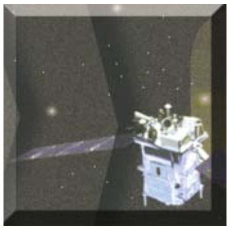

TIMED Mission System Engineering and System Architecture

David Y. Kusnierkiewicz

A space mission consists of more than just a spacecraft and scientific instruments. It also includes a ground system to support communications, command and telemetry processing and archiving, a mission operations team, and a launch vehicle. Before launch, all of these elements must be tested together in an integrated fashion. The Mission System Engineer is the chief architect of this system, is responsible for all technical aspects of the entire system, and directs trade studies to determine the partitioning of functions among subsystems and elements of the entire system. The TIMED mission and system were designed around a concept of low-cost mission operations. This concept was realized through the creation of a highly autonomous spacecraft, instrument operations that are decoupled from spacecraft operations, and payload (instrument) operations centers that are geographically distributed and connected through the Internet.

INTRODUCTION

A typical space system consists of more than a spacecraft bus and scientific instruments. The entire system also includes the ground system, mission operations, integration and test (I&T), and the launch vehicle. The instruments constitute the spacecraft's payload and perform the measurements that produce the data needed to conduct the scientific investigation. The spacecraft bus is designed to provide the resources necessary to support the instrument requirements of power, mass, data volume, fields of view, stability, etc. The ground system consists of a ground station, a mission operations center, and a mission data center. It provides the RF uplink and downlink capability to communicate with the spacecraft on orbit. A mission operations center processes the spacecraft commands and telemetry. Commands are sent to both the spacecraft subsystems and instruments, and the telemetry from the spacecraft includes both scientific data collected from the instruments and engineering "housekeeping" data that indicate the health and performance of the spacecraft and instruments. A mission data center archives all the data and allows access by the engineering and science teams. Mission operations involve planning and executing the operation of the spacecraft on orbit throughout the mission. These day-to-day activities are the responsibility of a mission operations team. I&T concerns assembling and testing the spacecraft bus, instruments, and ground system as an integrated whole prior to launch to verify that all program requirements are met. Finally, the launch vehicle provides the access to space, and the spacecraft must be designed to be compatible with the interfaces and environments it presents.

The Mission System Engineer is responsible for all technical aspects of a program that together form a single integrated system, serves as the chief architect of this overall system, and is uniquely positioned to direct trade studies among these various elements in order to arrive at an architecture that optimizes system design and performance within the resources allocated. The Mission System Engineer is supported by and directs a team of system engineers who are, in turn, responsible for the individual segments of the system (spacecraft, ground system, mission operations, etc.).

The roles and responsibilities of the Mission System Engineer are presented here, and the TIMED (Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics) system architecture and several of the key trade studies performed are discussed. (Complete information on the TIMED mission, including participants, status, science, etc., may be found at http://www.timed.jhuapl.edu/mission/.)

ROLES AND RESPONSIBILITIES

The Mission System Engineer leads the program System Engineering Team and is ultimately responsible for

- The technical performance of all elements of the mission, as noted above
- All hardware and software elements
- All traditional system engineering functions of requirements definition and flowdown to subsystems, documentation of traceability to science requirements, and assurance that all requirements and interfaces are verified before launch

Specific roles of the Mission System Engineer are to

- Lead trade studies to determine the optimum system architecture for the flight and ground systems, and manage the interfaces among mission segments
- Provide risk management throughout the life of the program
- Organize all major system reviews (Conceptual, Preliminary, and Critical Design) and track the closure of action items generated from these reviews
- Make decisions regarding implementation that do not affect cost and schedule or science requirements such as allocation of spacecraft resources of mass, power, data rate, data volume, etc. (Decisions that *do* affect cost and/or schedule must be made with the concurrence of the Program Manager. Decisions that affect science return must be made with the concurrence of the Project Scientist or Principal Investigator.)

Again, to execute all of these duties, the Mission System Engineer relies heavily on the segment system engineers in executing these roles and responsibilities. This relationship can be seen in Fig. 1, the TIMED organizational chart, and is discussed below.

The TIMED program was structured to fully integrate the software and hardware development efforts. The Mission System Engineer has a software counterpart, the Mission Software System Engineer, who has overall responsibility for the flight and ground software and oversight to ensure that software development follows the process defined in the Software Development and Management Plan. Each program segment has a technical lead with a software counterpart. In each case, the technical lead has prime responsibility for the development of the given segment.

