Transition Region And Coronal Explorer Mission

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Abstract—The Transition Region and Coronal Explorer (TRACE) mission is the fourth mission in the Small Explorer (SMEX) program series at the National Aeronautics and Space Administration's Goddard Space Flight Center. The primary objective of the TRACE mission is to explore the connections between the fine scale magnetic fields in the solar surface and features in the solar photosphere, chromosphere, transition region, and corona. The TRACE spacecraft, including the instrument, weighs 250 kilograms, uses 200 watts of power, and will cost approximately 35 million dollars for the entire mission. It will launch into a sun-synchronous Low Earth Orbit (LEO) in September 1997 and collect movie-like images of the sun with one arc second spatial and 1 second temporal resolution; these images will be made available on the Internet daily.

This paper shows NASA's approach to small spacecraft development. It discusses some trades in the design of each subsystem to accommodate instrument and spacecraft heritage as well as new mission requirements. Topics include: a solid state Command and Data Handling (C&DH) system; solid state memory using 20 Megabyte modules approximately 1" x 1" x 0.2" each; a fully digital Attitude Control System (ACS); a guide telescope fine error sensor for spacecraft attitude and control as well as image motion compensation to better than arc second levels. Adaptations in ground systems and operations are also included as well as the systems engineering approach.

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1. INTRODUCTION

The SMEX program began in 1988 at the National Aeronautics and Space Administration (NASA's) Goddard Space Flight Center (GSFC). These small payloads were intended to cost around 35 million dollars

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for a three year development and the first thirty days of operations on-orbit (not including launch cost). The mission design life is one year and operations past 30 days are funded separately. The SMEX program serves space physics and astrophysics and intends to launch at approximately one year intervals. SMEX launches are currently mandated to use the Pegasus launch vehicle.

The TRACE mission was first proposed in response to an August 1992 NASA Announcement of Opportunity and was subsequently chosen for mission definition in September of 1993. TRACE was then selected to go ahead for flight development in the fall of 1994 with an intended launch date of September 1997.

The SMEX mission technical approach utilizes a small dedicated and co-located core team. [1] This team consists of a lead engineer for each major subsystem and a mission systems engineer. This team was first assembled to evaluate the proposals and fine tuned to the mission's needs during the definition phase. Most of the approximately twenty TRACE core team members have been working on TRACE since September of 1993.

The instrument team uses the same core team approach. The TRACE instrument was proposed by the Lockheed (later merged with Martin Marietta) Palo Alto Research Laboratory (LPARL). Many of the instrument scientists and most of the instrument engineers, technicians, fabricators, and managers were co-located in Palo Alto. Most of this team also worked together on an earlier instrument development.

Having established and co-located teams on both the spacecraft and instrument is a great advantage. The instrument will come to GSFC for its final environmental testing about three months before the beginning of integration with the spacecraft.

2. SCIENCE OVERVIEW

The TRACE Mission will investigate the connections between fine scale magnetic fields and the associated plasma structures on the sun. The TRACE instrument will image the photosphere, chromosphere, transition region, and coronal plasmas. It will collect images of solar plasmas from 10^4 to 10^7 degrees Kelvin. Of particular interest will be the transition from the photosphere to the corona.

TRACE will provide the first comprehensive multispectral time series imaging of the sun in high spatial and temporal resolution. TRACE will observe in the following wavelengths: 5000, 1700, 1600, 1550, 1216, 284, 195, and 171 angstroms. It will also be the first transition region or coronal imager to observe the beginning of a solar cycle.

TRACE data is extremely important for calibration of recent advances in numerical magnetohydrodynamic simulations. [2] TRACE also observes coronal holes and coronal mass ejections which have "profound effects on our space environment and the earth's magnetic field." [3]

When TRACE is operational in 1998 it will allow for joint observations with the Solar and Heliospheric Observer (SoHO). SoHO is scheduled to launch in the fall of 1995 and collect solar images and spectral data at a lower resolution than TRACE out to 30 solar radii. The complementary high resolution and low resolution data along with spectral data is of greater value to both experiments when observed simultaneously. Therefore, the TRACE and SoHO missions are operating with co-located Experimenter Operations Facility's (EOF's) at GSFC. They are performing joint planning and observing while maintaining mission independence.

3. MISSION OVERVIEW

Since TRACE is a solar observer the obvious orbit choice is sun-synchronous. TRACE is launching into a 6 a.m./6 p.m., 600 km circular sun-synchronous orbit at 97.8 degrees inclination. Due to insertion errors and orbit perturbations, however, TRACE will see eclipses in the first year of the mission. The launch window is constrained by the requirement to achieve two continuous 27-day periods of full sun plus three weeks of check-out time on-orbit before the first eclipse. Changing the ascending node time from 6 p.m. to 6 a.m. (effectively reversing the inclination angle by letting the earth rotate 180 degrees) makes any time of the year acceptable for launch. However, launch windows beginning in mid February or mid September give a maximum number of full sun orbits before the first eclipse.

Note that there will be no data collection during eclipsed orbits. The decision was made early on to forego observations during the eclipse seasons rather than greatly complicate the thermal design.

The SMEX philosophy is not to try to develop a standard spacecraft bus, but rather to standardize interfaces and try to reuse components from previous missions. Following those guidelines, the TRACE system architecture is built on the heritage of the Submillimeter Wave Astronomy Satellite (SWAS) (See Figure 1). The power electronics, C&DH system, ACS, and many of the sensors and actuators will have flown on SWAS before the TRACE launch. The TRACE 9 amp/hr Super NiCad battery and radiator design is a duplicate from the Fast Auroral Snapshot Explorer (FAST) mission. The TRACE 5 watt S-band transponder is a duplicate from the Advanced Composition Explorer (ACE). The mechanical design as well as the thermal and solar array design are completely new and unique.

