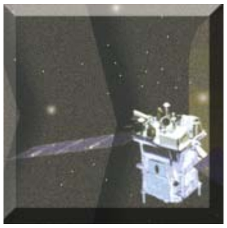

An Overview of the TIMED Spacecraft

David Y. Kusnierkiewicz

The Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics (TIMED) spacecraft was designed at APL as the first Solar Terrestrial Probe in NASA's Solar Connections Program. The spacecraft supports the operation of four scientific remote-sensing instruments for a minimum of 2 years from a circular orbit 625 km in altitude with an inclination of 74.1°. TIMED has been designed with a significant amount of onboard autonomy, as it is run with a low-cost mission operations concept. The robust spacecraft with redundant subsystems features an Integrated Electronics Module that contains RF and digital subsystems in a common card cage. The TIMED GPS Navigation System uses the GPS for onboard tracking, navigation, and "event-based" commanding, and is key to the implementation of low-cost mission operations.

INTRODUCTION

The TIMED spacecraft design is driven by the accommodation requirements of its scientific payload of four instruments and the concept of mission operations. (Complete information on the TIMED mission, including participants, status, science, etc., may be found at http://www.timed.jhuapl.edu/mission/.) The spacecraft flies in a nadir-pointing orientation from its 625-km circular orbit at a 74.1° inclination. The instrument complement is designed to remotely sense the region of the atmosphere from 60 to 180 km below the spacecraft to determine energy sources and sinks as well as the atmospheric state variables of pressure, density, temperature, and winds. The instruments are:

- The Global Ultra-Violet Imager (GUVI), which scans cross track from horizon to horizon to measure the spatial and temporal variations of temperature and constituent densities in the lower thermosphere, and to determine the importance of auroral energy sources and solar extreme ultraviolet sources to the energy balance in that region
- The Solar Extreme ultraviolet Experiment (SEE), which tracks the Sun for about 10 min each orbit to measure solar radiation in the atmospheric region of interest
- The Sounding of the Atmosphere using Broadband Emission Radiometry (SABER), which measures infrared emissions in the atmosphere below 120 km
- The TIMED Doppler Imager (TIDI), which continuously measures wind direction and speed in the region

The spacecraft is three-axis stabilized, with no onboard propulsion. Mission operations are designed around a single 8-h shift per day.

DRIVING CONCEPTS

The TIMED spacecraft is designed around a concept of low-cost mission operations.[1] To achieve this, the spacecraft was built with a considerable amount of onboard intelligence as well as an abundance of onboard resources. This approach minimizes the burden on the mission operations staff, thus enabling the spacecraft to be operated with a small team.

Mission operations typically require intensive planning on the ground. The orbit of the spacecraft takes it over various points of scientific interest such as terminator crossings and auroral zones over the poles. Passage through the South Atlantic (magnetic field) Anomaly is also important to the spacecraft and instruments, since the enhanced heavy particle environment in the region may cause upsets in onboard electronics. Passage over ground stations is of interest to the operators, as contacts for uploading commands and downloading recorded data must be scheduled. Instrument gains may need adjusting when the spacecraft is passing from daylight into darkness. Typically, the time of such events is determined on the ground, and time-tagged commands are uploaded to the spacecraft to effect the desired onboard actions. Since many of these events are repetitive in nature as the spacecraft completes one orbit every 97 min, the command uploads are also repetitive, differing only in the times at which they execute.

TIMED uses an operations concept called "event-based" commanding, which eliminates the need for repetitive time-tagged commands. The TIMED GPS Navigation System (GNS) enables this mode of operation. Using the GNS, which consists of a GPS receiver and orbit propagator, the spacecraft knows its position and velocity at any given time and can predict events such as terminator crossings and passages over auroral zones and ground stations. Notifications of these events can be broadcast to the instruments, which can then respond accordingly to obtain the desired data, or the spacecraft transmitter can be triggered to initiate a downlink to the ground. Spacecraft time is also derived from the GPS, thus greatly simplifying spacecraft operations.