Co-location of the hardware and software developers is highly desirable, and was implemented to the extent practical. For instance, a closely integrated and co-located hardware and software team (including algorithm developers) developed the GPS Navigation System (GNS), an onboard GPS receiver and orbit propagator that is a key technology asset enabling the system architecture. Similarly, ground system development was more efficient when the assessment tool developers worked closely with the mission operators. This collaboration produced the tools that would be most helpful in allowing the Mission Operations Team to process the raw spacecraft engineering data to assess the health and trends of spacecraft performance.

SYSTEM ARCHITECTURE

Components

The TIMED system architecture is presented in Fig. 2. The main elements of the orbital mission are the spacecraft and ground system, including the Mission Operations Center (MOC); ground station for communicating with the spacecraft; remote Payload Operations Centers (POCs) for each instrument; and Mission Data Center (MDC) where the data are archived. The TIMED ground station, MOC, and MDC are located at APL, as is the Global Ultra-Violet Imager (GUVI) POC; the Solar Extreme ultraviolet Experiment (SEE) POC is located the Laboratory for Atmospheric and Space Physics in Boulder, Colorado; the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) POC is at NASA Langley Research Center in Langley, Virginia; and the TIMED Doppler Interferometer (TIDI) POC is at the University of Michigan Space Physics Research Laboratory in Ann Arbor, Michigan.

Key Features

Event-Based Commanding

Traditional mission operations involve constant planning on the ground to determine where the spacecraft will be at any given point in time. For instance, when the spacecraft passes over the "terminator," i.e.,