The heart of the TRACE system architecture is an 80386 processor and the MIL-STD-1553 data bus. The TRACE instrument interfaces directly to the spacecraft 1553 data bus. The ACE also interfaces over the 1553 data bus as well as the power electronics.

In order to reduce cost and complexity the SMEX architecture is single string. Selective redundancy is used for certain critical items and areas considered less reliable. TRACE uses 4 reaction wheels, redundant ACS sensors, redundant heaters in wax actuators and, of course, strings in the solar arrays. There is also redundancy in certain cabling and thermal subsystem heaters.

TRACE will downlink data to two primary ground stations four to six times daily. The two primary ground stations will be at Wallops Island, Virginia and Poker Flat, Alaska. The Deep Space Network (DSN) will act as a backup. Data will be downlinked in the S-band at a maximum rate of 2.25 Mbps. Solar images will be easily compressed from 2-20 times on-board. The science data set will be 80 MB or more per pass with no planned capability for redumping data. We will risk rare data loss in order to maintain a maximum

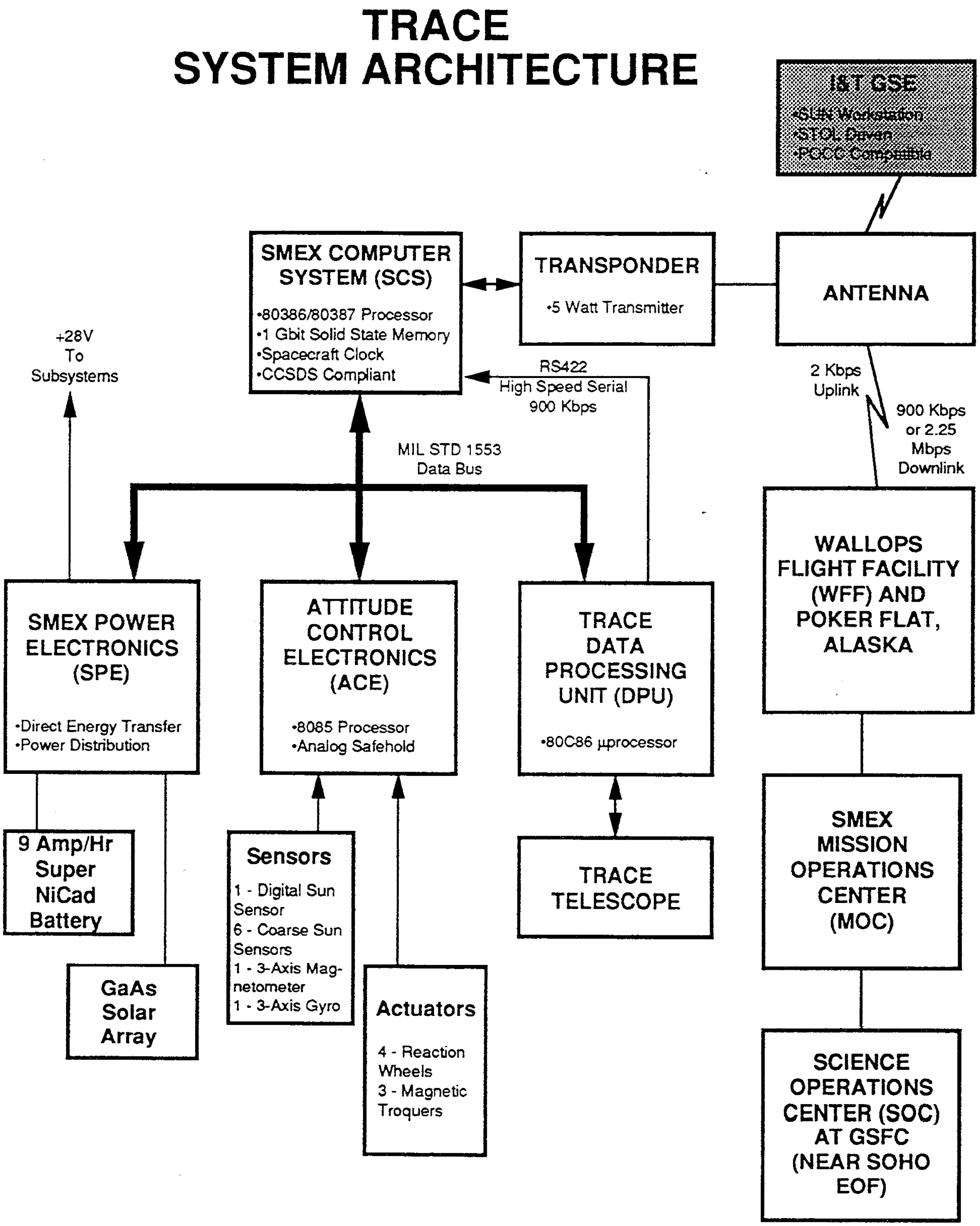

Figure 1. TRACE System Architecture

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data volume. This will simplify ground data post processing and operational contingency modes substantially.

4. INSTRUMENT SYSTEMS

The TRACE instrument is based on the Michleson Doppler Interferometer (MDI) instrument on SoHO. The TRACE instrument consists of a main telescope, a guide telescope and a Data Processing Unit (DPU). The DPU is essentially a copy of the MDI version. The guide telescope uses the same error sensors as MDI. The main telescope, although much larger than MDI, uses the same CCD camera and cooling radiator design as well as almost identical mechanisms. This strong heritage is a prerequisite for selection by the SMEX project because experimenters must deliver flight hardware within two years from the beginning of contract.

