The SWAS, TRACE, and WIRE
Attitude Control Hardware Design

Keith A. Chamberlin, NASA Goddard Space Flight Center, Greenbelt, MD 20771
Keith.Chamberlin@gsfc.nasa.gov 301-286-2580

Thomas E. Correll, NASA Goddard Space Flight Center, Greenbelt, MD 20771
Thomas.Correll@gsfc.nasa.gov 301-286-6047

Abstract. This paper will address the authors' experience with the current SMEX (SMall EXplorer) ACS (Attitude Control System) hardware design. The authors have been responsible for the design, development, fabrication, and testing of all the in-house ACS hardware for the common design which will fly on the SWAS (Sub-Millimeter Wave Astronomy Satellite), TRACE (Transition Region and Coronal Explorer), and WIRE (Wide field InfraRed Explorer) satellites. These missions have very different ACS requirements which lead to different sensor complements on each mission; however, they are all low-cost, small scientific satellites which require three-axis fine attitude control. It will be shown how the common hardware design which was used has allowed a faster, better, and cheaper solution to the ACS requirements of these three missions.

The standard hardware design includes an interface to a standard set of sensors, drivers for a standard set of actuators, and a hardware safehold mode controller (re-used from SAMPEX – Solar Anomalous and Magnetospheric Particle Explorer - an earlier SMEX mission). The standard sensor and actuator hardware also includes a three-axis inertial package (with a redundant gyro), four reaction wheel assemblies, and a magnetometer. The remaining ACS sensors and actuators are procured hardware. The in-house hardware includes a 8085 microprocessor to perform formatting for a MIL-SID-1553B interface with the main spacecraft computer (80386/80387), as well as an analog safehold which is not dependent upon either processor. Although the in-house hardware was configured with the intent to support simpler missions with a reduced hardware set, this capability has never been used.

The paper will also discuss problems encountered in the process of developing and using this hardware. There were a series of difficulties encountered in the initial design and build (SWAS) which were corrected in the later builds; the authors will examine the sources of these problems. In addition, there were a series of initially unplanned requirements which developed for the later builds; the authors will discuss how these requirements were met by adaptation, rather than by redesign. This process led to a cheaper, more robust, and faster development of these later missions (TRACE and WIRE); which, otherwise would have followed the more traditional path to become essentially new designs – with related expenses and risks. Finally, the authors will discuss how this experience has led to the planned development (currently underway) of the next generation ‘SMEX-Lite’ attitude control hardware design.

Acronyms

ACE - Attitude Control Electronics
ACS - Attitude Control System
ADC - Analog-to-Digital Converter
AIAA - American Institute of Aeronautics and Astronautics
B.S. - Bachelor of Science
CSS - Coarse Sun Sensor
DAC - Digital-to-Analog Converter
DC - Direct Current
E.E. - Electronics Engineering
EMI - Electro-Magnetic Interference
ETU - Engineering Test Unit
FAST - Fast Auroral SnapshoT explorer
FET - Field Effect Transistor
GSE - Ground Support Equipment
H/W - HardWare
IC - Integrated Circuit
I/O - Input/Output
LET - Linear Energy Transfer
LSB - Least Significant Bit
M.E. - Master of Engineering
MIL-STD - Military Standard
NASA - National Aeronautics and Space Administration
PCB - Printed Circuit Board
PROM - Programmable Read-Only Memory
PWM - Pulse Width Modulator
RAM - Random Access Memory

Keith A. Chamberlin

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RC – Resistor - Capacitor
RT – Remote Terminal
SAMPEX – Solar Anomalous and Magnetospheric Particle Explorer
SCS – Spacecraft Computer System
SEU – Single Event Upset
SMEX – Small EXplorer
SPE – SMEX Power Electronics
SWAS – Submillimeter Wave Astronomy Satellite
S/W – SoftWare
TRACE – Transition Region And Coronal Explorer
TRIG – Tuned Restraint Inertial Gyro.
VDC – Volts Direct Current
WAES – Wide Angle Earth Sensor
WIRE – Wide-field Infra-Red Explorer

**Introduction**

The Small EXplorer (SMEX) Project is a NASA program for building small scientific satellites intended for launch into low Earth orbit by expendable launch vehicles. To date, all SMEX satellites have been built in-house by Goddard Space Flight Center, and have carried out-of-house experiments.

The existing SMEX missions, in order of construction, are the Solar Anomalous and Magnetospheric Particle EXplorer (SAMPEX), Fast Auroral Snapsho.T (FAST) explorer, Sub-millimeter Wave Astronomy Satellite (SWAS), Transition Region And Coronal Explorer (TRACE), and the Wide-field Infra-Red Explorer (WIRE). In each case, the selected SMEX missions have required (and delivered) more capability than was believed possible in a satellite with the given budget and weight.

