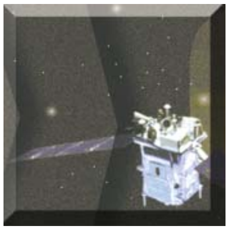

TIMED Ground System and Mission Operations

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The Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics (TIMED) mission operations concept was developed with the intent of minimizing life-cycle expenditures. The operations concept and mission operations system were designed to reduce personnel costs and take advantage of automation and existing standards. The mission's end-to-end data system design was based on the concept of decoupled operations between the spacecraft bus and the science instruments. The TIMED operations system includes the Mission Operations Center, Mission Data Center, and Satellite Communications Facility at APL; four Payload Operations Centers located at facilities across the country; and the distributed Science Data System.

INTRODUCTION

APL designed and built the TIMED spacecraft for NASA. TIMED is the first mission in the agency's Solar Terrestrial Probes program. It is a science mission that will enhance our understanding of the largely unexplored mesosphere, lower thermosphere/ionosphere region of the Earth's atmosphere. Mission operations and instrument data distribution are the responsibility of the Laboratory. These functions are performed at the TIMED Mission Operations Center (MOC) on the APL campus.

Post-launch mission operations and data analysis expenditures for scientific satellite missions are normally dominated by staffing costs. To reduce these costs without degrading science goals, several unique strategies were implemented early in the TIMED mission development phase. Operations would run 7 days a week, but the MOC would only be staffed for a single shift during daytime hours. Time-consuming analytical functions such as orbit determination, orbit propagation, and attitude determination would be automated onboard the spacecraft. A common ground system would be used for subsystem-level testing,[1,2] integration and test, and mission operations. The ground system would provide a high level of automation. The spacecraft would be designed to implement onboard event-based and rule-based commanding.[3] And finally, instrument and spacecraft operations would be decoupled to reduce the overhead associated with resolving onboard resource or scheduling conflicts.[4] Further cost savings were enabled through the use of standard communications protocols and links as well as the Internet, which eliminated the need for dedicated leased lines between facilities.

SYSTEM ENABLERS FOR LOW-COST OPERATIONS

The TIMED spacecraft was designed with a high degree of autonomy[3] to enable inexpensive mission

Table 1. TIMED instruments and the location of their POCs.

Instrument	Institution	Location
GUVI (Global Ultra-Violet Imager)	APL	Laurel, MD
SABER (Sounding of the Atmosphere using Broadband Emission Radiometry)	NASA, Langley Research Center	Langley, VA
SEE (Solar Extreme ultraviolet Experiment)	National Center for Atmospheric Research, Laboratory for Atmospheric and Space Physics, University of Colorado	Boulder, CO
TIDI (TIMED Doppler Interferometer)	Space Physics Research Laboratory, University of Michigan	Ann Arbor, MI

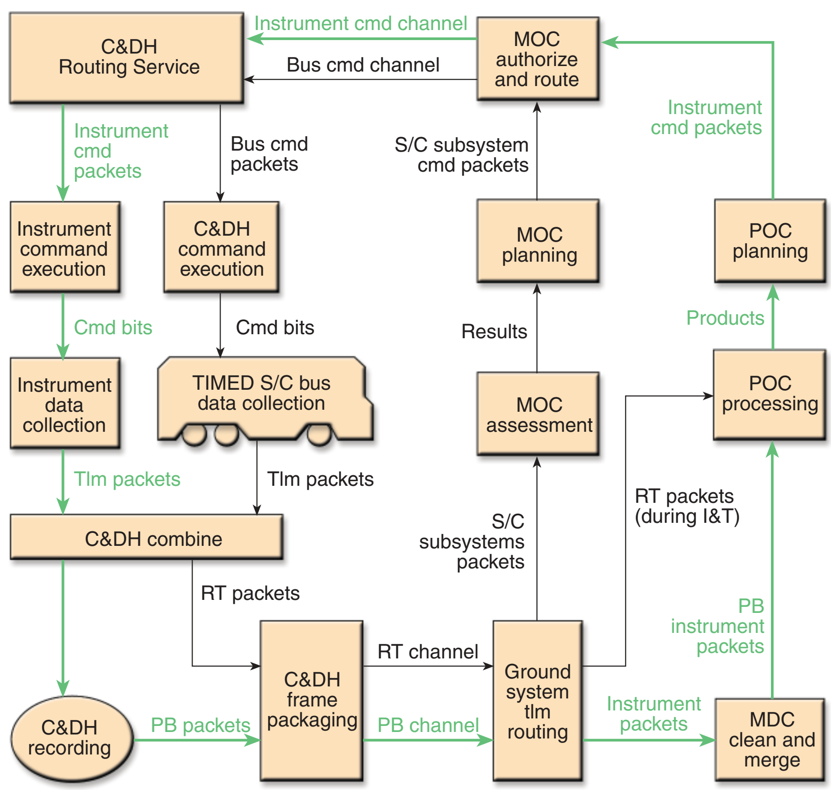

Figure 1. TIMED end-to-end data system. The outer path (green) shows the flow of instrument data, both commands and telemetry. The inner path shows the flow of spacecraft bus commands and telemetry. The left side represents spacecraft processes, while the right side represents ground processes. (C&DH = command and data handling, cmd = command, I&T = integration and test, MDC = Mission Data Center, MOC = Mission Operations Center, PB = playback, POC = Payload Operations Center, RT = real time, tlm = telemetry, S/C = spacecraft.)

operations using a small Mission Operations Team consisting of eight members. One key to making this possible is a decoupled instrument operations approach. TIMED is the first APL mission to be operated in this manner. The strategy is based on the concept that the spacecraft is the "bus" and the instruments are the "passengers." The spacecraft provides sufficient resources (power, thermal, data bandwidth) for the four instruments to operate unconstrained and independently. The instrument teams operate their instruments directly from Payload Operations Centers (POCs) located at the institutions where the instruments were developed (Table 1).