Main Telescope

The heart of the instrument is the main telescope. The main telescope is 30 centimeters in diameter and approximately 1.6m long. It weighs approximately 37 kg. It is a Cassegrain telescope with an effective focal length of 8.66 meters. The field of view is 8.5 by 8.5 arcmin. (The sun subtends approximately a half of a degree disc from low earth orbit.) The telescope is broken up into quadrants and a rotary quadrant selector near the entrance selects the quadrant for viewing. At the base of the telescope is a final filter wheel assembly, a rotary shutter, a CCD camera and a passive radiator. This radiator views cold space and cools the 1024 x 1024 CCD detector to approximately -65 degrees Celsius (see Figure 2).

During the definition phase it was decided to move the CCD camera electronics from the spacecraft to the base of the telescope. This simplified the thermal, mechanical, and contamination concerns for the instrument but complicated the mechanical interface to the spacecraft. In order to leave the camera electronics attached to the telescope during integration, the base plate attachment ring on the spacecraft had to be notched. This was complicated because the primary axial loads would be carried through this ring. After lengthy analysis it was determined that the notching could be allowed. This was considered very significant because it removed the need for disassembling the telescope for spacecraft integration and that relieved a major contamination concern.

The TRACE secondary mirror is active and is mounted on three piezoelectric transducers (PZTs). An error signal, generated by the limb sensor in the guide telescope, drives these PZTs in the appropriate direction to cancel the unwanted spacecraft jitter. The spacecraft jitter is specified as less than 20 arc seconds and the reduced jitter to the camera is less than 0.1 arcseconds.

Guide Telescope

The guide telescope also provides the error signal for the spacecraft ACS. Four photodiodes in the guide telescope measure the amount of offset between the solar disk and the guide telescope boresight. These diodes generate linear error signals out to about ±110 arc seconds. [4] There are two circular wedge shaped prisms near the entrance to the guide telescope. Rotation of these prisms allows for pointing off the sun center by up to 1 degree. The instrument controls the pointing of the main telescope by controlling the wedge