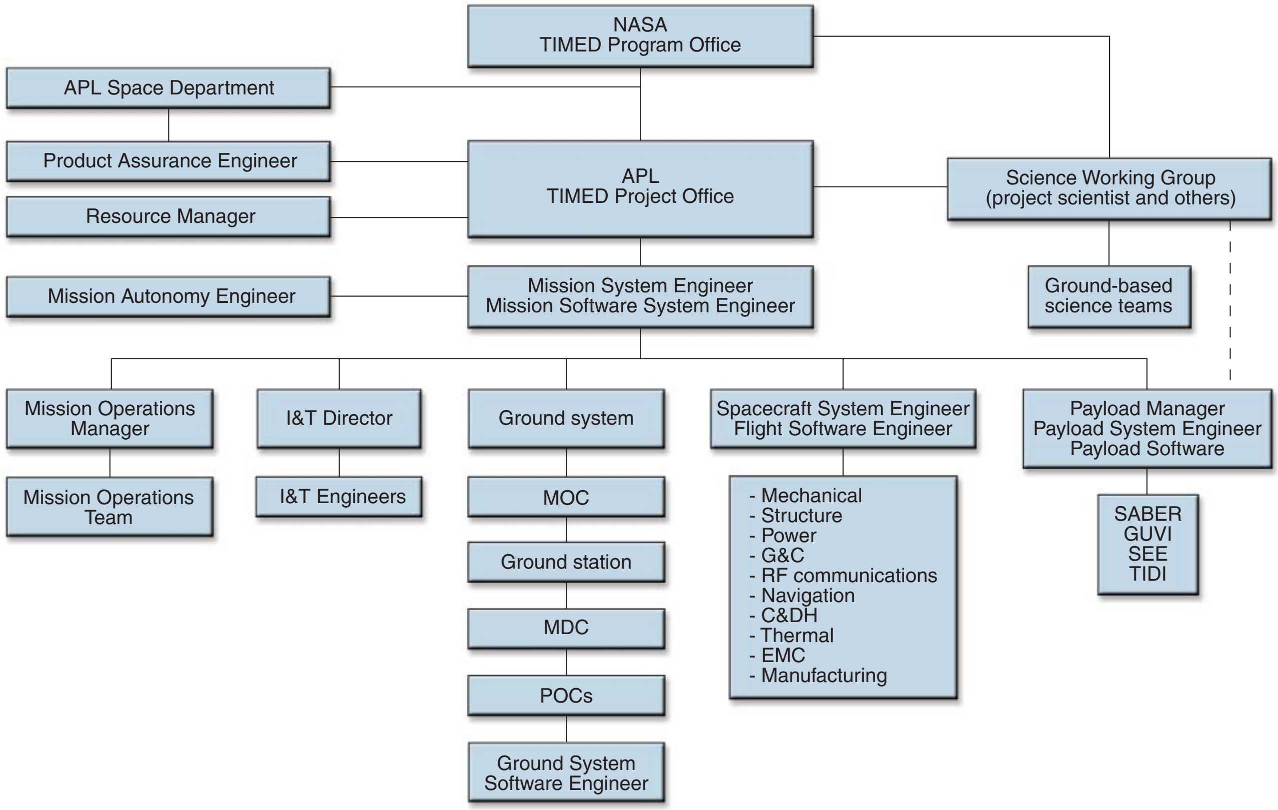

Figure 1. The TIMED project organization chart shows the major program segments and the relationship of the Mission System Engineer to those segments. Note the integration of software engineering functions within most segments. (C&DH = command and data handling, EMC = electromagnetic compatibility, G&C = guidance and control, I&T = integration and test, MDC = Mission Data Center, MOC = Mission Operations Center, POC = Payload Operations Center.)

the dividing line between day and night on the Earth, an instrument viewing the scene below the spacecraft may need to change gain to retain the proper measurement sensitivity. Other events that may be of interest include passage over the Earth's polar regions or through the South Atlantic (magnetic) Anomaly. The Mission Operations Team is also concerned with periods when the spacecraft is in view of a given ground station so that contacts can be scheduled to upload commands and downlink recorded data. Once the times for these events are determined on the ground, a series of "time-tagged" commands are uploaded to the

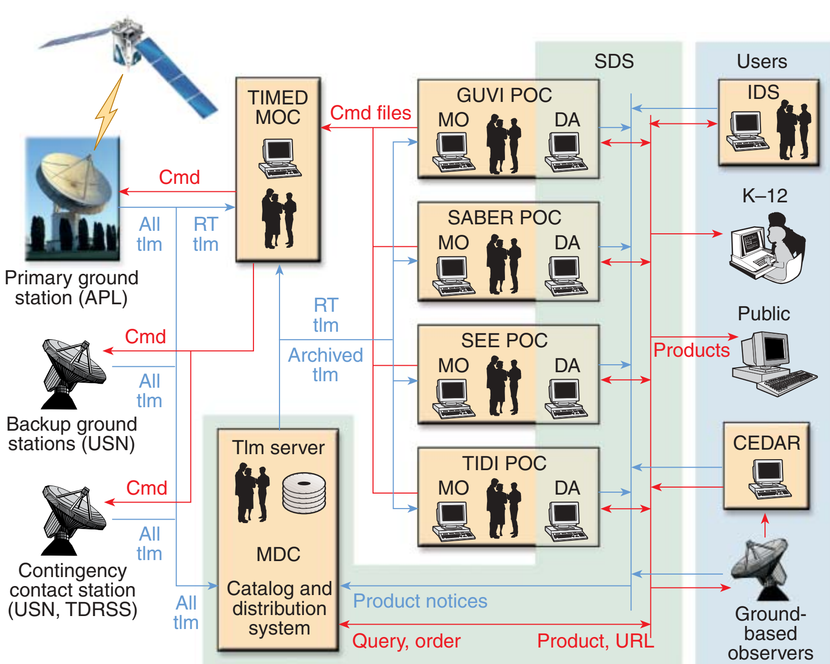

Figure 2. Block diagram of the TIMED system architecture in the operational configuration, showing the major flight and ground elements. The Internet is used extensively to tie geographically distributed elements together, distribute science products to the scientific community, and allow public access to educational products. (Cmd = command, DA = data analysis, IDS = interdisciplinary scientists, MO = mission operations, RT = real time, SDS = Science Data System, tlm = telemetry, TDRSS = Tracking Data Relay Satellite System, USN = Universal Space Network [provider of the backup ground stations]; CEDAR [the National Science Foundation's Coupling, Energetics, and Dynamics of Atmospheric Regions Program] is a collaborative study with TIMED.)

spacecraft and are executed when the spacecraft clock reaches the time tag of the command.

For TIMED, however, a scheme called "event-based commanding" was implemented in keeping with a key element of the TIMED system architecture—design around low-cost mission operations. To accomplish low-cost operations, increased intelligence and functionality had to be added to the spacecraft.

Many of the events of interest and the desired actions onboard the spacecraft occur repetitively as the spacecraft orbits the Earth. Event-based commanding replaces the need for daily uploads of time-tagged commands to the spacecraft to effect the desired onboard action for both the spacecraft and science instruments. This relieves the Mission Operations Team from having to perform intensive, repetitive planning on the ground.