The decoupled operations approach is further illustrated in Fig. 1. Mission data flow in two paths. The outer path, indicated in green, represents the science data flow of commands and telemetry and shows the principal activities of the POCs. All of the processes in the spacecraft, as well as the mission operations ground system portion of this path, are automated. The inner path of bus activity is the mission operations data flow, which is generated and processed independent of the science data flow. Thus the Mission Operations Team operates the spacecraft bus while the instrument teams operate their instruments. No personnel effort is expended to merge the two sets of activities, thereby saving a great deal of operational costs.

Another mission design feature that reduces mission cost is the inclusion of event-based commanding onboard the spacecraft. Typically, space mission activities must be executed at specified absolute times based on long strings of uploaded commands. That is, every event is time-tagged; when the time is reached, the command is executed. The TIMED mission has replaced time-tagged commands with event-based commanding for repetitive events. With this approach, the instruments are preprogrammed to respond to event messages that are distributed onboard the spacecraft. This enables the instruments to change modes as desired, every orbit, without having to predict when events will occur and to repeatedly upload time-tagged commands. Significant operational savings are realized since event-based commanding greatly reduces the volume of commands necessary to operate the instruments on a day-to-day basis.

Event-based commanding is made possible because the onboard GPS Navigation System (GNS) developed by the Laboratory maintains continuous knowledge of spacecraft position, velocity, and time. Based on this knowledge, the GNS can automatically notify the instruments when the spacecraft enters or exits the South Atlantic Anomaly and polar regions and when it crosses the day/night terminator. In addition, the GNS knows where the primary and secondary ground stations are located and provides messages that allow the spacecraft to autonomously turn the RF transmitter on and off when it is over the operational ground stations. The GNS also uses its onboard position data to predict the spacecraft's orbit track. These data are downlinked each pass as short-arc two-line element sets and are used by the ground station on future passes to accurately point the antenna at the spacecraft. All of this onboard processing reduces the planning and scheduling activities required on the ground.

MISSION OPERATIONS OVERVIEW

Staffing

The unique features of the TIMED concept of operations allow a small (eight-person) team to efficiently conduct operations 7 days a week. Several members of the operations team have been trained to specialize in particular spacecraft subsystems and are known as spacecraft specialists. Others are trained to have more in-depth knowledge of ground system operations or focus on keeping operational processes and procedures up to date and accurate. All members of the team are expected to have the breadth of knowledge necessary to conduct daily planning, control, and assessment functions, as well as advanced planning and long-term trending of engineering data.

The six on-console team members share duties by rotating through the various operational positions. Two shifts of two people each are scheduled to perform daily planning, conduct contacts, and perform daily assessment of the spacecraft's state of health. One shift works 10 h/day from Sunday through Wednesday, while the other works 10 h/day from Wednesday through Saturday. The two people on the third shift work 8 h/day from Monday through Friday and are responsible for advanced planning and long-term assessment.

The entire team is on site each Wednesday when a status debrief is conducted to maintain continuity between the on-console teams. Team members rotate assignments every 3 weeks, which allows them to maintain their knowledge of the various functions of mission operations.

Spacecraft Planning and Scheduling

The TIMED mission operations planning cycle was originally designed for a 2-week period. Following requests from the instrument teams, however, the period was extended to 4 weeks to accommodate long-range instrument activity planning. Every week, an operations team member is assigned to perform advanced planning for the spacecraft using the Scheduler software developed by APL for TIMED. This involves propagating orbit data and generating lists of potential contacts and orbit milestones. These data are stored in the scheduling database from which contacts are scheduled and planned timelines are generated. One or two staffed contacts and one or two unattended contacts a day are scheduled for the APL ground station. Also, a weekly checkout contact with Universal Space Networks, the backup commercial ground station provider, is scheduled.

Daily planning duties are assigned each week to a different team member, who is responsible for making final preparations for contacts scheduled that day and the next. The contact schedule is verified daily with the remote ground stations, and the most recently downlinked short-arc two-line element sets are transferred to the APL ground station. These sets are used to accurately point the ground antenna at the satellite. Commands planned for the next day for spacecraft bus maintenance are also reviewed. These typically include solid-state recorder commands, memory dump commands, and any necessary onboard parameter updates. Finally, the scripts needed to run each pass are generated and checked. The scripts needed for contact operations were developed prior to launch and are used as templates. The unique data for each pass are fed into the desired script template by the planning software. This level of automation increases system reliability by reusing tested scripts and only inserting a small amount of data into each template to create the contact scripts.

Automated Unattended Passes

The original TIMED concept of operations proposed taking only one pass a day during the daytime. Since TIMED passes over the APL ground station up to four times a day, operations have evolved to include all passes. There are usually two staffed daytime passes and one or two unattended passes that are executed at night.