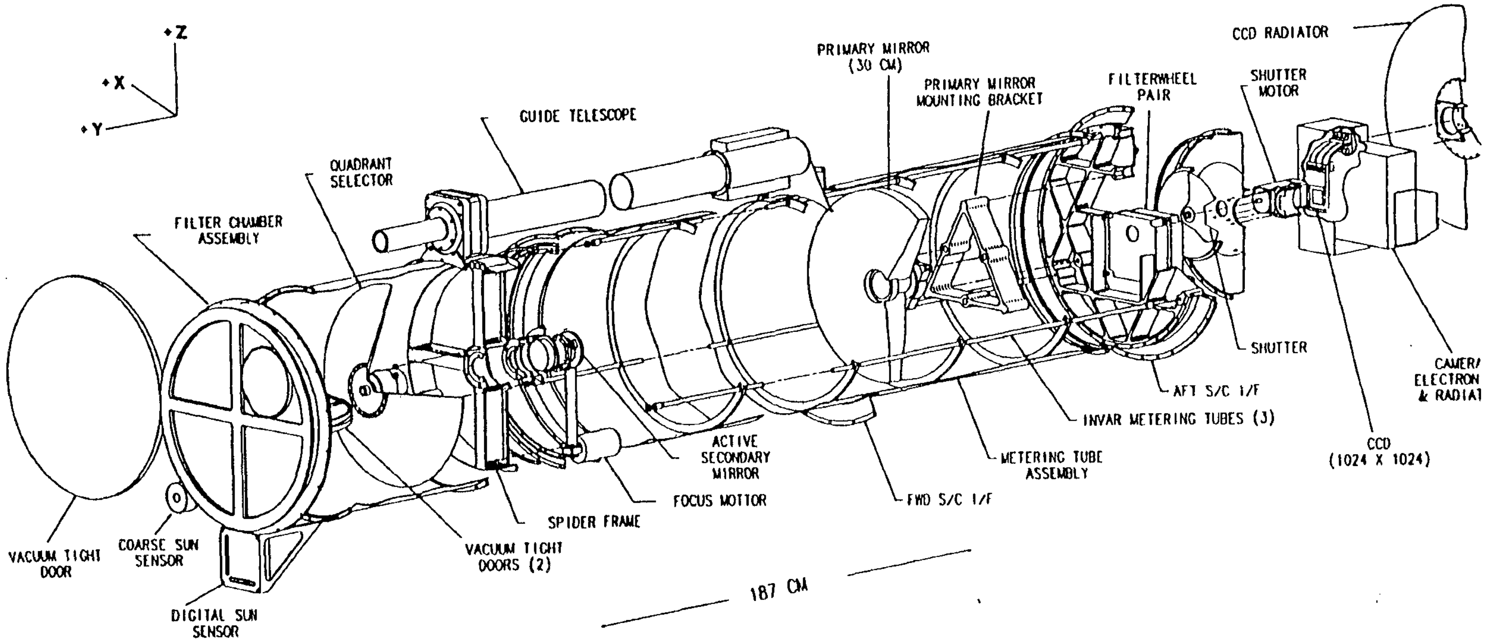


Figure 2. TRACE Telescope

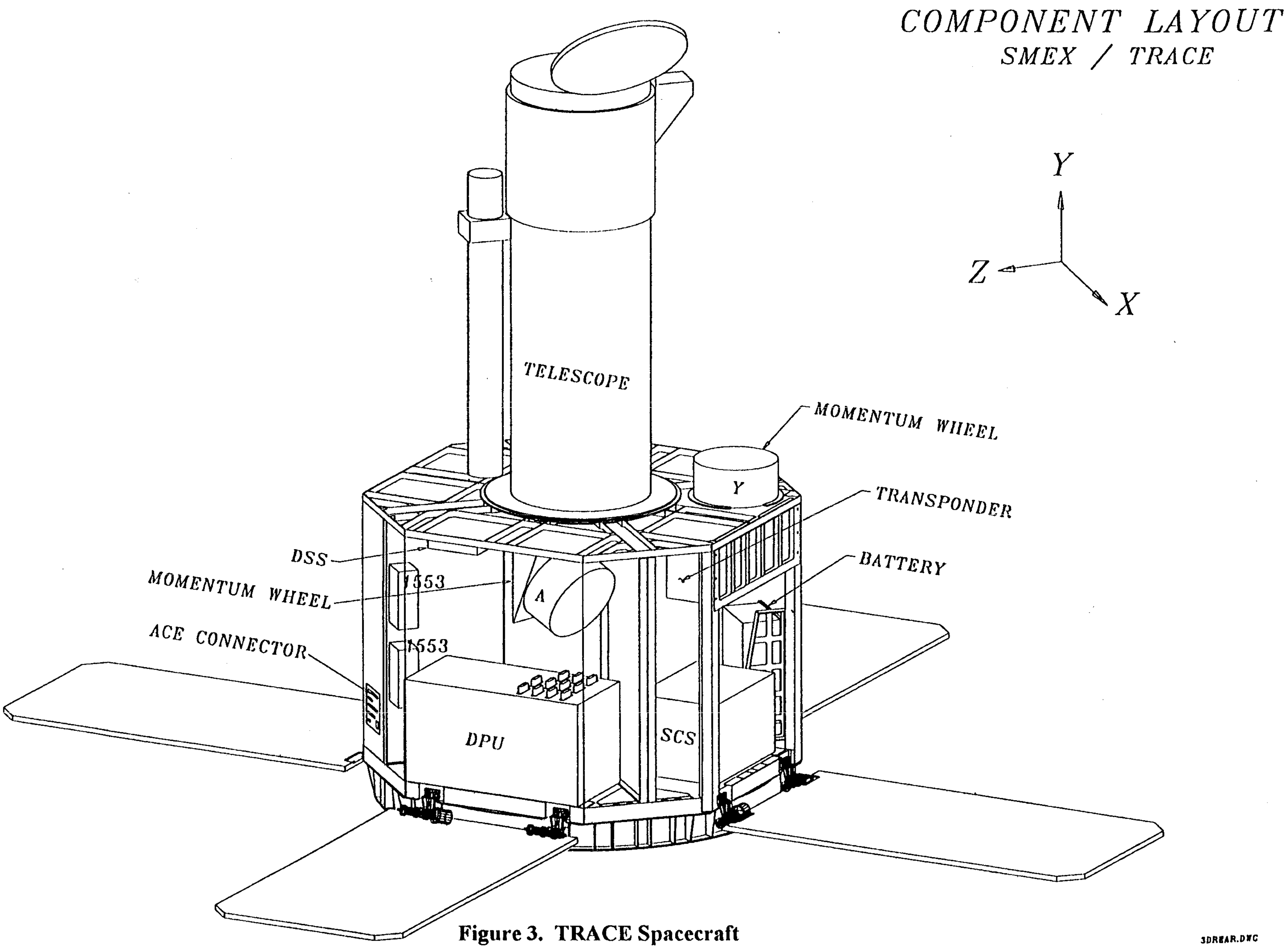
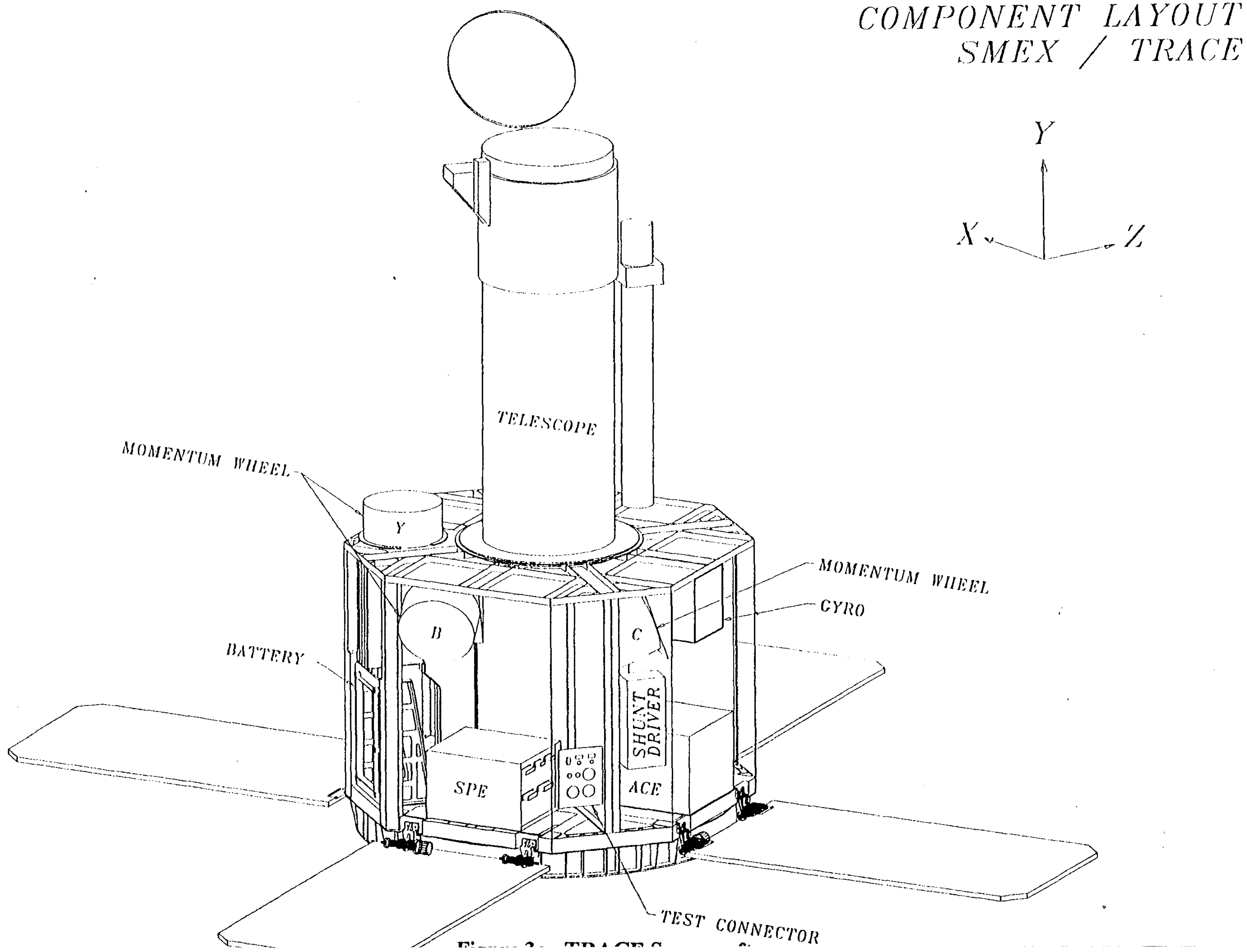