This mode of operation is analogous to the way commercial tour buses operate; the "bus" is the spacecraft, and the "passengers" are the instruments. The passengers do as they please, within limits (talk, read, eat, sleep, enjoy the scenery), while the bus driver announces upcoming events and points of interest (rest stops, upcoming destination cities, scenic views, etc.).

Another feature of TIMED operations enabled by the spacecraft design is a "decoupled" mode of instrument operations. By providing sufficient resources such as power and data storage capacity onboard the spacecraft to support all instrument operations at a duty cycle of 100%, any one instrument can operate unconstrained for the life of the mission. As the orbit of the spacecraft precesses, resulting in periods of differing eclipse times, and hence power generation, mission and science operations do not have to be modified to conserve power. Similarly, the spacecraft structure provides sufficient stability such that the motion or scanning activity of any one instrument does not affect the quality of the data obtained by any other instrument.

Figure 1 depicts the TIMED spacecraft on orbit. The most striking feature is the large solar arrays. In its 625-km, 74.1° inclined orbit, the spacecraft orbit plane precesses 3° a day with respect to the Sun. Thus it experiences periods ranging from full exposure to the Sun (maximum orbit average power generation) over the entire orbit to periods where it experiences eclipses every orbit (minimum orbit average power generation). The solar arrays, each approximately 4 ft wide and 16 ft long, provide sufficient power to enable all spacecraft and instrument operations continuously over the life of the mission. Also shown in Fig. 1 is a graphite-epoxy optical bench on the top of the spacecraft where the two star trackers and four TIDI telescopes are mounted. The TIDI telescopes point ±45° to the ram (spacecraft velocity vector) and anti-ram directions. The optical bench is required to provide a stable platform for these components so that the telescope pointing knowledge requirement of 0.03° can be achieved.

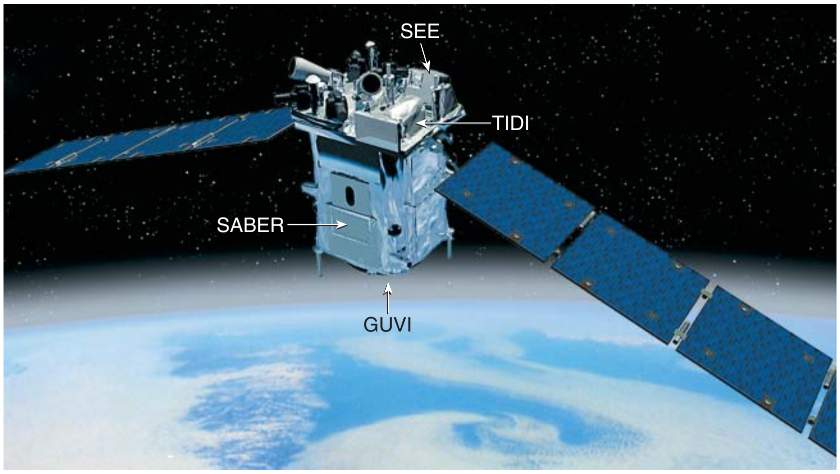

Figure 1. The TIMED spacecraft in its orbital configuration, with solar panels deployed. Visible in the figure are SABER on the cold (anti-Sun) side of the spacecraft; SEE and the TIDI profiler on the top deck; and the composite optical bench on which the four TIDI telescopes, star trackers, and GNS antennas are mounted. The GUVI instrument (not shown) is located on the bottom (nadir-viewing) surface of the spacecraft, inside the adapter ring that was the mechanical interface to the launch vehicle.

Also located on top of the spacecraft are the SEE instrument, GNS patch antennas, S-band communications antennas, and TIDI profiler. The GUVI instrument is located on the underside of the spacecraft, inside an adapter ring that was the mechanical mating interface between the spacecraft and the launch vehicle. Finally, the SABER instrument is located on the side panel of the spacecraft that is always kept facing away from the Sun.