Running unattended passes was a mission goal, not a requirement. The many layers of automation in the MOC, Mission Data Center (MDC), and ground station enabled an easy transition to running unattended passes, which have been performed successfully since a month after launch. During unattended passes, instrument commanding is not done, but spacecraft solid-state recorder dumps are executed and automatically "ingested" into the mission data archive for distribution to the science teams. Unattended passes are further automated to provide details of pass status and completion through the use of a monitoring tool called Generic Spacecraft Analyst Assistant (GenSAA)/Genie.[5] This expert system environment, developed by the NASA Goddard Space Flight Center, has been incorporated into the TIMED MOC and is programmed to autonomously monitor every pass for problems. If the system detects a problem, it immediately sends meaningful text messages to pagers carried by designated team members. This feature of the system allows for timely reaction by the Mission Operations Team and helps minimize the potential loss of science data.

Instrument Commanding

Some commands are still necessary to successfully operate the instruments. To accommodate these commands within the decoupled operations approach, a process was implemented for real-time and store-and-forward instrument commanding. This is a key development that enables the remote POCs to operate their instruments independent of spacecraft bus operations. The instrument teams develop the necessary sequence of commands for their particular instrument. Prior to a real-time contact, the POCs send, via FTP, the command sequence to the TIMED MOC instrument command Dropbox Directory. The commands are then automatically transferred to the appropriate POC command queue for checking and are queued for transmission to the spacecraft. There is no real limit on how far in advance a series of commands can be sent. The store-and-forward capability for instrument commanding is provided through the POC command queues. In addition, instrument commands can be sent during a pass, in which case they go through the command queues and are immediately forwarded to the spacecraft, providing real-time instrument commanding capability.

Spacecraft Health Assessment

An important function of mission operations is monitoring the health and status of the spacecraft and instruments. During each staffed contact, one spacecraft operator monitors the alarm status display and spacecraft subsystem status displays. If an anomaly is detected, it is documented and the actions specified in the spacecraft contingency plan are executed.

Following each pass, post-pass and daily plots and reports are automatically generated by ground system software. The assessment engineer reviews the printouts for power system performance, attitude system performance, and general spacecraft health. Plots of voltage, current, and temperature are reviewed. Alarm reports and state transition reports highlight predefined error conditions, and the mission operations spacecraft specialists use this information to assess mission impact and determine appropriate courses of action.

MISSION OPERATIONS GROUND SYSTEM

Unlike previous spacecraft ground systems, the TIMED ground system design was not driven by the spacecraft design. Instead, the end-to-end system design for both spacecraft and ground was driven by the desire to reduce operational costs by easing spacecraft and instrument operations. This led to a highly autonomous system that uses distributed processes communicating over local and wide area networks. Figure 2 is a diagram of the major components of the TIMED ground system.

The TIMED MOC is located on the APL campus near the Satellite Communications Facility (SCF). The MOC houses the computer systems used to operate the spacecraft, process and store the mission data, and serve the science community. Figure 3 shows a view of the primary and backup command workstations along with overhead displays of the TIMED ground track and the operator's console.

Computer Systems

The MOC contains a variety of computer systems that are used daily to control the spacecraft and process data. The spacecraft operators use SUN Unix workstations to command and monitor TIMED during the 5- to 11-min daily passes and PC-based software to plan and schedule activities. A Silicon Graphics workstation running Satellite ToolKit (STK) provides a visual display of the TIMED spacecraft orbit and attitude. The STK display is also used to monitor the position in space of several other Earth-orbiting spacecraft that are in similar orbits and are controlled from ground stations in Alaska. These spacecraft are monitored because they have the potential to interfere with TIMED RF communications.

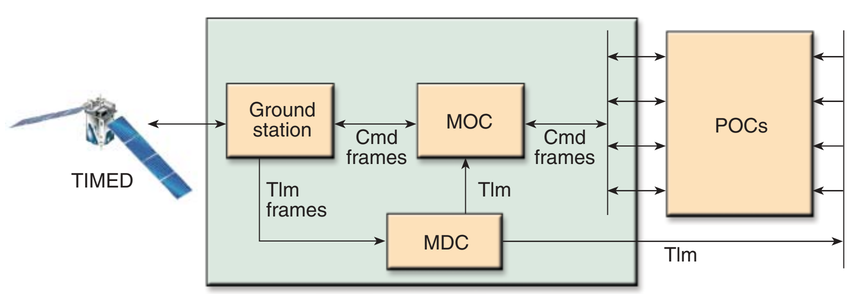

Figure 2. Simplified block diagram of the TIMED ground system (cmd = command, tlm = telemetry).

Figure 3. The TIMED MOC. The primary and backup command workstations are viewed by two of the TIMED Mission Operations Team members. The overhead displays are used to project spacecraft ground track, real-time attitude state, and spacecraft housekeeping data.

The MOC computer systems require little regular maintenance by systems administration staff. Disks are automatically backed up to a TIMED control center tape system. A Web-based utility is used to continuously monitor all of the critical computer systems. It has been configured to check for disks that are getting full, programs that should be continuously running, network utilities (e.g., FTP) that should work, and central processing unit overloading. If any of the designated checks fail, then, depending on the severity of the failure, the system autonomously sends either an e-mail or a text message directly to the system administrator's pager. This automated monitoring system is another aspect of the TIMED ground system that helps keep operational costs low and system performance levels high.

Software

Real-Time Spacecraft Control Software

The MOC command and control system is built around a commercial product called EPOCH 2000 from Integral Systems, Inc. The capabilities of EPOCH 2000 have been expanded for TIMED by integrating APL-developed software for additional functionality. Figure 4 shows a command and telemetry flow diagram depicting the following Laboratory-developed software processes.

