

# Calling Home in 2003: JPL Roadmap to Standardized TT&C Customer Support

Susan C. Kurtik

Jeff B. Berner

Michael Levesque

JPL Telecommunications and Mission Operations Directorate  
Engineering and Operations Office for Telecommunications Services

Jet Propulsion Laboratory

California Institute of Technology

4800 Oak Grove Drive MS 303-404

Pasadena, CA 91109-8099

818 354-3598

FAX: 818 393-6228

[Susan.Kurtik@jpl.nasa.gov](mailto:Susan.Kurtik@jpl.nasa.gov)

## *Abstract*

*The Telecommunications and Mission Operations Directorate (TMOD) at the Jet Propulsion Laboratory (JPL) provides tracking, telemetry and command (TT&C) services for execution of a broad spectrum of deep space missions. These services include end-to-end hardware and software systems and customer interfaces that extend from NASA's Deep Space Network to the Advanced Multimission Operations System (AMMOS) at JPL to remote customers around the world. The TMOD TT&C Service System is undergoing extensive upgrades and advanced development that will result in standardized customer interfaces and more robust systems for data access and reciprocal support. This paper describes the roadmap to changes in JPL's Deep Space Mission TT&C hardware and software systems, customer interfaces, data products, data access, and customer service boundaries.*

## **1. INTRODUCTION**

The JPL Telecommunications and Mission Operations Directorate (TMOD) provides tracking, telemetry and command (TT&C) services for execution of a broad spectrum of deep space missions. These service systems are being redesigned as end-to-end services in the TMOD Deep Space Mission System (DSMS). The DSMS TT&C ground systems include data service elements from the Deep Space Network (DSN) and mission service elements from the Advanced Multimission Operations System (AMMOS). They provide tracking data (measurements of the spacecraft range and carrier Doppler), spacecraft telemetry data and uplink command services. The DSN telecommunications systems include low-noise receivers, digital signal and tone processing, symbol decoding, tracking and telemetry data processing, and command modulation and transmission systems. The AMMOS TT&C mission services at JPL include mission control; tracking, telemetry and command data processing and delivery; and mission data management.

The roadmap for TT&C service system upgrades through the year 2004 will bring new capabilities and customer services, greater efficiencies, increased robustness, and new technologies. This paper focuses on the evolution of these TT&C facilities, including the technical techniques, challenges, and impact to customer support through the year 2004.

## **2. CHALLENGES FOR DEEP SPACE MISSIONS**

Deep space missions are usually distinguished from near earth missions by much higher round trip light times with significant communication delays, longer duration missions, higher criticality of data, limited spacecraft contacts and link bandwidth, multiple receiving stations with multiple ground data streams, more unstable spacecraft clock drift, and tighter spacecraft margins. In addition, radio science and deep space navigation's orbit trajectory solutions levy stringent stability and accuracy requirements on the uplink and downlink tracking systems. All of these factors affect the flight and ground design tradeoffs.

The DSMS's DSN and AMMOS systems have been optimized to work for the special requirements and challenges of deep space missions. In general, commercial systems are optimized around earth satellites and do not come close to the level of accuracy that is required for deep space. On the downlink side, commercial telemetry systems are generally designed for handling a faster data rate which means that they are more hardware based and do not guarantee frame sync lock-up right away. This is generally acceptable for a near earth spacecraft because a small amount of lost data is not significant. However, in deep space, each bit is important and sometimes, extraordinary efforts are taken to recover even a few data frames. The telemetry and command systems are optimized to work independently since long light time delays and on-board autonomy do not require close interaction between them. This provides more flexible uplink and downlink systems, but also complicates "closing the loop" between telemetry and command for command verification, delivery protocols, and data accountability. Spacecraft time correlation is also generally not supported by commercial ground systems and extensive work must be done to adjust for light time delays and spacecraft clock drift. Accuracy requirements for ranging are up to three orders of magnitude more stringent for deep space missions versus near earth.

Besides these unique technical challenges for deep space missions, other problems are causing JPL to revisit the system architecture and interfaces for customer services. The DSN is facing more missions than it can accommodate with limited antenna stations while it is struggling with rapidly decreasing budgets for operations and maintenance support. JPL missions are also seeking out non-DSN tracking stations during early launch support when the DSN sites are not in view or when they are simply oversubscribed.

## **3. JPL TT&C SERVICE BACKGROUND**

There are three DSN complexes around the world, located in Goldstone, California; Madrid, Spain, and Canberra, Australia. These provide continuous coverage for deep space missions.

When combined with the centralized AMMOS mission services, they provide the TT&C services described below:

### *Tracking service*

The DSN tracking service provides data that is used to determine the location of the spacecraft (Navigation) and the media which the signal passed through (Radio Science). The necessary measurements are normally done with the spacecraft operating as a coherent transponder of the uplink signal. Thus, measurements of what was sent (uplinked) are compared with what was received (downlinked); the difference between the two is a function of the spacecraft motion and the media that the signal passed through.

There are two types of measurements that are made. The first is a measurement of the carrier Doppler. This measurement is done by very accurately measuring and time-tagging the phase of the uplink carrier and the phase of the downlink carrier. These measurements can be expressed in many ways (as phase or carrier frequency, for example), but currently, the most common way is as a difference between scaled uplink and downlink measurements. This is referred as the Doppler count.

The second measurement is the range. A ranging signal (called the ranging code) is modulated onto the uplink carrier. The spacecraft demodulates the signal, filters it, and re-modulates it onto the downlink carrier. On the ground, the signal is demodulated and correlated against the transmitted signal. The alignment that gives the highest correlation provides a measurement of the round-trip light time (RTL) between the ground transmission time and the ground receive time, modulo the length of the ranging code. For deep space missions, this measurement is reported in units of Range Units; a Range Unit is derived from the period of the uplink carrier. This is done because of the long RTLs experienced by deep space missions (quite often measured in terms of hours). Depending on the user's needs, either the raw measurements or a processed version (called the observable) is delivered to the user. This delivery has normally been provided as a file in non-real time.