Figure 3. TRACE Spacecraft


COMPONENT LAYOUT
SMEX / TRACE
Y
X
Z
TELESCOPE
MOMENTUM WHEEL
Y
MOMENTUM WHEEL
GYRO
BATTERY
B
C
SHUNT DRIVER
SPE
ACE
TEST CONNECTOR

prism angles. The spacecraft continuously nulls the errors from the photodiodes to keep the spacecraft and hence the main telescope pointed at the appropriate offset while keeping the solar disk aligned to the guide telescope boresight. In order to remain in the linear region of the photodiodes response, wedge steps are required to be below 80 arc seconds each. Once the error falls below 20 arc seconds the Image Stabilization System (ISS) actively controls the secondary mirror using the same photodiode error signals.

Data Processing Unit

The TRACE DPU controls the CCD camera, the guide telescope, all of the mechanisms and sensors, and also provides the interface to the spacecraft data system. The TRACE DPU consists of 22 electronics boards, weighs about 15 kg and uses 25 watts of power. The DPU is responsible for all instrument commanding and telemetry generation. It uses an image processor in custom silicon; based on a bit-sliced architecture. An 8086 processor is the central controller for the DPU and interfaces with the spacecraft computer over the MIL-STD-1553 bus. The DPU contains limited memory but controls data storage in the spacecraft bulk memory.

5. SPACECRAFT SYSTEMS

Mechanical

The TRACE mechanical structure is aluminum. Casting the structure is being considered. Current studies show that casting is competitive cost wise while offering advantages of greater rigidity for comparable or less weight. Currently the structure is estimated to weigh approximately 47.5 kg. Figure 3 and 3a shows the integrated TRACE spacecraft and telescope with deployed solar arrays. Figure 4 shows the stowed arrays inside the Pegasus fairing. Table 1 gives the current weight and normal operating mode orbit average power estimates for the TRACE subsystems.

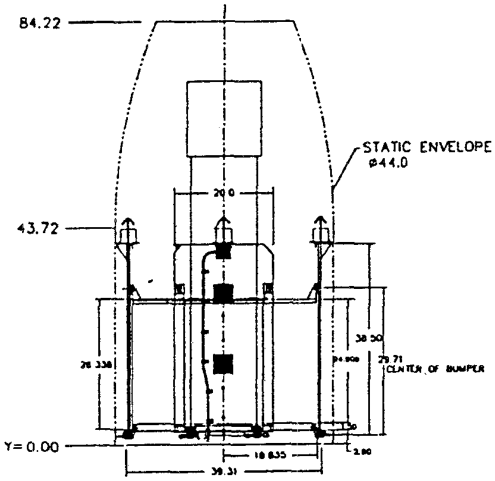


Figure 4. Solar Array Stowed

The TRACE structure derives its lightweight strength from its thrust tube and shear plate main structure design (see Figure 5). The TRACE telescope will be attached to the spacecraft through two attachment rings. The lower ring absorbs primarily the axial and thrust loads. The top ring is designed to absorb primarily the shear loads. The top spacecraft ring is matched drilled to the telescope at the time of spacecraft integration. This prevents the spacecraft structure from inserting torsional loads into the telescope at integration.