BuildTlm: ground data telemetry frame builder
cmdif: spacecraft bus command formatting interface
Derived_RT: derived telemetry processing
mpcf: MOC/POC command filter
pocd: POC command queue daemon
procd: processor memory dump processing
tlmif: telemetry interface to the MDC

The core EPOCH 2000 system provides a graphical user interface (GUI) called the EPOCH Viewer that is used to control the system. It also provides a scripting language (Spacecraft Test and Operations Language, or STOL) for automating command sequences, flexible telemetry display features, limit checking of data, and an ASCII event log. The TIMED program added the *BuildTlm* program to extend the telemetry processing capability to include software and ground support equipment status data as telemetry. This allows the status data to be displayed, limit checked, archived, and played back just like spacecraft telemetry.

The APL-developed MDC provides real-time and playback telemetry via TCP/IP socket interfaces. Because it required a unique protocol to access these data, APL developed the *tlmif* program to interface the EPOCH 2000 core system with the MDC. The *Derived_RT* program provides the capability to generate new telemetry values from existing data points. It is used to create calculated values and treat them as telemetry data. For example, a telemetry value representing a component's power can be created by multiplying its current reading and the bus voltage.

To accommodate decoupled instrument operations, software was also developed to process the instrument commands and merge them with the spacecraft bus command stream. To ensure the security of the spacecraft

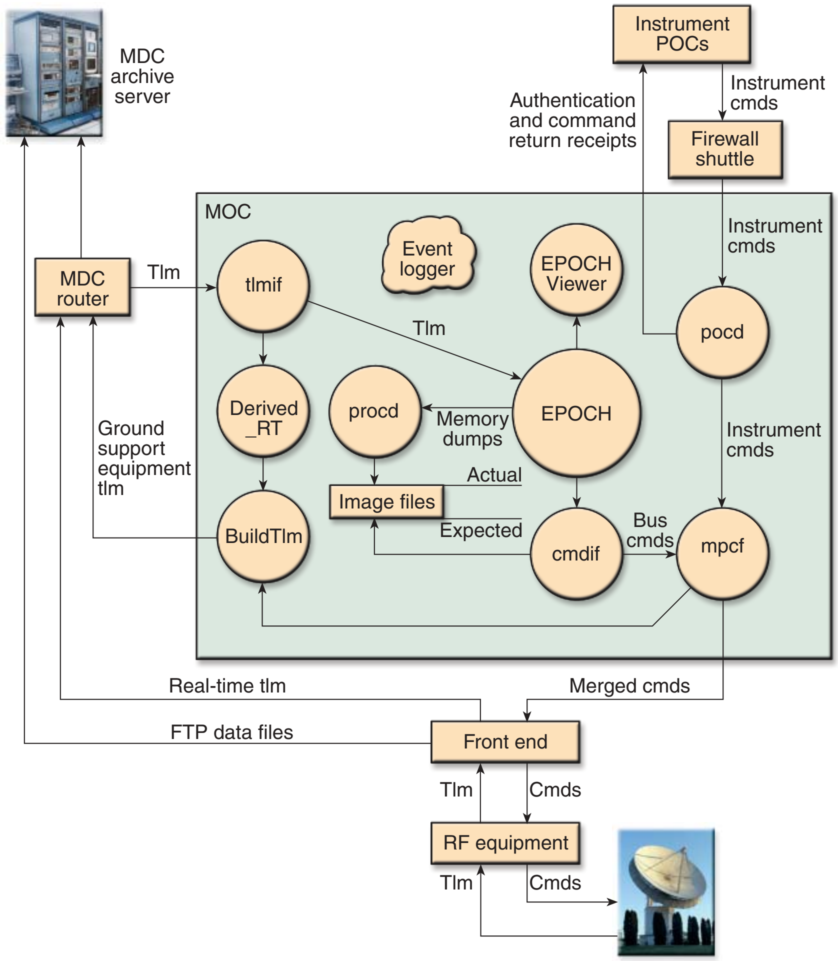

Figure 4. TIMED mission operations real-time software processes. The software is designed around the commercial EPOCH 2000 from Integral Systems, Inc. The other processes were developed at APL to enable decoupled instrument operations and to interface to the POCs and MDC.

and instruments as well as the integrity of the instrument command data, the Pretty Good Privacy (PGP) software package is used by both the POCs and the MOC, which communicate via the Internet. The instrument commands are sent to a firewall shuttle using FTP. The commands are then automatically moved across the TIMED firewall to the command workstation. The *pocd* software decrypts the incoming instrument command messages. It also manages the command queues that are used to control the flow of instrument commands. The MOC software does not inspect the contents of the POC commands, but it allows the operator to enable or disable individual instrument command queues or the entire instrument command stream.

Many different spacecraft bus command formats are required to operate the TIMED spacecraft. The *cmdif* software converts spacecraft bus commands from an ASCII mnemonic form into the binary bit pattern required to be transmitted to the spacecraft. It also stores expected image information that is used to confirm that data structure and software loads are successfully received by the spacecraft. The *cmdif* program works in conjunction with other programs to perform the load, dump, and compare processing. Telemetry data downlinked from the spacecraft that contain data structure or flight software dumps are directed to *procd* to be stored in actual image files. With the availability of both the expected image data and actual image data, an operator can confirm that the desired data have been properly stored on the spacecraft.

The *mpcf* software receives both the instrument commands and the spacecraft bus commands, merges them and forms telecommand transfer frames, and then transmits the frames to the TIMED spacecraft.