### *Telemetry service*

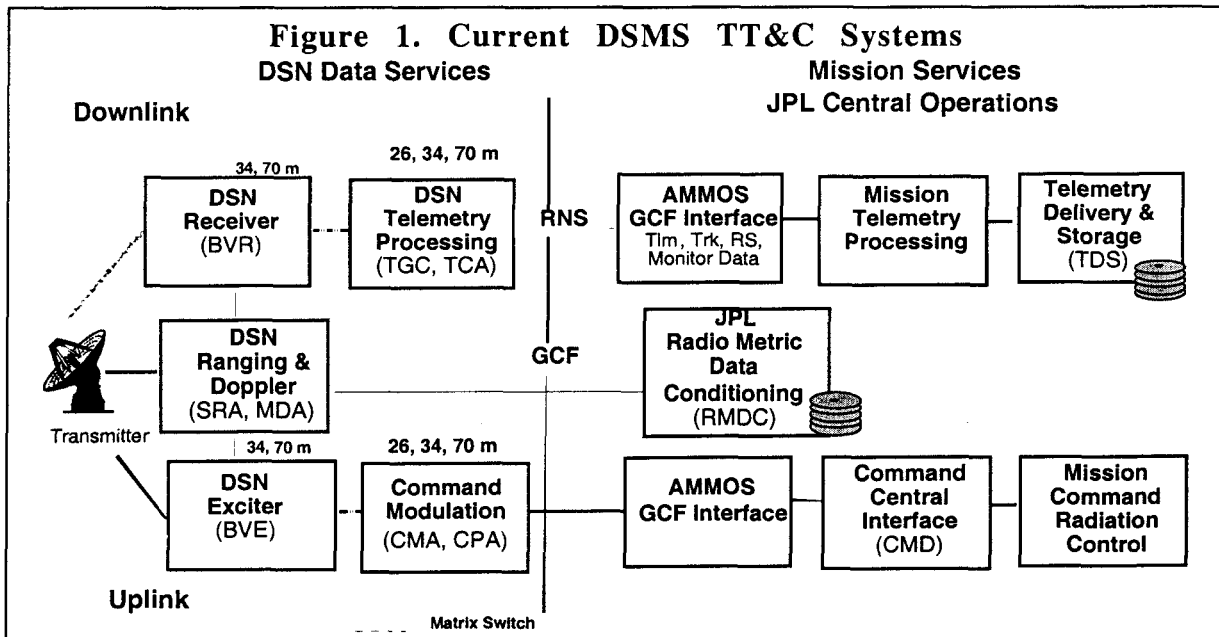
The DSN telemetry Services are for the acquisition, processing, storage, simulation and delivery of telemetry products to the mission control center. Due to the weak signal strength of the received signal by the time it reaches Earth, the data is encoded to reduce the effect of noise errors and the code parity bits added to the overhead of the transmission.

Once the signal is received from the antenna, the data is demodulated from the carrier (and subcarrier, if used). The data is then decoded, frame synchronized and routed by virtual channels to users. For high-rate data, certain virtual channels may be recorded for playback at a slower rate due to Wide Area Network (WAN) bandwidth constraints at the DSN. The AMMOS mission service users may receive the data at four levels of service: frame, packet, channel engineering data, and data set. The channel service includes converting DN to EU values, deriving computed parameters, and monitoring alarm conditions.

### *Command service*

The DSN command service receives command data from a mission control center that is then modulated onto a subcarrier and the modulated subcarrier is in turn modulated onto the uplink carrier. The spacecraft locks to the subcarrier and demodulates the commands off of the subcarrier. The command data is BCH encoded, so the spacecraft must also decode the data. Since commands may be sent in bursts, with time in between, the command system must send idle patterns to the spacecraft, to prevent the spacecraft from losing lock with the uplink command signal.

For deep space, the commands can be forwarded to the command modulation equipment at the antenna and the operators control when the data is sent at a specific first bit radiation time and modulation index. The AMMOS mission command services include software for a command database, electronic command request tracking system, and secure real-time command transmission, queuing, and radiation to the spacecraft.



#### 4. THE CURRENT TT&C ARCHITECTURE

The current architecture is discussed in the next two sections. The sections are divided between those equipment/processes that are done at the DSN complexes and those that are done back at AMMOS.