Power

The TRACE spacecraft requires approximately 200 watts of orbit average power. This power is provided from four

Table 1. TRACE Mass and Power

COMPONENT	MASS (lb)	Avg Pwr (W)
DATA SYSTEM	22.00	20
-SPACECRAFT COMPUTER SYSTEM (SCS)	20.00	20
-1553 DATA BUS COUPLER	2.00	
POWER SYSTEM	75.92	13.2
-SPACECRAFT POWER ELECTRONICS (SPE)	17.58	13.2
-SHUNT BOX 1	3.48	20
-BATTERY (9 AMP HR)	24.86	6
-SOLAR ARRAYS 4 panels	30.00	
ATTITUDE CONTROL SYSTEM	74.34	50.5
-ATTITUDE CONTROL ELECTRONICS (ACE)	21.34	33
-MAGNETOMETER (ON TELESCOPE)	0.50	0.1
-MOMENTUM WHEELS 4 ea.	30.32	4.4
-X TORQUE RODS 3 ea.	9.36	0.3
-GYRO BOX	10.66	12
-COARSE SUN SENSOR (CSS) (6)	0.22	
-DIGITAL SUN SENSOR (DSS) (ON TELESCOPE)	0.60	
-DSS ELECTRONICS	1.34	0.7
COMMUNICATIONS SYSTEM	9.74	6.5
-TRANSPONDER	8.90	6.5
-ANTENNA A	0.42	
-ANTENNA B	0.42	
THERMAL SYSTEM	11.50	25
-THERMAL BLANKETS	5.50	
-BATTERY RADIATOR AND BRACKET	6.00	
Spacecraft Heaters		25
ELECTRICAL SYSTEM	26.23	0
-TEST CONNECTOR PANEL	1.23	
-HARNESS	25.00	
STRUCTURE	104.50	0
MECHANISMS	17.00	0
-SOLAR ARRAY ATTACHMENT (4 HINGE LINES)	8.00	
-SOLAR ARRAY RELEASE MECHANISM	9.00	
PEGASUS	10.45	0
-38" PAYLOAD ATTACHMENT FITTING	8.70	
-Y-HARNESS	1.50	
-CONNECTOR COVERS	0.25	
TRACE INSTRUMENT (TOTAL)	122.08	69
-TRACE TELESCOPE (INC GUIDE & CCD ELECTRONICS)	78.93	4
CCD Electronics		7
-TRACE HARNESS	8.98	
-TRACE DPU	34.17	25
Instruments Heaters		33
TOTAL lbs. and watts	473.76	184.2
Plus margin	548.55	221.04
Total kg	249.3	

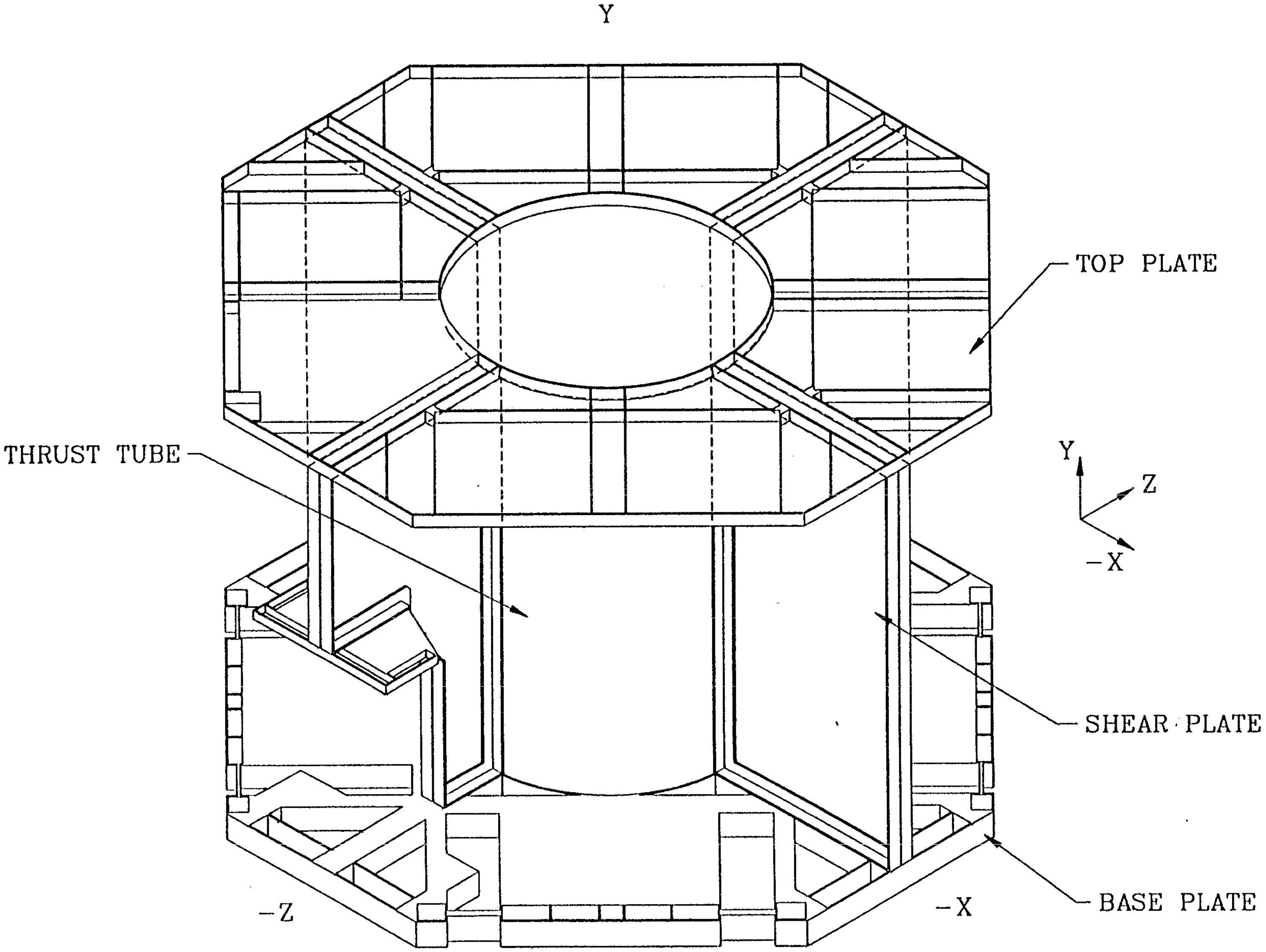


Figure 5. TRACE Primary Structure

solar array panels which provide a total of 1.89 square meters of solar cell area. The solar cells are approximately 18% efficient Gallium Arsenide on Germanium. Each panel is capable of producing 75 watts at 28 degrees Celsius. With normal operating temperatures around 80 degrees Celsius the array power turns out to be 265 watts at Beginning Of Life (BOL) and 229 watts at End Of Life (EOL).