SPACECRAFT DESIGN REQUIREMENTS

TIMED mission operations were budgeted at about \$2 million a year for 2 years (this did not include data analysis). NASA has recently extended the mission for additional years. To operate the spacecraft inexpensively, TIMED has been designed to support continuous instrument operations with a minimum amount of ground contact.[1] As noted earlier, many event-driven commands are generated onboard the spacecraft, not uploaded from the ground as are time-tagged commands. Spacecraft position and velocity are determined onboard using GPS satellites. Position is determined to less than 300 m (3σ), velocity to 25 cm/s (3σ), and time to 100 μs. Onboard processing extrapolates the orbit for autonomous event-based commanding. Instruments are notified of epochs (terminator crossings and the spacecraft's closest approach to the poles). Data on spacecraft attitude (roll, pitch, and yaw), position (latitude, longitude, and altitude), velocity, and time, as well as the location of the Sun, are available to the instruments once per second on orbit.

The TIMED instruments require a three-axis stabilized platform. Attitude control requirements are 0.5° (3σ), each axis. The TIDI telescopes have the most stringent attitude knowledge requirement, 0.03° (3σ) for each axis, which is met by mounting the star cameras to the optical bench shared by the TIDI telescopes. The maximum angular rate allowed is 0.0075°/s (driven by the SABER instrument). This is accomplished by the use of a three-axis gyro Inertial Reference Unit. Reaction wheel momentum is dumped using magnetic torque rods, and again, there is no onboard propulsion. Drag studies have shown that the orbit will decay about 25 km over its 2-year lifetime from TIMED's starting altitude of 625 km.

The four TIMED instruments produce approximately 1.6 Gbits of data per day. The onboard data storage capability of 2.5 Gbits is sufficient for 36 h of science and engineering data. S-band downlink rates of approximately 4 Mbps allow the entire recorder contents to be dumped in one 10-min ground station pass. (Since passes generally occur in clusters, additional passes during one 8-h shift are available for contingencies.) The S-band uplink rate is 2 kbps.

The power system must provide in excess of 400 W orbit average power to the spacecraft loads.

SYSTEM DESIGN OVERVIEW

Mechanical Configuration

The orbital configuration of the TIMED spacecraft (Fig. 1) is driven by the clear field-of-view requirements of the science instruments and the space required to locate and operate the solar arrays. Most of the spacecraft subsystems are located inside the structure. Electronics boxes are conductively mounted (thermally) to the structural panels, which then reject the dissipated heat to space. The single battery is split into halves to spread out the thermal load and balance the structure. The four reaction wheels are mounted to the interior of the bottom deck.

The spacecraft primary structure consists of aluminum honeycomb panels with embedded magnesium edge members. These edge members are the attachment points for the interpanel connections, providing a frameless design. A machined aluminum payload adapter ring is the mechanical interface from the spacecraft to the launch vehicle and also provides mounting brackets for the launch vehicle to the spacecraft's purge and electrical connections. The optical bench is an aluminum honeycomb sandwich design with graphite epoxy face sheets and titanium-threaded inserts. The bench is attached to the spacecraft via a three-point kinematic mounting system to eliminate the potential for thermal expansion distortions between the bench and the aluminum spacecraft bus. The bench is a passive thermal design and achieves a maximum of 30 arcsec stability between the bench-mounted components and the spacecraft bus. The spacecraft power and mass summary is given in Table 1.

Figure 2 is a block diagram of the spacecraft. The subsystems are single-fault tolerant by full redundancy or, in the case of the reaction wheels, any three wheels

Table 1. TIMED power and mass summary.