##### *DSN TT&C Equipment*

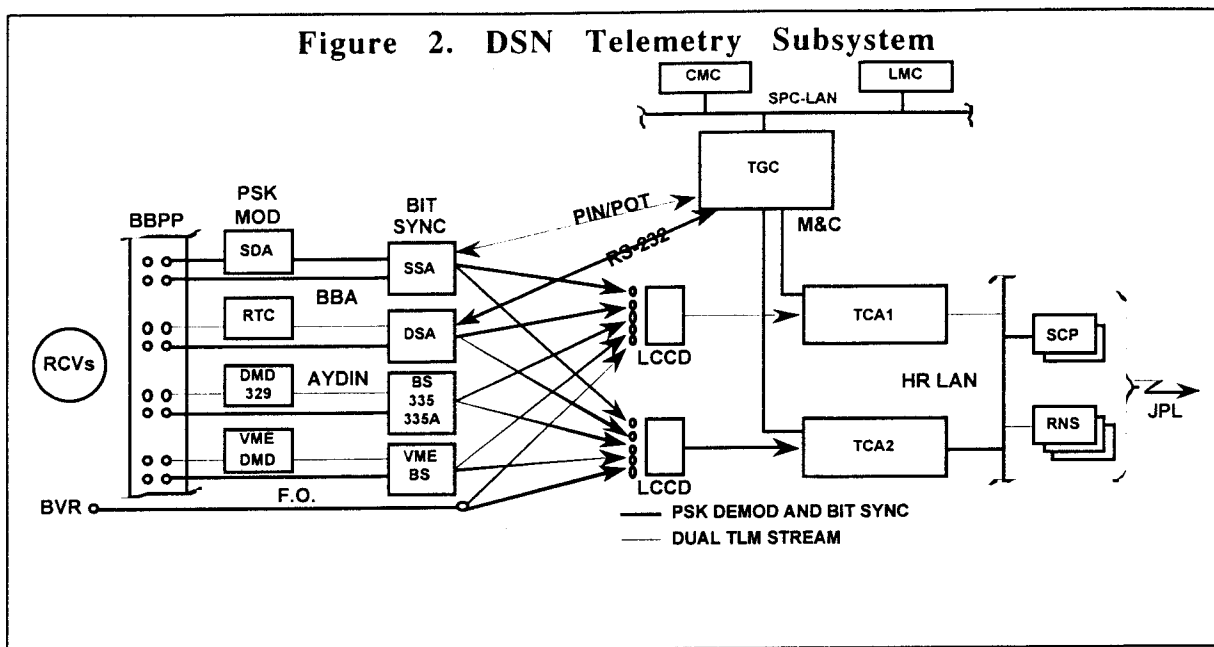
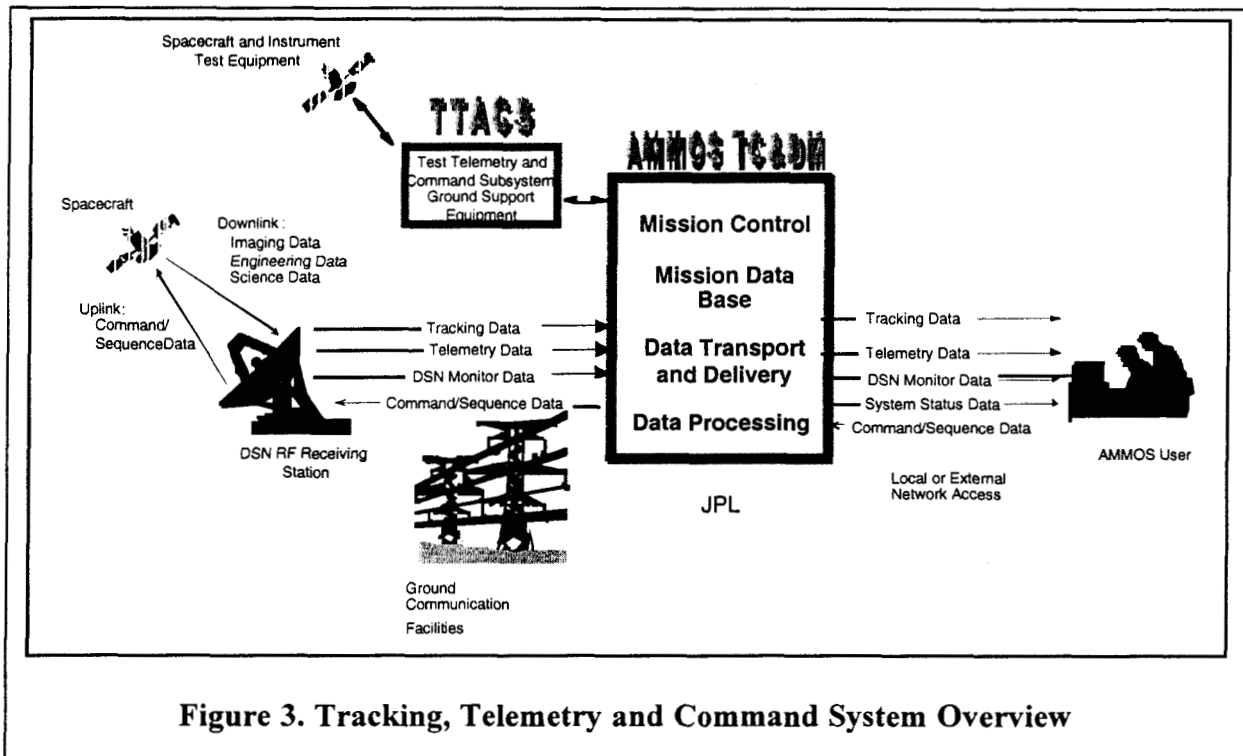


Figure 1 shows the current complement of equipment that resides at the DSN complexes for tracking spacecraft and Figure 2 shows the details of the DSN telemetry equipment. Currently, there is a combination of relatively new equipment and ten-to-twenty year old equipment, each with its own controller. Specifically, there is equipment to provide the uplink carrier (the Block V Exciter and the Transmitter, both controlled by the Exciter/Transmitter Controller), to produce command modulation (the Command Processor Assembly), to demodulate the received downlink signal (the Block V Receiver Channel Processor, controlled by the Receiver Control Computer), to decode the telemetry (the Telemetry Channel Assembly, controlled by the Telemetry Group Controller), and to generate the ranging and Doppler data (the Sequential Ranging Assembly, controlled by the Metric Data Assembly). Due to the hardware implementation, the receiver equipment is hardwired to the antenna signals; thus, each antenna has two sets of receivers, whether or not they are needed. Also, the ranging equipment interfaces hardwire the uplink equipment to the downlink equipment. This limits the capability of sharing resources between antennas. The telemetry equipment is switchable, using a patch panel, but only in groups of two channels; again, there is the problem of sharing resources.

### AMMOS TT&C ARCHITECTURE

Figure 3 shows an overview of the AMMOS TC&DM mission services element. It provides the ground system connectivity between the DSN and mission end-users, with about 500 workstations and 2,000 engineers and scientists around the world. There are over two million lines of code that has supported multiple instrument and spacecraft projects at JPL including Galileo, Mars Global Surveyor, Mars Pathfinder, Mars98, Mars01, Genesis, Stardust, Ulysses, Voyager, Cassini, SIRTf, SeaWinds and QuickScat instruments. New