There will be a few experimental multi-junction solar cells on the TRACE mission. These cells will not contribute power to the spacecraft. The power they produce will be contained in a closed loop and monitored to determine on-orbit efficiency and degradation. These experimental cells will be placed near the base of each solar panel near the hinge line. This will be an area where primary cells will not be placed because they could be shadowed during safehold. In safehold, the spacecraft might cone about the sun axis by 17-25 degrees. During normal operations TRACE will be fixed on the sun axis by better than 1 degree.

The power on TRACE is managed by the Spacecraft Power Electronics (SPE). TRACE is a Direct Energy Transfer (DET) system. This means the battery sits directly on the bus and the SPE must regulate the power levels from the array in order to power the spacecraft, charge the battery, and regulate the bus voltage. The bus voltage is specified at 28 ±7 volts. The SPE also fuses, distributes, and switches power to the spacecraft. There is a voltage/temperature charge controller as well as an amp-hour integrator. In addition, the SPE may operate with full autonomy from the data system during safehold.

The SMEX approach to reuse also includes evolution and the introduction of enhancements. As an enhancement to the SWAS architecture, the TRACE SPE replaces the hard to procure power distribution relays with Field Effect Transistor's (FET's). Some of these FET switches incorporate a new software resettable circuit breaker function. Unfortunately, cost constraints require that the new switching board be a one-for-one replacement of the current SPE relay board. This prevents the introduction of a more advanced software selectable trip point functions for the circuit breakers as well as inclusion on all channels. The more advanced design in the next generation SMEX architecture called SMEX•Lite utilizes these enhancements fully. [5]

The TRACE architecture also introduces some improvements over the SWAS solar array power shunting. The new design utilizes partial array shunting. In this architecture a center tap point is brought out on each array string. The tap is actually between cells 30 and 31 in a 49-cell string. This prevents reverse polarization. The strings are grouped into eight controlled partitions. Each partition is shorted as needed to regulate the bus voltage to a prescribed set point. Shorting the current into the first half of the array limits the current that can flow into the second half. This allows for regulating the complete array by only controlling half the current. The power dissipated in the controlling circuits is [I^2*R]. Thus dividing the current by two divides by four the power dissipated. This allows for the removal of the shunts on the back of the solar arrays. This significantly simplifies solar array fabrication, integration and testing.

Thermal Design

TRACE will drop into eclipse within the first six months for approximately 8 to 10 consecutive weeks. During eclipsed orbits the instrument will not gather science data. It will be in a safe mode where only survival heaters are required. In order to reduce the amount of survival heat required the radiators must be carefully located and sized. Survival heaters need to be as small as possible for two reasons: first, because they are not switched off in safehold when power may be critical; and second, because in initial acquisition higher heater requirements would require a larger battery. It turned out that for these reasons surfaces perpendicular to the vector to the sun are better suited for thermal radiators. Although these surfaces will see earth albedo for some portion of every orbit degrading their radiating capability that same albedo will reduce the makeup heater power required during eclipses.

The TRACE telescope is thermally isolated from the TRACE spacecraft. The center of the spacecraft is a thrust tube into which the telescope is mounted. The telescope is lined with Multi Layer Insulation (MLI) to reduce radiative coupling to the spacecraft. Also, the attachment rings are long and thin with insulation bushings if needed to reduce conductive coupling between the spacecraft and telescope. With this isolation 33 watts of instrument heater power is currently needed in order to maintain the telescope isothermally for focusing. Hopefully this number reduces after more detailed modeling and thermal vacuum balance testing. Already, by design, the relationship of the primary and secondary mirrors is held relatively still by three invar metering rods (see Figure 2).

Attitude Control System

The TRACE ACS utilizes an 8085 processor in the Attitude Control Electronics (ACE) box in conjunction with the 80386 processor in the SCS for fine pointing. This provides for a completely digital ACS. Should the main processor fail, the 8085 processor will place the spacecraft in safehold. Also, an analog safehold exist in the ACE as a final safety net for the spacecraft. The sensor and actuator complement are listed in Figure 1.

For maximum reliability the analog safehold should also be able to perform sun acquisition. Acquisition needs to be as quick as possible in order to minimize the battery Depth of Discharge (DOD). However, greater momentum bias about the sun-line combined with slower slewing provides a better safehold. It turns out that, because of the shape of the TRACE telescope, momentum biased about the sun-line is about a minor inertial axis. While this means that losing the momentum wheel about the boresight would put TRACE into a flat spin, it also helps with acquisition. A balance is achieved which allows acquisition with the 9 amp-hour battery and coning off the sun-line in safehold by less than 25 degrees. While somewhat serendipitous, this is quite significant. The next SMEX mission, the Wide-Field Infrared Explorer (WIRE), which has a similar mass, is momentum biased about a major axis of inertia but may need to augment its 9 amp-hour battery for acquisition. [6]

The spacecraft ACS will use the guide telescope as its fine sun sensor. The spacecraft ACS will acquire the sun to within 0.5 degrees using the digital sun sensor before beginning the hand-off to the guide telescope. Once one of the quadrant photodiodes in the guide telescope becomes illuminated, the spacecraft ACS will drive the sun onto the boresight, illuminating the other three. At this point the spacecraft will begin to null the error signals from the guide telescope. As the error drops below 20 arc seconds the Image Stabilization System (ISS) will engage. The investigator will then have control of spacecraft pointing via wedge prism rotations. Effectively the investigator will drive the spacecraft. He can track features across the sun, hunt for sun spots, or create full sun mosaics. The spacecraft will not screen these commands but rather will wait in the background, limit checking and watching for the guide telescope to loose its lock. When this happens the spacecraft will take over again and depending on the circumstances wait for stored or ground commands to get back on schedule.