The onboard GNS enables this operational mode and is an example of the kind of architectural partitioning the Mission System Engineer performs, since the use of this technology affects the spacecraft design and the operational concept of the mission. The Spacecraft System Engineer and Ground System Engineer do not make this type of decision; their authority is confined to their specific segment, although they do work closely in managing and negotiating the interface between segments once the architecture is decided upon.

The GNS enables the spacecraft to know where it is at any given time, and through its orbit propagator, can predict upcoming events. When the spacecraft is in a particular region of interest described above, an "event" notification is broadcast to the instruments, and the instruments respond with a stored response to effect the desired action. In similar fashion, the spacecraft transmitter is turned on during contact with a ground station to initiate communications with the ground. Thus the TIMED spacecraft can be operated with a small Mission Operations Team, lowering the cost of its on-orbit mission. TIMED has been operating with a Mission Operations Team of only eight spacecraft operators (not including instrument operators).

Payload Operations Centers

Another key TIMED architectural decision made early in the program by the Mission System Engineer was the implementation of remote POCs, along with decoupled instrument operations.

Typically, instrument operations teams have been co-located at the spacecraft MOC. Instrument commands have been merged with spacecraft commands in command uploads, then held by the spacecraft command and data handling (C&DH) system until it is time to transmit to the instrument for execution. Instrument command loads must often be vetted on the ground to ensure that adequate spacecraft resources (power, data bandwidth, recorder capacity, etc.) are available. The TIMED spacecraft, however, had to provide adequate onboard resources to allow all four scientific instruments to operate 100% of the time without interfering with the other instruments or the spacecraft.

By sending command uploads to the TIMED MOC via the Internet, instrument teams at the remote POCs can operate their instruments at their home institutions. The only instrument command vetting that occurs at the MOC is to confirm that the commands are properly addressed to the instrument. Once onboard, the spacecraft C&DH system routes the command to the instrument, where it may execute as a time-tagged or event-based command. Instrument data are transmitted to the MOC, and then transferred via the Internet to the home POC for analysis. Dial-up phone modems are used as backup in case of Internet outages.

Integration, Test, and Launch

A third decision made by the Mission System Engineering early in the program was the approach to I&T and launch operations. Past APL programs have carried two more or less complete copies of the ground system. One was used to support pre-launch I&T activities, following the spacecraft from the I&T facility at APL, to Goddard Space Flight Center for environmental testing, and finally to the launch site to support pre-launch processing and launch operations. The other ground system was used post-launch in mission operations. The schedule during I&T often leaves little time for mission operations training.

TIMED elected to make one very capable, flexible ground system that could be reconfigured to support *all* phases of I&T and launch operations as well as on-orbit operations. This ground system remained at APL; only a minimum set of equipment was required to follow the spacecraft to the various locations before launch. Spacecraft I&T, environmental testing at Goddard, and pre-launch testing at Vandenberg Air Force Base were all performed with this single ground system. Data links between APL and these various locations were established to allow this remote communication with the spacecraft.

Several advantages were realized with this approach.

- The spacecraft was "tested as it was to be flown," providing for longer periods of end-to-end system verification prior to launch.
- Mission operations personnel had more opportunity to operate the spacecraft pre-launch, enhancing their readiness at launch. Mission operations personnel were also integrated into the I&T team.
- Fewer people were required to travel to remote sites for extended stays during environmental testing and launch processing; the majority of the engineering team could remain at APL.
- Operating the spacecraft at the launch site from APL and flowing seamlessly into on-orbit mission

operations at the Laboratory also enabled the availability of the full engineering team for anomaly resolution during the critical early operations phase immediately following launch.

CONCLUSION

The decisions that defined the TIMED system architecture described above all had cost and schedule implications, and therefore could not be made without the full knowledge and concurrence of the Program Manager. The Mission System Engineer, as the chief system architect, drove the architectural trade studies.

TIMED was launched on 17 December 2001 from Vandenberg Air Force Base in Californina, and was declared operational on 22 January 2002. The goal of low-cost mission operations was realized through the design and implementation of a sophisticated spacecraft that provides the resources necessary for independent, decoupled instrument operations and automates repetitive tasks that formerly required intensive planning on the ground by the Mission Operations Team. In addition, the ground system makes extensive use of the Internet, thus allowing for the most efficient application of technical and human resources.

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