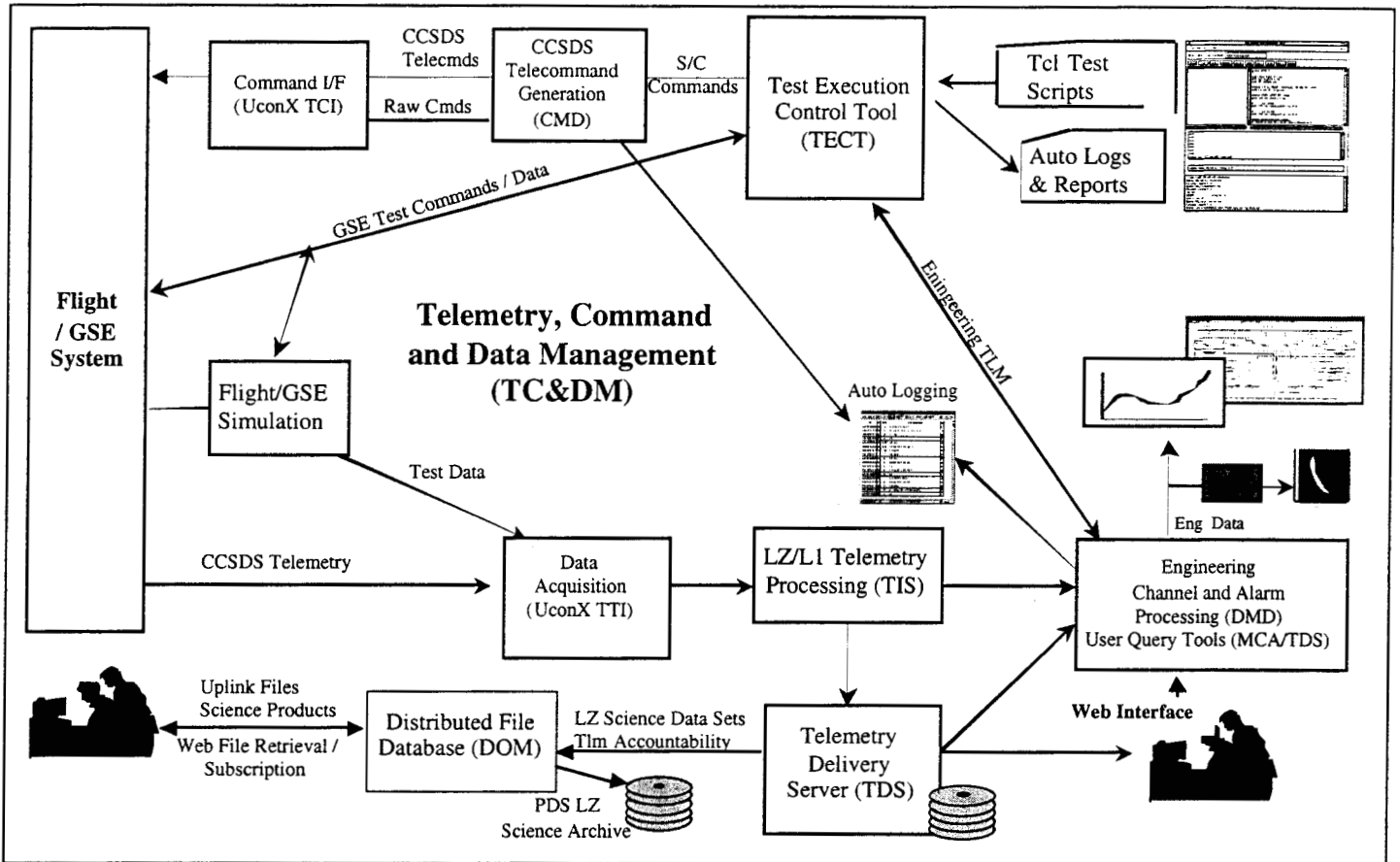
Millennium DS1, and Lunar Prospector at NASA Ames. The AMMOS was designed as a generic data system to be easily adapted for multiple missions in various test and flight environments. It is based on a distributed client/server architecture, with powerful Unix workstations, incorporating standards and open system architectures. The distributed architecture allows remote science and mission operations, while also providing capabilities for centralized system control with reliable fault-tolerant configurations. The AMMOS has been scaled to handle a spectrum of missions from large planetary flight projects with high data volumes to providing ground support equipment (GSE) for small instruments in assembly and test.



**Figure 3. Tracking, Telemetry and Command System Overview**

The same source code supports telemetry processing and commanding for spacecraft and instruments, not only in flight operations, but also in early design phases, in testbed and simulation labs, and in assembly, test, and launch environments. New GSE interfaces and test scripting tools have been added to the AMMOS tools to support these test environments, commonly referred to as the Test Telemetry and Command System (TTACS).

Figure 4 provides an overview of the telemetry processing, distribution, storage, and analysis capabilities in the AMMOS TTACS for Spacecraft Test. The telemetry processing data flow begins with the interface to the support equipment and data acquisition in which the telemetry, monitor, and tracking data is wrapped and time tagged as standard formatted data units (SFDUs). Data moves through a virtual circuit connection to the Telemetry Input Subsystem (TIS) for mission processing, including telemetry frame sync, packet extraction, decommutation, and generation of quality, quantity and continuity records.



The data is then loaded using mission ‘besting’ algorithms into the Telemetry Delivery Subsystem (TDS) for short-term and life-of-mission cataloging and storage of data. The TDS includes tools for queries of stored data, near real-time data broadcast, data routing, status reporting, catalog viewing, and TCP/IP interfaces for connecting to external applications. The user query tools include both a GUI interface for interactive use and a command line interface for off-line batch mode queries. As a ‘data management’ system, TDS is better described as a ‘record’ management system and was designed to make up for the limitations of the previous complex relational database approach. Telemetry data management is basically a linear process since the only index that really matters is time and there is no significant need for random access. To handle the very high transaction rates and expected volume and depth of data, we

needed a simple solution and file technology provided a better solution that was extensible and flexible to meet the needs of future missions.

Data can then be processed, displayed and analyzed in real-time or off-line using several toolkits including a Data Monitor and Display (DMD) tool, a generic data browser toolkit, generic SFDU libraries, and Multimission Spacecraft Analysis (MSAS) tools. The applications can all be run on the same workstation or distributed across multiple remote workstations using a common set of core system communication libraries. The communication libraries allow data to be distributed via virtual circuit connections, network broadcasts, or file transfer.

### FAULT-TOLERANT CONFIGURATIONS

An innovative fault-tolerant telemetry processing, delivery and storage system has become the backbone of a distributed telemetry data management architecture which supports users around the world. The TDS delivery function is based on a client-server design that allows reconfigurable, fault-tolerant data flow configurations.

Figure 5 shows a distributed system configuration for fault-tolerant telemetry delivery. The system configuration is based on a cascade of TDS instances that reliably migrate data all the way from the DSN to individual users all over the world. The TDS instances can be configured at each stage of the data flow path with a backup to provide failover redundancy that ensures continuous flow of data during real-time operations. The highly scaleable design and ease of use has provided a deep, on-line repository to projects where gigabytes of storage is required, as well as managing small to moderate sets of working data for small missions. The distributed TDS approach also allows project control of the distribution of science and engineering data, with local TDS storage and query capabilities at an end-user site.