Planning and Scheduling Software

All contact planning for TIMED is performed on a Microsoft Windows–based PC using the Scheduler application described earlier. Scheduler uses an integrated Microsoft Access database. Data from the Scheduler database are used to automatically drive a computer-generated voice, called the MOC Announcer, that warns of upcoming passes. The data are also used to post a continuously updated list of upcoming passes on the TIMED Science Data System (SDS) Web site.

The Scheduler software interfaces directly with the antenna scheduling software in the SCF. Schedule requests are transmitted via TCP/IP sockets to the facility. The two-line element sets mentioned above are sent via FTP to the SCF and are later used to point the antenna during each pass. The Scheduler also interfaces with the MDC to retrieve spacecraft ephemeris data and deposit both planned and as-flown timelines.

Assessment Software

For the TIMED mission, a system has been developed and implemented that automatically generates reports and plots to enable efficient monitoring of spacecraft health. Following each pass, the Pass Manager, Plot Manager, and Plotter software run and extract all of the designated housekeeping data that were just dumped from the onboard solid-state recorder during the pass. These data are usually for the preceding 24-h time period. A set of plots (e.g., temperature, voltage, current) and reports (e.g., alarm, state change, data gap) is automatically generated that provides the Mission Operations Team with assessment information on the attitude, navigation, power, and thermal systems. These plots and reports are especially useful in conjunction with unattended nighttime operations, since they are waiting for mission operations personnel in the morning when their shift begins. In addition to post-contact reports, daily, weekly, monthly, quarterly, and yearly trending plots are automatically generated as well.

Spacecraft State Management

It is important to maintain knowledge on the ground of the configuration of the spacecraft. This is accomplished with several tools developed by APL for TIMED mission operations. The Memory Allocation Examiner (MAX) is derived from the *StateSim* application used on the NEAR (Near Earth Asteroid Rendezvous) program. MAX plays an important role by providing a daily chronological log of all spacecraft commands as well as a graphical display of onboard macro, autonomy rule, and time-tagged command memory usage. This utility maintains the state of the above data structures loaded in the C&DH system processors.

A separate utility is used to monitor the configuration of the two attitude subsystem processors. The parameter input GUI (PIG) is an APL-developed Web-based tool that stores and retrieves all current and past loadable parameter values for the Attitude Interface Unit and Attitude Flight Computer. The user can query the system and display current or past settings. PIG also displays separate values for data loaded to RAM and data written to flash or EEPROM memory for permanent storage.

MISSION DATA CENTER

The MDC was developed to support the TIMED mission concept of operations in which geographically dispersed POCs operate their instruments remotely and independent of spacecraft bus operations. To support this approach, a data system was developed that provides completely automated online data archival and delivery functionality.[6]

The MDC provides the POCs and MOC with several essential services including

- The capability for real-time monitoring of spacecraft and instrument telemetry during ground station passes
- On-demand playback of spacecraft and instrument data
- Short- and long-term data archival
- The production of supporting mission data products

The Router and the Archive Server are the two main software components that make up the MDC's Telemetry Server. These workhorses provide the data delivery and archival functionality. Figure 5 depicts the flow of data from a ground station, through the Router and Archive Server, to the final archive.

By connecting to the MDC's real-time Router via TCP/IP socket connections as output clients, the POCs and MOC monitor the spacecraft and instrument health in real time while the TIMED spacecraft passes over a ground station. The Router accepts data from multiple input clients (such as spacecraft telemetry via a ground

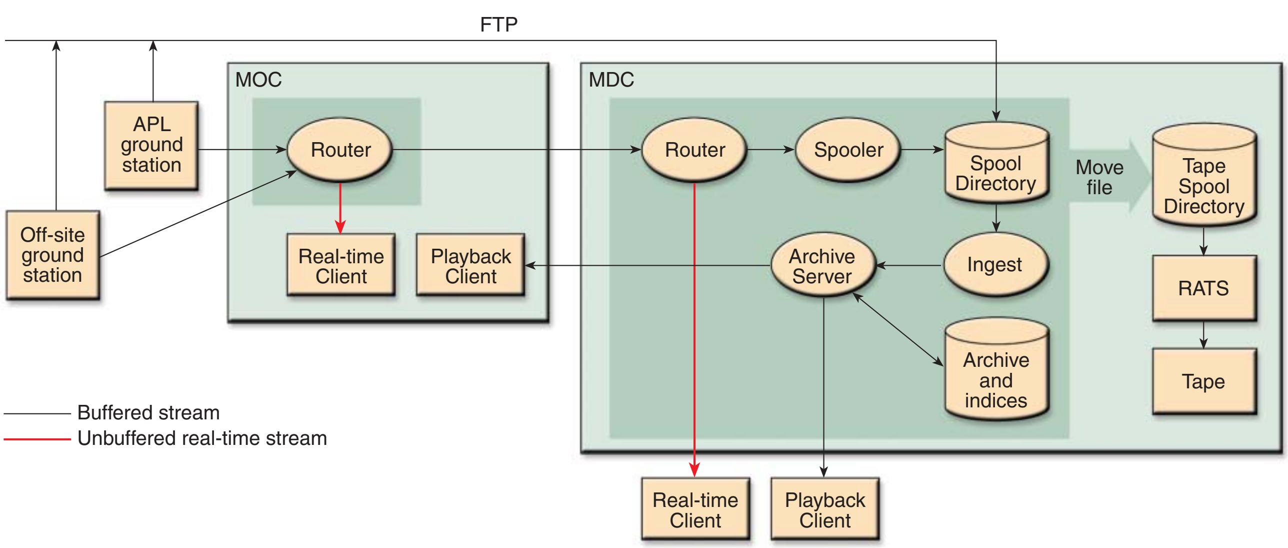

Figure 5. The TIMED Telemetry Server data flow. Spacecraft housekeeping telemetry data downlinked from the TIMED spacecraft to APL and remote ground stations flow in real time to a router process located in the MOC for display on the spacecraft operator's console. The data are also forwarded to another router process in the MDC that begins the archive process. Instrument science data are transferred directly from the ground stations to the MDC for ingest into the archive and distribution to the POCs (RATS = Raw Archive Tape Spooler).

station and ground system status data via various ground system applications) and routes the data it receives to one or more output clients (the MOC and POCs). These output clients may receive all the data passing through the Router or a filtered subset of the data as dictated by ASCII-based command directives provided to the Router upon connection by the client.