Additionally, the SMEX team is currently designing a standard spacecraft bus called SMEX-Lite that will have even lower weight and cost, and at least maintain the performance. Responses to an existing Announcement of Opportunity are currently being evaluated, and may yield additional SMEX missions using the new SMEX-Lite architecture.

Four of the five existing SMEX missions (FAST was the exception) have used a common system architecture for the satellite bus (see figure 1). This SMEX architecture is designed around a central 80386-based processing unit (called the Spacecraft Computer System, or SCS, for SWAS, TRACE, and WIRE), which communicates with remaining spacecraft hardware over a MIL-STD-1553B data bus. The Attitude Control Subsystem (ACS) includes control algorithm software running on this 80386, a hardware interface box (called the Attitude Control Electronics, or ACE), and assorted sensors and actuators.

This paper is principally concerned with the in-house Attitude Control System electronics design for the SWAS, TRACE, and WIRE missions. Some of this hardware was re-used from the SAMPEX mission; the remainder of the hardware was designed for SWAS, and re-used with some minor modifications on the TRACE and WIRE missions. Reuse of hardware

![SMEX Spacecraft Architecture](image)

Figure 1. SMEX Spacecraft Architecture

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Table 1: SWAS, TRACE, and WIRE Sensor and Actuator Complements

<table>
<thead>
<tr>
<th>ACS Component</th>
<th>SWAS</th>
<th>TRACE</th>
<th>WIRE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Three-Axis Magnetometer (in-house build)</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Coarse Sun Sensors (Adcole)</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Digital Sun Sensor (Adcole)</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Bright Object Sensor (Adcole)</td>
<td>1</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Wide Angle Earth Sensor (Servo Corporation)</td>
<td>-</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>Instrument Guide Telescope (Stanford Lockheed Institute for Space Research)</td>
<td>-</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Star Tracker (Ball Aerospace CT601)</td>
<td>1</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Magnetic Torquer Bars (Ithaco)</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Gyros (Textron gyros with in-house servo electronics)</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Reaction Wheels (in-house build)</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

Designs to any extent practical will generally save money, manpower, and schedule, and also reduce risk.

The SWAS ACS design takes some advantage of reuse, by using two cards from the SAMPEX design. In addition, the SWAS ACS design uses multiple identical copies of circuits wherever practical to reduce cost and risk.

In the case of TRACE and WIRE, where the ACS reused the SWAS hardware design almost completely, a substantial amount of money, time, and manpower was
saved. This extensive re-use allowed elimination of most costs associated with coding and debugging new ACS interface software and test procedures, designing and debugging new ACS hardware, and coding and debugging new ACS analysis models for the hardware.

In addition, the TRACE and WIRE hardware was built simultaneously, which allowed increased savings due to the ability to share resources between the two builds.

**The SWAS Hardware Design**

The SWAS mission requires an extensive complement of Attitude Control hardware (see figure 2): a star tracker, a three-axis inertial reference package, a magnetometer, a complement of sun sensors (including a bright object sensor for instrument safety), three magnetic torquers, and four reaction wheels. The star tracker interfaces directly via the MIL-STD-1553B data bus; the remaining sensors and actuators require interface hardware to connect them with the data bus. The full sensor and actuator complement is listed in Table 1.

The SWAS in-house hardware build includes the magnetometer, the reaction wheels, the gyro pack (which contains gyro's built by Textron), and the ACE box. Hardware supporting each of the in-house sensors and actuators is divided between the ACE and the sensor or actuator itself in such a fashion as to minimize the interface between the two.

Many SWAS design decisions were made with re-use in mind; although, the lack of knowledge of the requirements (and selection) for any future missions hampered this process. The division of functions among electronics cards makes it relatively easy to build a smaller, lighter, and lower power box for any future mission which requires less wheels, or does not require gyro's.

Two cards (the micro-processor and the safehold) are also re-used from SAMPEX with minor modifications. In addition, several sensors (the sun sensors and magnetometer, and their interface circuits), are re-used from the SAMPEX design. The torquer bars are also similar to those used for SAMPEX.

**The ACE Box**

The SWAS ACE Box is a mechanical enclosure that houses 15 electronic card assemblies (see figure 3). An EMI partition separates the power supply electronics from the low level analog and digital signals. The cards in the power supply section are: four Reaction Wheel Power Supplies, three Gyro Power Supplies and a Main Power Converter Card (that is, nine custom DC-DC converters on eight electronics assemblies totaling the size of two 9 in. x 9 in. surfaces). The cards in the signal conditioning section are: an EMI Filter (for power), a Microprocessor (8085) Card, an Acquisition/Safehold Card, a Torque Rod Driver Card, a Reaction Wheel Tachometer Card, a Gyro ADC Card, and the (ACE) Motherboard (that is, a total of five 9 in. x 9 in. plug-in cards, plus a motherboard and the Power Filter). All cards in the signal conditioning section (except the power filter card and motherboard) are plug-in cards; the remaining cards are bolted in, and soldered to the box wiring as they are built.