Subsystem	Orbit average power (W)	Mass (kg)
SABER	76	75
TIDI	36	40
GUVI	29	18
SEE	33	29
Power	34	181
IEM	53	23
Attitude	95	65
Thermal	40	16
Structure and harness	6	145
Margin	24	—
Total	426	592

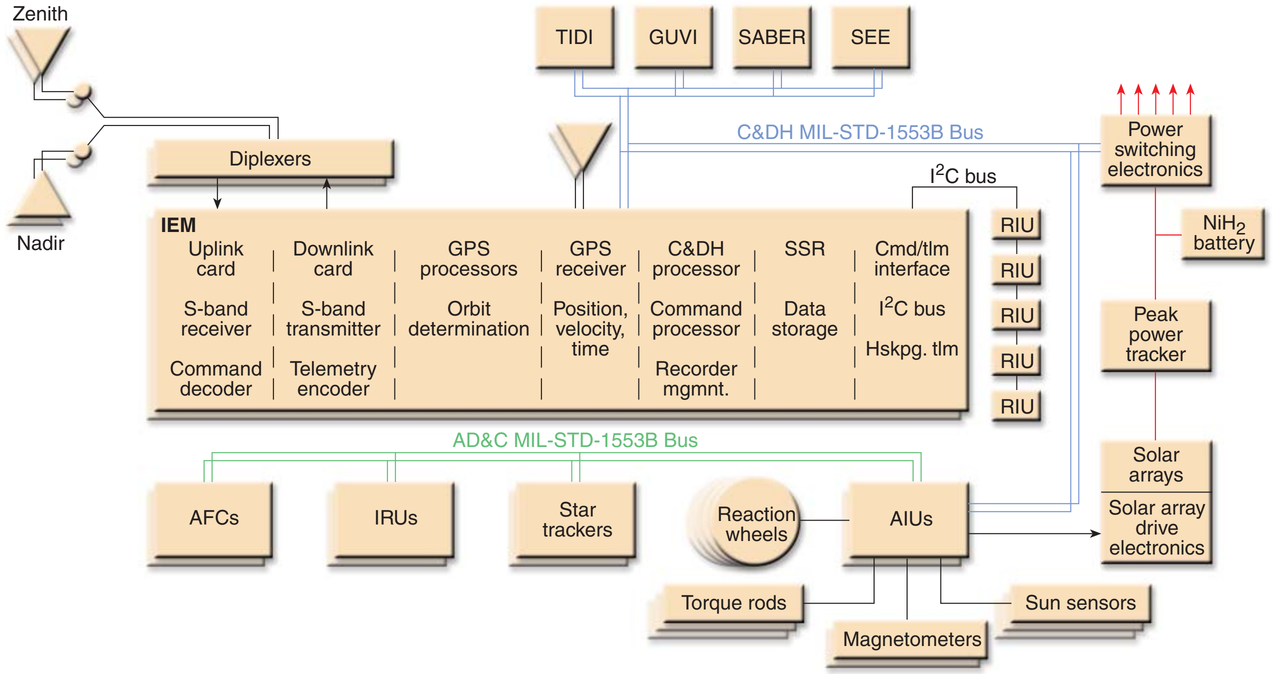

Figure 2. The spacecraft block diagram is built around the Integrated Electronics Module (IEM). The IEM contains three spacecraft subsystems (C&DH, GNS, and RF communications) and mixes RF and digital subsystems in a single card cage. Instruments communicate with the IEM over a MIL-STD-1553B serial data bus. Most of the spacecraft subsystems are redundant, either internally, or by the use of an identical redundant unit.

can provide full three-axis control. The instruments are single string, and no one instrument is considered mission critical. The spacecraft is designed around the Integrated Electronics Module (IEM), a card cage that contains the RF communications, GNS, command and data handling (C&DH) system, and solid-state recorder (SSR) on plug-in cards. The cards within the IEM communicate over a Peripheral Component Interconnect parallel data bus. Two identical IEM modules are used, both communicating to other spacecraft subsystems and the instruments over a redundant 1553 serial data bus.