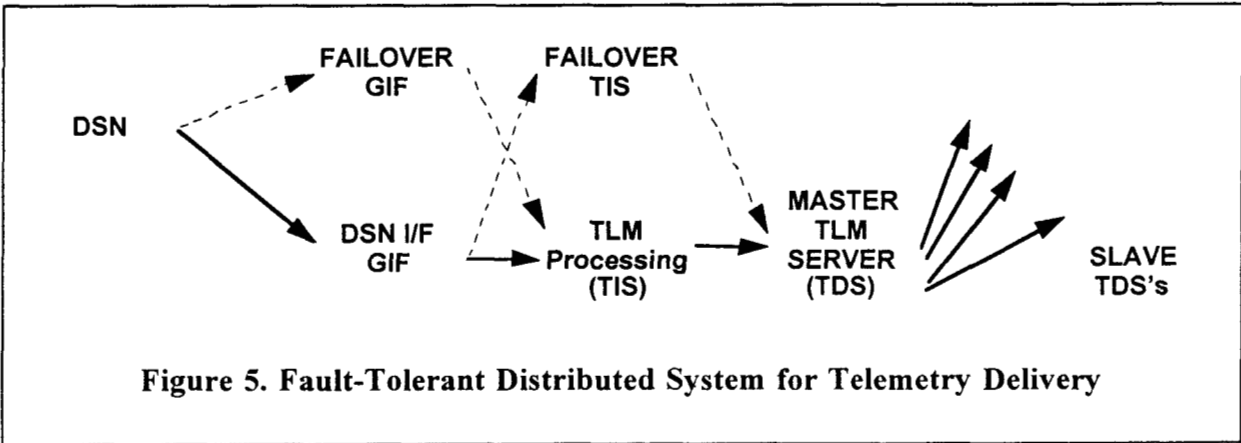
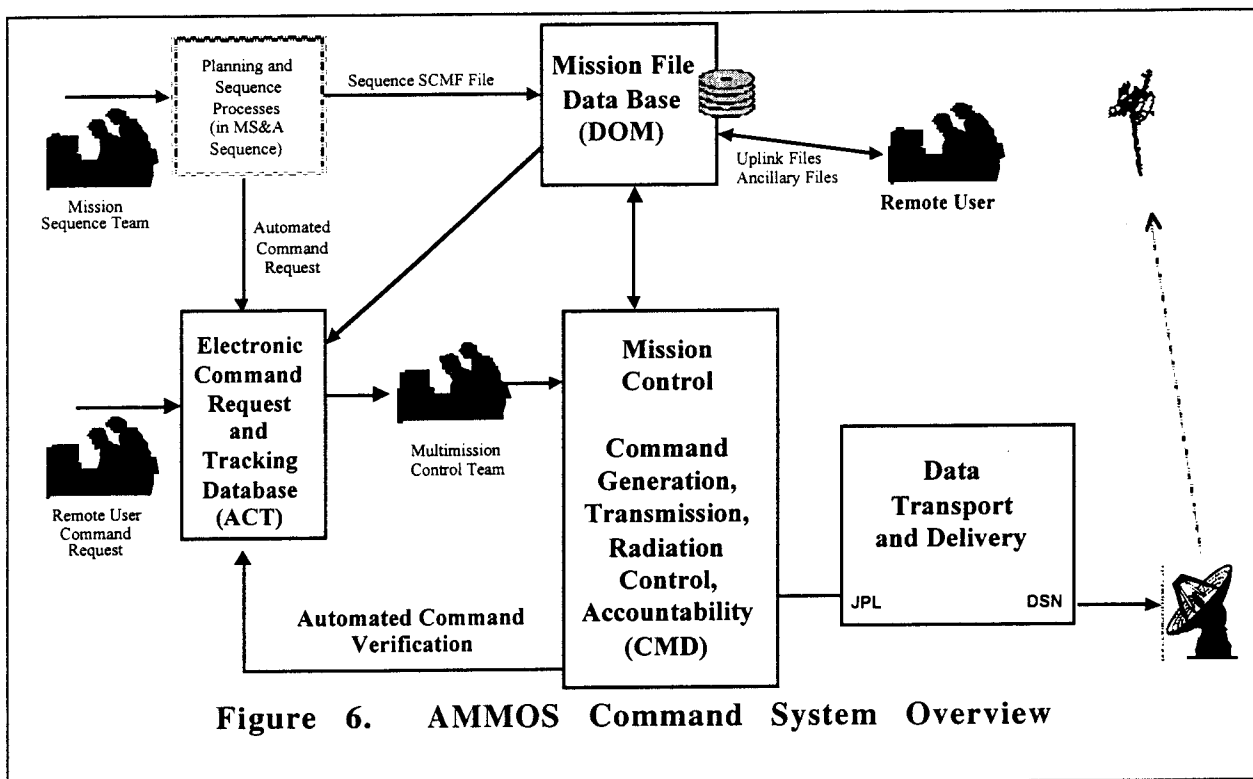


Figure 5. Fault-Tolerant Distributed System for Telemetry Delivery

### DEEP SPACE COMMANDING WITH AMMOS



Figure 6 shows an overview of the AMMOS command uplink process. The current AMMOS Command System is based on the old store-and-forward protocol of the DSN, but this protocol is to be decommitted and replaced with the new CCSDS Forward SLE service. A major redesign of the AMMOS Command system is underway to layer an automated file delivery service on top of the SLE service, which will include buffering at the station and file management control at JPL. The AMMOS Command functions include real-time command generation, command translation and radiation, status reporting, remote control of DSN antenna functions, and command file management. A distributed, network-based, graphical interface is provided to give real-time command radiation status to users at remote sites. The Command System provides security functions including authentication for different user privilege levels, internal security checks, and a command database for approved command files which are also linked to a command request tracking system with electronic-signature command request forms.