The signals between the two ACE sections are connected using a harness with feed-through filters to reduce the transfer of noise between the sections. In addition, the electronic assembly placement was selected with emphasis on reducing the potential for EMI problems. The power supply compartment is on the ‘bottom’ of the box (i.e., the mounting surface) for heat sinking purposes. The microprocessor card is the top card in order to allow access to the microprocessor for In-Circuit Emulation, if needed during development.

The only significant deficiency in this system design has proven to be the difficulty of accessing the power supply compartment for debug purposes. This is a consequence of heat sinks (which must be bolted between the cover of the compartment and the body of the ACE box) added late in the design cycle, rather than an inherent basic design problem. The ability to add these heat sinks when components proved hotter than expected is an example of the extreme flexibility of the mechanical design used.

**Microprocessor Card**

The Microprocessor Card (re-used from SAMPEX) contains three main sections: the 8085 microprocessor (including memory, timer, and watchdog), the magnetometer electronics, and the MIL-STD-1553 interface electronics.

The 8085 microprocessor was used because of its combination of flight heritage with high radiation hardness (over 100 Krad, and LET over 20). The memory provided by this design consists of three 8 Kbyte RAM chips and two PROM sockets that can accommodate PROMs of either 2 Kbytes or 8 Kbytes apiece. Two of the 8 Kbyte RAMs are shared memory between the 1553 interface and the microprocessor,

Keith A. Chamberlin

![Figure 3. ACE Box](image-url)
with the remaining one devoted solely to use by the processor. The processor supports a 16-bit I/O data bus on the ACE backplane, and a timer (for time coding data). It also has a watchdog timer (for recovery from single event upsets), a power-up reset circuit, and three interrupts (power-up reset, 1553 access, and a backplane interrupt). The backplane interrupt is devoted to the Gyro ADC conversions on SWAS, TRACE, and WIRE.

The magnetometer circuitry provides the excitation signal required by the core of the magnetometer head, and de-modulates the results to obtain an analog output for each of the four measurement axes (the magnetometer design inherently provides one redundant axis).

The SAMPEX design provided for the connection of a redundant MIL-STD-1773 data bus module. For SWAS, a daughterboard was added (in place of the module) to connect a redundant MIL-STD-1553 data bus for communication with the spacecraft 80386 processor. The ACE is a Remote Terminal (RT) on this data bus, with a permanently jumpered address.

The only additional modification (beyond changing the data bus driver module to a custom daughterboard) made to the SAMPEX processor card was a shift in timer resolution to support the perceived needs of the gyro design.

At the time of the SWAS build, the (rad-hard) 8K byte PROMs were not yet available, and the result was severely limited program space (4 Kbytes total split into two 2 Kbyte non-contiguous sections). Despite the addition of significant code (for the gyros, and for additional methods - and volume - of data collection), careful management of the software design allowed the results to barely fit in the same space which had been used for SAMPEX.

Re-use of the SAMPEX Micro-processor Card design allowed re-use of most of the ACE software (written in assembly language), with its many test procedures, development tools, and test equipment; it also allowed the use of extensive experience gained during SAMPEX and FAST (which used a different 8085 processor card).

**Acquisition/Safehold Card**

The Acquisition/Safehold card was also re-used from SAMPEX, with some modifications required. The design provides a multiplexed 12-bit ADC, which is used by the ACE for both control signals and housekeeping telemetry. It also provides interface for a ground sensor complement (Digital Sun Sensor, and six Coarse Sun Sensors), and analog control law electronics to implement a basic safehold controller (BDot rate damping with bang-bang control of a single magnetic torquer bar to provide sun pointing control). In addition, the card provides several miscellaneous features: a hardware signal indicating safehold control, a spin/despin controller, and a ‘loop-back’ to allow substitution of test magnetometer signals.

This card is designed to provide processor-independent power and thermal safe spacecraft attitude control, and is also used for initial attitude acquisition after injection into orbit. It does not provide any orientation control around the sunline (for SWAS and WIRE, this means that the instrument boresight is not controlled with respect to the Earth). The control law used assumes that the spacecraft has a net +Y momentum (normally stored in a reaction wheel which must be controlled by another card).

Since the SWAS mission has significantly different mass properties and actuator scalings from the SAMPEX mission, the resistor values for the analog gains had to be adjusted. Also, the addition of a sixth CSS required the addition of pins to the interface connector (because SAMPEX did not have this sixth CSS, the card does not have a sun presence detection tripped by the sixth CSS). The safehold timer was also modified to allow the use of a new redundant timer (placed on the Torque Rod Card). Otherwise, the Acquisition/Safehold Card was completely re-used as on SAMPEX.