The IEM collects housekeeping data from other cards and subsystems through a 100-kHz twisted-pair housekeeping (I^2C) bus. A custom remote input/output integrated circuit (Remote Interface Unit [RIU]) is used to buffer readings from temperature sensors, current monitors, voltage monitors, etc.

The C&DH, GNS, and Attitude Flight Computers (AFCs) use Synova Mongoose-V 32-bit RISC processors with 2 Mbytes of RAM and 4 Mbytes of Flash EEPROM. The C&DH processor card manages the traffic over the 1553 bus. It coordinates the messages among the C&DH system, GNS, attitude determination and control (AD&C) system, and instruments and manages the SSR. The C&DH processor card also monitors the health of the Attitude Interface Unit (AIU) safing processors. When the C&DH receives a message from the AIU regarding lost attitude, the C&DH can switch between AIUs and begin the recovery process.

The normal flight configuration is to power only one IEM, AIU, AFC, and Inertial Reference Unit (IRU). Both star trackers are continuously powered to meet the attitude pointing knowledge requirement. All four instruments are powered continuously as well. Unpowered components are cold spare redundant units to be used in case a primary unit fails. The command receivers in each IEM are continuously powered to ensure the ability to get a command to the spacecraft.

Global Positioning System Navigation

The GNS consists of two cards in the IEM that function as a GPS receiver, along with two embedded 32-bit RISC processors to provide onboard tracking and navigation solutions. Patch antennas mounted on graphite epoxy tubing interfaced to the optical bench via titanium mounting flanges are used for the reception of the L-band GPS signals. Spacecraft position is determined to within 300 m (3σ), velocity to 25 cm/s (3σ), and time to 100 μs using a single-frequency Standard Positioning Service GPS receiver. The instruments can receive this information once per second over the 1553 bus (1-Hz time tags are given to the instruments, accurate to within 100 ms). The GPS extrapolates the spacecraft orbits for the next 24 h, updated on an hourly basis. The GPS provides the basis for onboard event prediction such as terminator crossings and ground station contact.

Attitude Determination and Control

The AD&C subsystem has its own dedicated 1553 bus for communication among the attitude sensors (star trackers and IRUs), AIUs, and AFCs. The AIU controls other attitude actuators such as reaction wheels and torque rods, as well as the solar array drive. The AIU also contains a 16-bit radiation-hardened RTX 2010 processor for safing the spacecraft in the event of a loss of attitude.

The attitude system uses the Mongoose-V processor for processing data from the star trackers and IRU (a three-axis gyro) and for controlling, through the AIU, the reaction wheels and torque rods. (Recall that four reaction wheels are used, any three of which can provide the required three-axis stability). Built-up momentum in the wheels is dumped using the three orthogonal torque rods, which interact with Earth's magnetic field. The two narrow field-of-view star trackers mounted on the optical bench on the zenith end of the spacecraft are canted at 90° to each other and 45° up from the top deck. Precise alignment of the star trackers over varying thermal and environmental conditions is maintained by the design of the graphite epoxy mounting brackets. The star trackers are pinned to the brackets and the brackets are then pinned to the optical bench. The attitude system also controls the pointing of the solar panels through the solar array drive.

By giving the AD&C subsystem its own 1553 bus, the development of the attitude system became decoupled from the rest of the spacecraft subsystems, allowing for the easy implementation of autonomy and safing algorithms. The loss of a single component in the attitude system does not result in an immediate, critical loss of attitude. If an AFC stops processing sensor data, the RTX 2010 processor in the controlling AIU can determine if the AFC or one of the sensors is bad and change the system configuration. A complete loss of attitude due to a failure of the attitude 1553 bus controller can be recognized by the C&DH processor, which can switch to the redundant AIU. That unit can zero the spacecraft body rates, point the panels to the Sun, and either initiate a system reconfiguration or maintain the spacecraft in a safe mode until the next ground contact.