The real-time data that pass through one or more routers are ultimately directed downstream to an archival process known as the Archive Server, which is the MDC component that provides the "on-demand" playback of recorded data. Like the Router, this is a software application that resides on the Telemetry Server computer system. Unlike the Router, this process does not serve "live" real-time data, but rather data that have been previously archived on disk. Although the real-time data also end up in the archive and are available for later playback, the bulk of the data stored in the archive arrive not through the real-time Router (which is usually limited to approximately 10 min of data from a pass over a ground station), but through an FTP transfer process that follows a spacecraft pass. During such a pass, the spacecraft dumps a full day's worth of recorded telemetry through a high-speed downlink to the ground station, which in turn FTP's the data to the Archive Server. These "dump" data received at the MDC are typically ingested and made available to the users within 20 min of arrival at the MDC. Once in the archive, the data are then available for on-demand playback by the POCs and the MOC.

Once the real-time and dump data are stored in the MDC, they are considered archived for both short- and long-term purposes. Other than backing up the data to tape, no other post-processing or reformatting of the data is necessary. The archive is in its final form and is available to the users throughout the entire mission.

Supporting the Router and the Archive Server in their primary real-time, playback, and archival services are other auxiliary processes that, while working largely in the background, significantly contribute to the around-the-clock running and automation of the MDC. These include the Spooler, Ingest, and the Raw Archive Tape Spooler (RATS) processes as shown in Fig. 5. The Spooler process continuously collects all the incoming real-time telemetry data and stores them in intermediate hourly archive files. The Ingest process reads the Spooler's output files and transfers their data into the Archive Server through a socket connection. Ingest is also used to read the dump files received at the MDC via FTP and to transfer the dump data into the Archive Server. RATS is an automated process that runs nightly and backs up to tape all of the new raw data files in the exact form in which they were received at the MDC. Although not as visible to the users as the Router and Archive Server, Spooler, Ingest, and RATS are integral parts of the MDC that assist in the routine automated delivery of mission data services.

The MDC also performs routine creation of data files that support mission operations and data analysis. The MDC automatically produces two types of files for the MOC: archive map files and predicted position, velocity, attitude, and time (PVAT) files. The archive map files are used to determine what data exist in the archive and where data gaps exist. The MOC uses the data gap information to determine what data need to be recovered from the spacecraft during the following contact. The MOC uses the predicted PVAT files to propagate the orbit and predict future ground station contacts. Both of these files are generated automatically by MDC processes and are available to the MOC without human intervention.

The predicted PVAT files that the MDC makes available to the MOC are also made available to the POCs via the Internet. The POCs use these files to plan scientific experiments with their instruments. In addition to the predicted PVAT files, the MDC automatically creates actual PVAT files. These are used during data processing to determine the true position and orientation of the spacecraft, which are essential data for creating the higher-level science data products.

By providing a highly automated, efficient, and full-time online data service, the MDC fulfills a critical role in making the TIMED mission a low-cost operational and scientific success. The ability of users to obtain data from the MDC at any time, day or night, via the Internet/Intranet from wherever the POC and MOC equipment resides has contributed to the success of the decoupled spacecraft and instrument system and has been another factor in the resulting cost savings.

GROUND STATIONS

TIMED is a low-Earth–orbiting satellite that passes over ground stations in the Northern Hemisphere two to four times a day. Each pass over a ground station lasts for approximately 10 min.

Primary Ground Station

The SCF was chosen as the primary ground station for TIMED flight operations. It is located at a latitude that supports daily daytime contacts and provides a high level of automation that keeps operational costs low.[7]

The TIMED program uses a 60-ft antenna (Fig. 6), the largest of the three antennas at the APL facility. The 60-ft antenna was originally built in the early 1960s to support the development of the Navy Transit Navigation satellite system and was then used in the 1980s as the primary ground station for the GEOSAT mission. For the TIMED mission, upgrades to the feed system and station RF equipment were made to support the spacecraft S-band RF communications, and

Figure 6. The APL 60-ft antenna is remotely controlled from the SCF. It is the primary antenna used to control the TIMED spacecraft.

improvements to the antenna control computer systems were made to provide a fully automated antenna system.

Passes are scheduled remotely from the TIMED MOC scheduling computer and automatically run on the 60-ft antenna. Each pass is automatically executed, with the RF and baseband equipment remotely configured to support the TIMED data rates and data formats.

TIMED normally operates at a 4-mbps downlink data rate, but in a spacecraft emergency, it will autonomously transition to a much lower 10-kbps rate. The APL ground station incorporates dual chains of RF equipment, one configured to receive and lock on the higher data rate and one configured to receive and lock on the lower data rate. This design ensures that the station will automatically lock on the telemetry stream, even if the data rate has changed. This element of redundancy is another example of the automation designed into the end-to-end data system that minimizes staff levels and maximizes data throughput.

