enabling a significant expansion in the ability to correlate spacecraft telemetry with flight dynamics conditions.

IV. Conclusions

This paper details the history of ITPS development and integration of flight dynamics data with the ITPS in support of numerous missions, including Landsat-7, GLAST, SDO, LRO, TRMM and the EOS missions, Aqua, Aura, and Terra. ITPS was developed based on a collection of the best features of existing NASA and USGS housekeeping archive and trending systems, while at the same time advancing the USGS requirement for reducing cost, enabling access to the entire mission housekeeping database, and securing remote access. ITPS is a flexible and comprehensive trending and plotting system providing user access to entire mission full-resolution spacecraft telemetry archive in mission control centers and remotely via the internet. ITPS has been integrated with flight dynamics systems to enable filtering of spacecraft telemetry data based on orbit conditions and events, which has proven to be very helpful in power management, science and image planning, and anomaly resolution.

In 1999, Landsat-7 pioneered ITPS integration with flight dynamics products, including nodal crossing, eclipse, and sunlight information to enable improved telemetry filtering based on orbit conditions, resulting in improved power management and anomaly resolution. LRO has made FDS ITPS enhancements, adding in the lunar terminator and beta angle predictions to enable improved science data collection and improved power management. TRMM has added the SAA to be integrated with ITPS, which will help engineers plan for operations during SAA passage and correlate SEUs and resets to SAA. The EOS Aqua, Aura, and Terra missions are planning to significantly expand the FDS ITPS integration by adding over 25 new flight dynamics products and/or data formats. This expansion will enable a significant improvement in the spacecraft engineer's ability to correlate spacecraft telemetry with flight dynamics conditions.

With the significant expansion of FDS ITPS integration being planned to support EOS, and the broad collection of FDS products being collected and archived by ITPS for EOS, it is anticipated that EOS FDS ITPS expansion may cause the ITPS to become an essential FDS application for trending, archiving, and analysis of critical FD data and parameters. These expanded ITPS FDS features lead way for the ITPS tool to naturally become an important tool in the FDS suit for control centers with integrated FDS (Flight Dynamics Systems), which are always looking for innovative ways to consolidate resources and reduce costs, as well as modernize processes. The expanded ITPS FDS integration being developed in support of EOS, allows all ITPS customers the ability to incorporate these improvements into their ground system architecture, thereby, providing an excellent opportunity to centralize and modernize FD archival data in various control centers and facilities utilizing ITPS.

The integration of orbit data with ITPS data extraction and plotting features adds critical meaning and context to spacecraft telemetry, enabling improved power management, improved anomaly resolution, and improved science planning. This paper discusses specific flight dynamics ITPS features, why these features are important to missions, and how they impact mission science, mission planning, and flight operations.

Acknowledgments

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