Power

The power subsystem uses two rotating wings, each consisting of four solar panels. Each solar panel is an aluminum honeycomb sandwich design with graphite epoxy face sheets. Solar cells are gallium arsenide, and the entire array system (both wings) total approximately 128 ft^2 in area. Each wing has a free deployment type of design and is deployed via dual pyrotechnic-activated separation nuts. Each interpanel hinge employs a torsion spring regulated by a tuned viscous damper to control angular momentum. The yoke uses a constant-force leaf spring, also regulated by tuned viscous dampers. When fully illuminated, each wing produces 1250 W of electrical power. Panel pointing is done through a one-axis, Moog-Schaeffer Type 2 actuator drive employing a harmonic drive and stepper motor drive train. Wing rotation is limited to 90° of total travel by hard stops located in the drive motor. Power is managed through a peak power tracker, which minimizes the solar array area. Without the peak power tracker, the solar arrays would need to be approximately 25 to 30% larger. A 50 A-h nickel hydrogen individual pressure vessel battery is used to support loads during eclipses. The battery bus voltage varies from 22 to 35 V. Battery charging and solar array power management are controlled by the main C&DH processor in the IEM. The C&DH processor also provides load-shedding functions in case of excessive battery discharge, with a low-voltage protection feature implemented in hardware in the power system as a final safety measure.

RF Communications

The RF communications subsystem, contained on cards in the IEM, provides for a CCSDS-210.0-B-1–compatible S-band uplink at 2 kbps and an S-band downlink at 4 Mbps with robust link margins. Transmitted RF power from TIMED is 3.0 W, with downlink encoding rate 1/2, $k = 7$ concatenated with Reed-Solomon. Quadrifilar helix antennas on the zenith and shaped-beam hemispherical antennas on the nadir end of the spacecraft ensure near omnidirectional coverage in the event of any attitude emergencies.

CONCLUSION

The TIMED spacecraft was successfully launched from Vandenberg Air Force Base on 7 December 2001 aboard a Delta-II launch vehicle. Science operations officially began on 22 January 2002. The low-cost mission operations concept, using significant onboard autonomy enabled by the GNS, has been successfully validated.

REFERENCE

[1] Cameron, G. E., and Herbert, G. A., "The Engineering of Cost Efficient Operations," in *Proc. Ninth Ann. AIAA/USU Conf. on Small Satellites*, Utah State University, Logan, UT (1995).

ACKNOWLEDGMENTS: The author gratefully acknowledges and appreciates the dedication and efforts of the entire TIMED team at APL and in particular the following people: S. Ali, M. Butler, G. Cameron, U. Carlsson, G. Dakermanji, C. Deboy, W. Dellinger, W. Devereux, D. Grant, P. Grunberger, R. Harvey, K. Heffernan, W. Knopf, S. Kozuch, R. Nordeen, J. Perschy, E. Prozeller, W. Radford, E. Schaefer, G. Seylar, D. Temkin, D. Tracey, S. Vernon, B. Williams, S. Williams, S. Yee, and all members of the TIMED Mission Operations Team.

THE AUTHOR

DAVID Y. KUSNIERKIEWICZ is a member of APL's Principal Professional Staff, assistant supervisor of the Space Department's Space Systems Applications Group, and supervisor of the Systems Engineering Section. He received a B.S. in electrical engineering in 1976 and an M.S. in electrical engineering in 1982 from the University of Michigan. Since joining the Laboratory in 1983, he has contributed to numerous NASA and DoD programs. Mr. Kusnierkiewicz was the Spacecraft System Engineer for the TIMED mission, and in 1999 was also appointed the Mission System Engineer. He is currently the Mission System Engineer for the NASA New Horizons mission to Pluto. His e-mail address is david.kusnierkiewicz@jhuapl.edu.