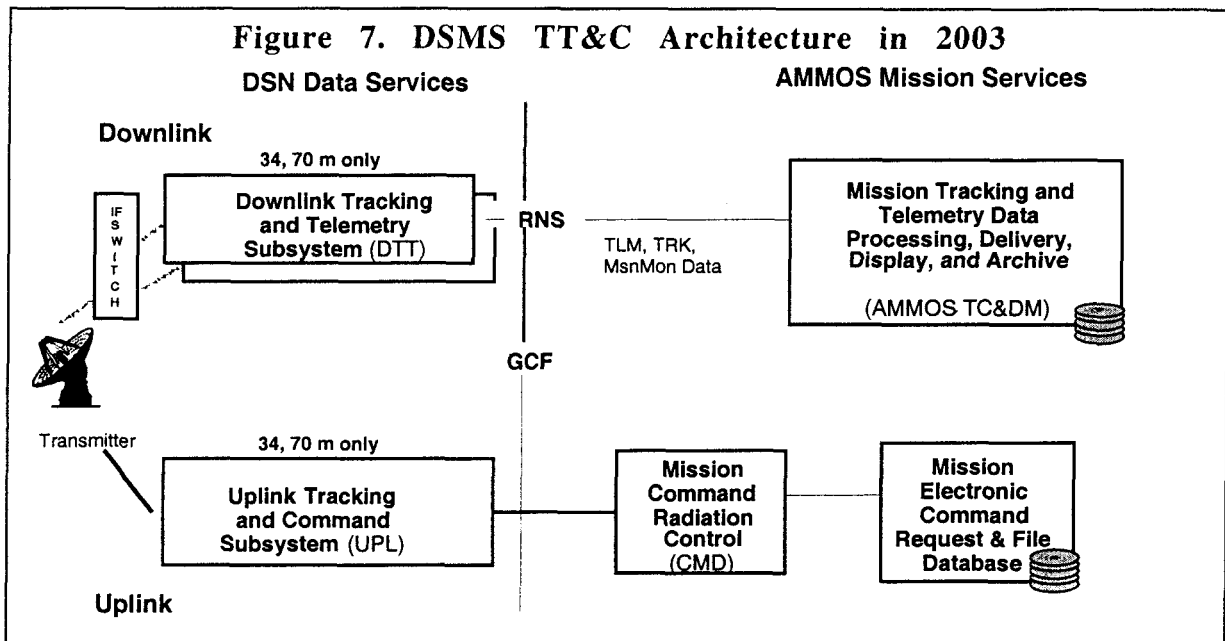
## 5. THE NEW TT&C ARCHITECTURE

The TT&C architecture is being modified by five major thrusts: Network Simplification, New Customer Interfaces, an End-to-End Tracking System Redesign, New Uplink Services, and an Evolution of the Mission Data System into an Integrated Flight-Ground System. Provided below is an overview of the road map to this new architecture and then a more detailed discussion of the five major thrusts. There are several projects underway for these changes:

- (1) the Deep Space Network Simplification Project (NSP);
- (2) new CCSDS file delivery protocols, SLE services, and monitor data interfaces;
- (3) redesign of the tracking data delivery system and its integration with real-time telemetry services;
- (4) new command request and file uplink services; and
- (5) evolution of the AMMOS mission data systems with new flight-ground architectures and web-based interfaces for data delivery and data management.

### Road Map Overview

There are four major TT&C tasks in the Network Simplification Project (NSP): the DSN Downlink Consolidation Task, the DSN Uplink Consolidation Task, the AMMOS Tracking Data Delivery System (TDDS) Task, and the Turbo Decoder Implementation Task.



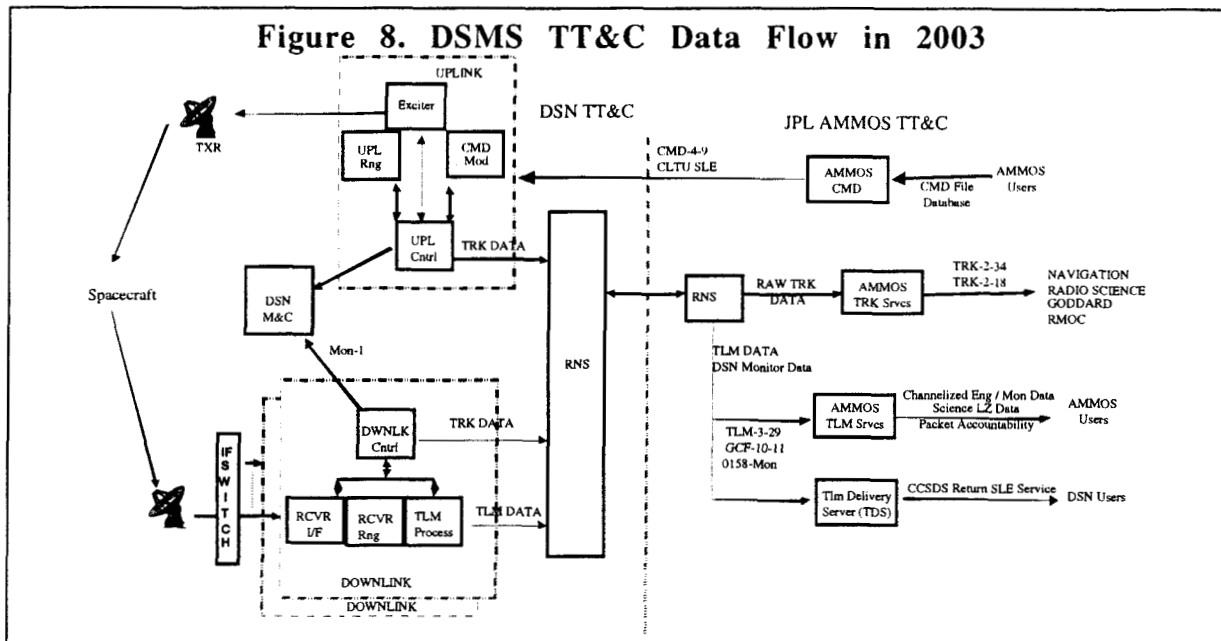
This will result in the replacement of the DSN downlink telemetry, ranging and doppler equipment, replacement of the command modulation equipment, consolidation of uplink subsystems and downlink subsystem controllers, and replacement of the JPL radiometric data conditioning system. The tracking data products have been redesigned and telemetry products have been standardized across missions. Other tasks are underway to add new CCSDS space link extension (SLE) and space link access (SLA) services at the DSN and at JPL mission control centers to enable cross-support with other space agencies' control centers and spacecraft. The JPL AMMOS mission data systems will provide automated end-to-end mission data accountability and web-based internet delivery systems. The data management and data transport systems on board and on the ground will be enhanced as part of the MDS

Project to provide a unified flight-ground architecture. The flight-ground data transport and management systems of the future will be based on persistent storage and retrieval of data products, management of state-based value history collections, policies on transport links, and reliable delivery protocols. Data accountability will be an end-to-end system with closed loop status and acknowledgment based on matching the goal on the ground with the system that initiated its creation. As all of this work progresses together, the boundary between the DSN, the AMMOS systems and the spacecraft will become increasingly interlinked with transparent interfaces and standardized protocols. This work will produce changes in the end-to-end "DSMS" TT&C systems and its customer interfaces, data products, data access, and customer service boundaries.