Backup Ground Stations

Universal Space Networks (USN) was selected to provide backup ground stations. Their services were heavily used during the launch and early operations phase of the mission. Once into normal operations, USN has provided emergency and supplemental ground station services as needed.

The USN ground stations in Alaska, Hawaii, and Australia are used by the TIMED program. The station in Alaska supports all spacecraft modes, including the 4-mbps telemetry downlink needed to dump the solid-state recorder. The stations in Hawaii and Australia support real-time commanding and the 10-kbps emergency telemetry rate. During the launch and early operations stage of the mission, USN provided the interface to a Swedish Space Corporation facility in Kiruna, Sweden, that supported all spacecraft modes similar to the USN Alaskan station.

Tracking and Data Relay Satellite System

The planned trajectory of TIMED following launch left large periods where the spacecraft was out of contact with controllers in the TIMED MOC. To supplement contacts with the APL and USN Earth-based ground stations, NASA's Tracking and Data Relay Satellite System (TDRSS) was enlisted. The use of TDRSS was an important element in the successful launch and commissioning of the TIMED spacecraft. The system yielded valuable real-time coverage during planned maneuvers in the 40-day launch and early operations phase of the mission. The capability to operate through the TDRSS will be maintained throughout the TIMED mission as it could be helpful with troubleshooting and recovery if a spacecraft anomaly occurs.

SCIENCE DATA SYSTEM

An important goal of the TIMED mission is to quickly create and disseminate processed atmospheric science data to the scientific community, K–12 educators, and the general public in addition to the TIMED program elements. The objective is to produce an initial version of routine science products, available to all TIMED users, within 54 h after telemetry acquisition on the ground. To accomplish this the TIMED ground system includes a distributed SDS. The SDS is composed of the TIMED MDC and those portions of the POCs involved with the processing and distribution of science data products (Fig. 7). As in the typical space mission science center, the SDS is responsible for the acquisition, generation, distribution, and archiving of science data necessary to support the TIMED mission. Unlike a traditional mission science center, however, these functions of the SDS are distributed over its component facilities. Supporting its goal of disseminating science products, the SDS uses a Web site as its common user interface and relies on standard protocols of FTP and Web document transfers across the Internet.

Planning Tools

To help the instrument teams prepare operations plans, a number of other services are provided through the SDS Web site. Among these are access

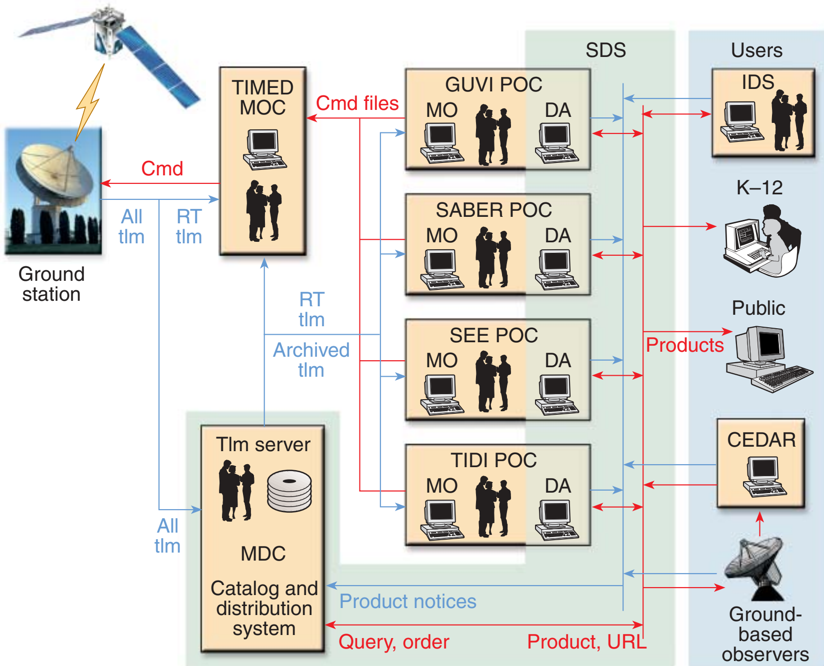

Figure 7. The TIMED SDS includes the data archive and distribution functions of the MDC as well as the science data processing portion of the POCs. It provides the data interface to other external collaborators and users. Blue lines represent MDC and POC data input; red lines represent their data output. (DA = data analysis, IDS = interdisciplinary scientists, MO = mission operations; CEDAR [the National Science Foundation's Coupling, Energetics, and Dynamics of Atmospheric Regions Program] is a collaborative study with TIMED.)

at APL; a 3-min coincidence is predicted to occur between the SABER field of view (cyan track) and that of the APL site (red oval). The accuracy of predicted coincidences as far as 2 months into the future is within a few minutes.

Contact Schedule

It is important for the instrument teams to have access to the MOC's most recent contact schedule in order to plan their activities. The SDS provides access to the MOC's continuously updated 4-week forecast of planned contacts with the TIMED spacecraft. These files, in both text and graphical formats, are rolled over to an Internet-accessible archive for historical reference as the passes are completed.

Timelines

Although candidate command loads give a precise plan of activity, a more generalized overview of to predictions of each instrument's field of view, planned ground station contacts with the spacecraft, planned activity timelines for the spacecraft and each instrument, and merged reports of planned activities for all mission elements.