The guide telescope can not give any information on roll attitude. Therefore the spacecraft must rely on gyro and magnetometer inputs. It turns out that the science data can also help in this area. Correlation of TRACE solar images with images from ground based observatories allows corrections in TRACE roll knowledge to better than 0.1 degrees. This allows for correction of gyro and magnetometer biases on orbit as well as post processed results.

A spacecraft mockup with duplicates of the actual flight torque rods and invar metering rods and other magnetic materials has already been built and tested in the GSFC magnetic calibration facility. This test was done in order to optimize magnetometer placement, study torque rod interactions with the metering rods and study any permanent magnetization effects.

Command and Data Handling

TRACE uses a copy of the SWAS Spacecraft Computer System (SCS). Surface mount technology is used extensively in this box. The processor card utilizes an Intel 386 processor with a 387 co-processor. There is 64k of boot PROM, 128k of boot EEPROM, 384k of flight programmable EEPROM, 1 MB of radiation hard Static Random Access Memory (SRAM) and 128k of RAM shared with the 1553 bus controller. A custom Application Specific Integrated Circuit (ASIC) controls the interface buses and performs Error Detection And Correction (EDAC). An I/O board with a 12 bit A-to-D handles sensor interfaces as well as Pegasus separation signals. There is also a special card which interfaces to the transponder and provides uplink and downlink encoding and decoding. [7]

The TRACE memory card replaced the SWAS memory card with Dynamic Random Access Memory (DRAM). The SWAS memory card contained 110 MB of SRAM. The SWAS memory was the result of a 4-year, $7.4-million ARPA-funded program which produced 3-D memory cubes in 10 MB Multi-Chip Modules (MCMs). Eleven of these modules covered both sides of the approximately 11.5 by 7.5 memory card. The new TRACE modules were developed for LANDSAT and the Small Satellite Technology Initiative (SSTI) and contain 20 MB per module. Fifteen modules can be placed on one side of the memory board for 300 MB total. The back side of the board was not populated because the downlink rate of 2.25 Mbps prevented sending that much data to the ground within a reasonable pass duration. The new modules were configured with 8 bits of onboard EDAC and were designed to be routinely scrubbed for Single Event Upsets (SEUs). This DRAM is an order of magnitude cheaper than the SRAM and the next upgrade a 40 MB module is already being produced.

6. GROUND SYSTEMS

A study is currently under way to determine what the final TRACE ground system architecture will look like. A strong emphasis is being placed on a single system for use in the development, integration, and operational environments. Standardization of interfaces is key in achieving this. The current plan is to move away from NASCOM protocol to the industry standard TCP/IP. This should be in place for the TRACE mission between GSFC, Wallops Flight Facility, and Poker Flat, Alaska. Some backwards compatibility to NASCOM for DSN is still required.

Currently the TRACE instrument team has a development system based on the MDI SoHO system. In order to maintain the rapid delivery schedule, this system will be used for instrument development. However, the spacecraft team will go to the experimentor's and integrate the ground system before delivery of the instrument. This will include converting to STOL procedures. In future missions the plan will be to have the SMEX ground system advanced enough to allow the experimenter to develop on it from the beginning and use that same system through the end of the mission.

The TRACE EOF will be near the SoHO EOF at GSFC. TRACE will be operated somewhat as if it were another instrument on SoHO. Many members of the science observation team will be on both missions.

As part of the new ground system architecture, the TRACE science team will perform Level Zero Processing (LZP) for the first time. The GSFC operations team will provide the equipment and training for the eventual transition of the LZP responsibility to the TRACE science team.

The TRACE science team will make their data available to the public without delay. The TRACE Principal Investigator (PI) will make the TRACE solar images available daily on the Internet a remarkable feat. Additionally, all of the software developed to study the data, complete with users guides, and all the calibration data will be available.

7. CONCLUSION

The TRACE mission exemplifies the SMEX charter to provide quick turn-around mission capabilities to the space physics community. The TRACE instrument and spacecraft start with mature building blocks and recombine them into a different application for a unique new science gathering capability. At the same time innovative new technologies and architectures are blended with the old to enhance a continually evolving program.

TRACE will incorporate new ground system architectures, enhanced pointing systems, improved power systems, and more capable switching technologies. TRACE scientists will do their own data processing and make the data available daily via the Internet. TRACE will have pointing stability to 0.1 arc seconds and generate nearly half a gigabyte of data daily. These attributes in this cost class would not have been considered a few years ago. However, after TRACE launches, they will become the stepping stones of the new SMEX•Lite architecture and the next generation SMEX missions.

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Joe came to NASA in 1985. He developed the command generator and high-speed data ingest ground systems for the Cosmic Background Explorer (COBE). He also developed the flight Command and Telemetry Terminal (CTT) for the Small Explorer Data System (SEDS) the first 1773 fiber-optic data system on orbit. He has also developed numerous other avionics including the Earth Observing System (EOS) Capillary Advanced Pump Loop (CAPL) data system. This system recently flew successfully on the Space Shuttle Endeavor- STS 69. He has a BSEE from the University of Maryland.