### *Network Simplification Project*

The Network Simplification Project (NSP) is tasked to reduce the cost of operations and maintenance with more reliable and operable TT&C systems. This will be accomplished by replacing aging, custom designed equipment with new, commercial equipment; integrating linked functions under one controller; removing unneeded hardware interfaces; and moving functions from the DSN complexes to AMMOS (or vice-versa), as the design requires. In addition, a new CCSDS-compliant turbo coding scheme is supported, allowing missions to increase their data return and to reduce their tracking time.

The scope of the consolidation by the NSP can be seen in Figure 7 and 8. When compared with Figure 1, the number of controllers and equipment is significantly reduced. For an uplink, the exciter, transmitter, command modulator, and ranging modulator are all controlled by a single uplink controller; for the downlink, the receiver, telemetry decoding, and ranging correlation are controlled by a single downlink controller. Both controllers provide high level, configuration/prediction file driven control; normal operations for the entire pass can be done with one or two operator directives. Ranging and Doppler processing is done back at AMMOS, in the new Tracking Data Delivery Subsystem; this allows the removal of the Sequential Ranging and the Metric Data Assemblies. With the separation of the ranging function between uplink and downlink, the downlink channels are no longer hardwired to a particular antenna. An IF (Intermediate Frequency) switch allows the connection of multiple channels to one antenna, allowing for supports of multiple spacecraft per antenna (such as a future Mars infrastructure), or spacecraft with multiple downlink signals (such as Cassini, which, when doing radio science, will have 1 X-band and 2 Ka-band downlinks).



In addition to the removal of the old controllers and the ranging/Doppler equipment, the Command Processor Assembly is replaced by a new Command Modulation Generator, and the Telemetry Channel Assembly is replaced by a new Telemetry Processor. Both are based on commercial equipment. The new Telemetry Processor allows for the easy addition of the new turbo decoder, which runs on TI Digital Signal Processors (DSP). Two commercial VME boards, each with 4 DSPs, will be installed in each Telemetry Processor to perform the symbol domain frame synchronization and turbo decoding, initially up to a rate of 250 kbps.

### *End-to-End Tracking System Redesign*

The revamping of the DSN equipment due to the NSP implementation allowed for the redesign of the tracking system (ranging and Doppler). The current Radio Metric Data Conditioning (RMDC) system consists of equipment out at the DSN complexes that act solely as data formatters, outputting the data back to JPL in a bit packed format, that suffers from lack of bits and is very difficult to modify. At JPL, the RMDC assembly processes the data (sometimes undoing the formatting that the DSN assemblies did), generating the necessary observables, and then outputs it in several different formats to users such as project navigation and radio science. The RMDC provides its own database server and archiving of the data, independent of any other standard archive. Insight into the data is limited; problems with the data are normally noticed by the end product users, not the service providers, and often, days after the fact.

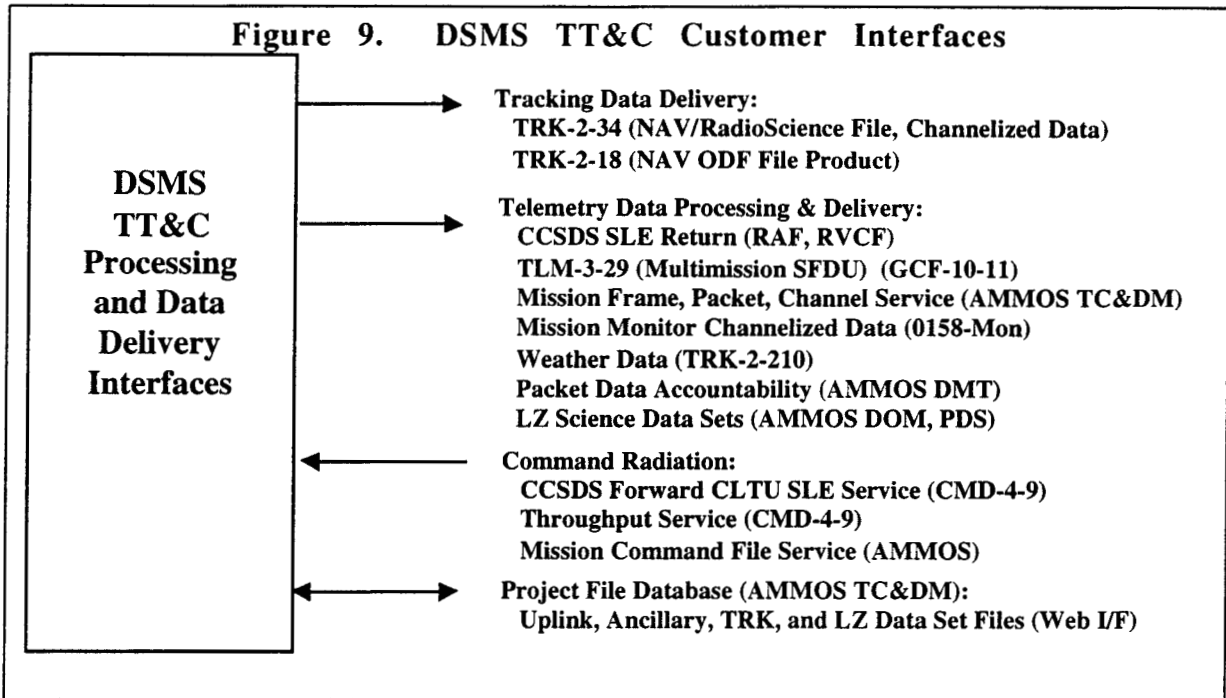
The new DSN ranging system delivers the new data in a less processed form to the AMMOS Tracking Data Delivery System (TDDS). This raw data contains all of the configuration and performance data of the link, in addition to the actual raw measurements.