Coincidence Planning Tool

An important aspect of the TIMED mission is collaboration with ground-based investigators. Radars, lidars, interferometers, spectrometers, and imagers at ground sites around the globe provide important measurements for comparison with those derived from the TIMED space-based instruments. In order for instrument teams and ground-based observers to plan coordinated measurements, it is necessary to predict when their respective fields of view will coincide. To meet this need, a coincidence planning and visualization tool was developed. Figure 8 presents an example visualization of SABER coincidence with a fictitious ground observatory

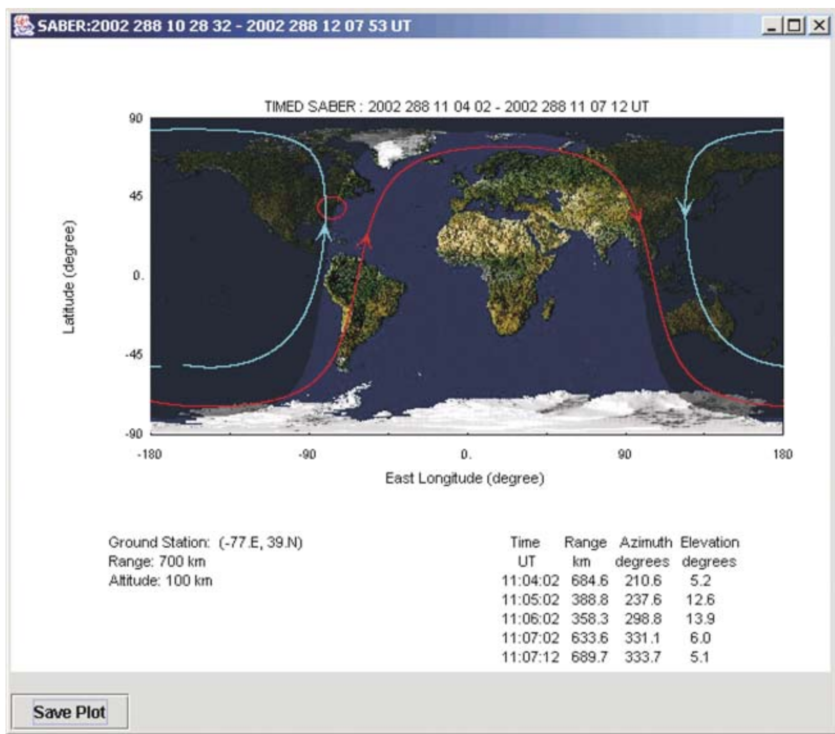

Figure 8. This Coincidence Planning Tool display shows the predicted TIMED spacecraft ground track (red line) between 10:28:32 and 12:07:53 UT on 15 October 2002 (day of year 288), the corresponding SABER instrument observation ground track (cyan line) at a 100-km altitude, and the at-altitude coincidence of this SABER observation track with a fictitious ground-based observatory at APL between 11:04:02 and 11:07:12 UT.

proposed activities is needed. To provide this capability, TIMED employs ASCII text files, referred to as timelines, that list instrument and spacecraft modes or events up to 8 weeks in advance. Modes are defined as stable and mutually exclusive configurations that are generally high level and change infrequently; examples are calibrate, test, standby, and operational. Events are shorter-duration occurrences such as yaw maneuvers and software uploads that potentially overlap in time. By combining a sequence of time-tagged event and mode entries, each instrument can provide a high-level timeline of its planned activities that is more manageable than detailed command loads.

When such planned timelines from each instrument, the MOC, and the TIMED spacecraft are merged, the result is a mission planning product called a long-range planning report. This report can help the POC teams and scientists to coordinate experiments among the TIMED instruments and ground-based observers. Moreover, when these timeline data are entered into the MDC catalog, they can be used as selection criteria for data product searches.

To document actual activities, teams issue as-flown timelines, which are definitive records of those activities. Like the planned timelines above, all contributed as-flown timelines are merged into a single as-flown report that represents a historical record of TIMED mission activities.

Data Access and Retrieval

From instrument-specific telemetry streams provided by the MDC, the POCs routinely create higher-level science data products that are to be made available to all TIMED users. Rather than transfer these products to a central site such as the MDC, they remain stored at the remote facilities, and notices containing descriptions of the individual data products, time ranges, and remote storage locations are sent to the MDC. The MDC maintains these product availability notifications and updates a catalog containing information on all available TIMED science data products. It is then possible, via the SDS Web site, to query the catalog to locate data products based on a variety of selection criteria. The result of such a query is a list of products that can be selected and then submitted as a data order deliverable through either an HTTP or FTP protocol service.

Ground-Based Investigator Data

Because ground-based observations are important to TIMED science investigations, the TIMED program has established formal collaborations with a group of ground-based investigators (GBIs). As part of this commitment, data products from these GBI sites are integrated into the TIMED SDS. In a manner similar to that for the POCs, GBI data products are archived remotely and the SDS is informed of the data product descriptions and locations.

SUMMARY

To meet the scientific goals of the TIMED mission, while minimizing life-cycle costs, an end-to-end data system was designed and implemented that uses a high degree of automation to support a mission concept based on decoupled spacecraft and instrument operations. Staffing requirements have been minimized by removing the need to integrate spacecraft and instrument activities and by automating much of the planning, scheduling, data processing, data distribution, and contact execution functions. System automation has been expanded to include unattended contacts performed at night. After the first year in orbit, every single byte of science data collected onboard the TIMED spacecraft has been successfully downlinked and provided to the science team for processing. This is an extraordinary achievement that can be attributed to the talent and dedication of the entire TIMED mission operations and ground system teams.

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