The end-user tracking data products include both the raw data and the observable radio metric data that is needed for radio science investigations and for navigation processing of trajectory solutions. The new data product (TRK-2-34) is stored in SFDU format and archived in the AMMOS mission database, the same as the telemetry data. Thus, users have one source of file data and also have access to tracking stream data. The new SFDU interface allows the re-use of all of the user interface capabilities of AMMOS, such as the real-time broadcast, query, and display tools of the telemetry delivery system. The TDDS validation and conditioning processes will occur in real-time and allow broadcast of tracking channel parameters during the actual pass. The TDDS will provide both automated verification tools, to allow data verification before it reaches the customer, and also manual editing and visualization tools. Since the raw data is archived as part of the TRK-2-34, problems can be tracked down long after the pass, without the tedious process of trying to figure out what happened several days earlier.

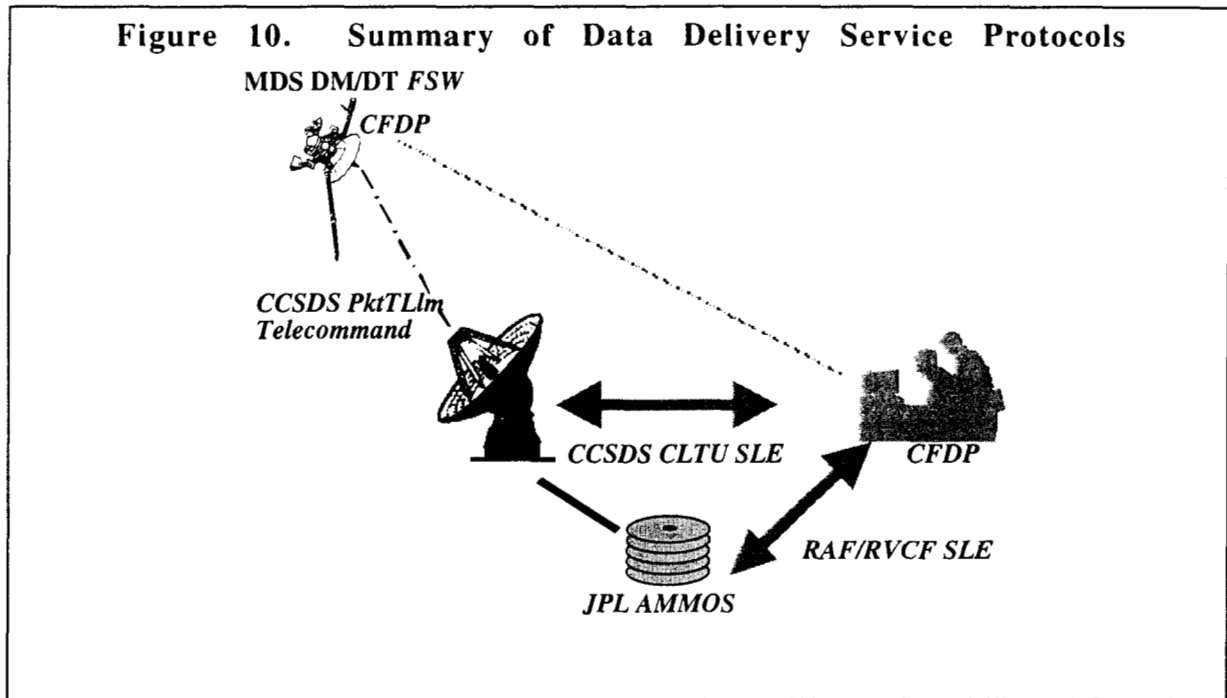
### *Final DSMS TT&C Customer Interfaces*

The DSMS TT&C customer interfaces are summarized in Figure 9. The tracking data products include the legacy TRK-2-18 orbit determination file and the new NSP-era TRK-2-34 data product. Figure 10 summarizes the telemetry and command delivery service interfaces for DSN customers, which include the new CCSDS Space Link Extension (SLE) services and the end-to-end file delivery protocol (CFDP). The new SLE service interface provides international interoperability with the use of standardized protocols for exchange of data between external customers and the DSN tracking stations. This increases tracking station options for mission support and allows an investigator to control their science mission from their site.

**Figure 9. DSMS TT&C Customer Interfaces**



**Figure 10. Summary of Data Delivery Service Protocols**



*Evolution of Mission Data Systems with Flight-Ground Architectures*

The data management and data transport systems on board and on the ground will be enhanced as part of the MDS Project to provide a unified flight-ground architecture and end-to-end information system. The MDS architecture is characterized by reusable object-oriented designs, state-based monitor and control, and goal-driven operations scenarios. The flight-ground data transport and management systems of the future will be based on persistent storage and retrieval of data products, management of state-based value history collections, policies on transport links, and reliable delivery protocols. Data accountability will be an end-to-end system with closed loop status and acknowledgment based on matching the goal on the ground with the system that initiated its creation. The spacecraft-to-user file transfer will be based on the CCSDS File Delivery Protocol (CFDP), which will be implemented in the AMMOS and layered on the CCSDS packet telemetry and telecommand standards.

**6. CONCLUSIONS**

The JPL TMOD Telecommunications Service System is undergoing extensive upgrades and advanced development that will result in end-to-end service interfaces, more robust systems for DSN signal processing and data delivery, and more flexible protocols for reciprocal support across international tracking networks. The roadmap includes changes to JPL's tracking, telemetry, and command mission services as a result of: (1) the Deep Space Network Simplification Project; (2) new CCSDS file delivery protocols, SLE services, and monitor data interfaces; (3) redesign of the tracking data delivery system and its integration with telemetry services; (4) new command request and file uplink services; and (5) evolution of the AMMOS

mission data systems with new flight-ground architectures for data delivery and data management.

## **7. ACKNOWLEDGMENTS**

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Biography of Presenter:

Susan Kurtik is the program manager for Telecommunications Services in the Telecommunications and Mission Operations Directorate (TMOD) at JPL. She holds advanced degrees in Physical Chemistry and Computer Science and a Ph.D. in Electrical and Computer Engineering from the University of California.