**Torque Rod Driver Card**

The Torque Rod Driver Card provides all additional signal processing functions which would be required by a SAMPEX-style mission (one with two or less reaction wheels, and no gyros). It provides support electronics (tachometer timers, power supply control, low voltage switching, and a 12-bit torque control DAC) for each of two reaction wheels, one with a bang-bang safehold speed control to a solder-jumper configurable speed. In addition, it provides magnetic torquer bar drivers for three magnetic torquers (switched between hardware control for the analog safehold, and DAC control for normal operations). It also provides a redundant safehold timer, multiplexing of assorted housekeeping signals, and some thermistor conditioning (including a box temperature measurement with a thermistor on the case).

This card was a fresh design for SWAS; however, the conceptual design, and many circuit fragments were copied from successful SAMPEX experience. In addition, multiple functions (two wheels, and three magnetic torquers) were built using the same design (which only had to be debugged once).

Some problems were encountered in designing current-limited power switching circuitry for this card (which was then copied onto the Reaction Wheel Tachometer Card).
Card, and the Gyro ADC Card). The primary problem appears to have resulted from an attempt to mix too many functions into a single circuit. While this eventually worked, it would have saved money and time to use multiple circuits with a clean differentiation of functionality between the current limits and the power switches (this would also have allowed the switches to be interlocked more optimally).

**Reaction Wheel Tachometer Card**
The Reaction Wheel Tachometer Card is very similar to the Torque Rod Driver Card in design. It does not have the magnetic torquer bar drivers, or safehold control circuitry, but does still have support for two additional reaction wheels. Also, there is additional housekeeping I/O on the Reaction Wheel Tachometer Card, including support for an seventh Coarse Impulse Driver Card in design.

This card is also a fresh design for SWAS. Many observers have commented on the unusual division between the two (Torque Rod Driver and Reaction Wheel Tachometer) cards: the Torque Rod Driver is very tightly packed, while the Reaction Wheel Tachometer is sparse. This division was accepted as necessary to support re-use on future missions which might only require a reaction wheel (or two).

Although most of the circuit designs were copied from the Torque Rod Driver Card, differences in layout led to EMI problems on this card which had not been encountered in the Torque Rod Driver Card. These EMI susceptibilities were then fixed on both card designs.

**Gyro ADC Card**
The Gyro ADC Card provides a 16-bit, 8-channel current ADC for the gyro signals; the 8 channels are used to provide two measurement axes for each gyro, and two reference channels for calibration. It provides low voltage power switching and power supply control (including a 12 bit voltage DAC) for each of the three gyro sensors in the SWAS ACS. It also provides housekeeping interfaces for many gyro signals.

At the time of the SWAS design, there were no 16-bit ADC's available on the market which satisfied the SMEX program SEU requirements. Thus, the SWAS Gyro ADC Card is a custom multiple-slope integrating ADC design with built-in multiplexing and filtering. Conversion of two redundant reference channels allows elimination of most systematic errors from the null of the ADC.

The SWAS Gyro ADC design had a number of anomalies which were accepted (with software corrections to minimize the impact) due to schedule constraints. It is worth noting that only extensive testing uncovered these anomalies - in at least one case, a low probability glitch led to a completely erroneous reading on one in approximately three hundred thousand conversions at room temperature; however, the frequency increased significantly when the box was taken to temperature extremes. If undetected, this could have caused unexplained control noise, and it would have been almost impossible to track down (or fix) in flight.

**Power Filter Card and ACE Motherboard**
The Power Filter Card receives unregulated 28 VDC power from the spacecraft power system. The filter is a passive EMI filter built in three sections. There are two differential-mode filters, and a single common-mode filter. Each of the two large capacitor banks required has active 6 A inrush current limiting, with the timing adjusted to not overlap any other such inrush within the ACE.

The ACE Motherboard is a 192 pin backplane which supports the five plug-in cards. For debug purposes, the pinout of the backplane has been divided into two (keyed) sections of duplicate card slots. Thus, a card can be moved to verify that the problem is not a backplane connector. In addition (with a few exceptions due to a shortage of pins), all signals are passed on two shorted connector pins to reduce the likelihood of a backplane connector causing a failure.

Both of these cards were fresh designs for SWAS, although the backplane connectors (and pinout in one section) were the same as for SAMPEX (allowing reuse of plug-in cards).

**Main Power Converter Card**
The Main Power Converter Card contains two custom low voltage DC-DC converters. A large internal capacitive filter bank has active inrush limiting set to avoid overlap with the Power Filter Card inrush peaks. A push-pull DC-DC converter provides +12 VDC (referenced to the primary ground) and -5 VDC (referenced to the primary ground) for use in the PWM ICs in the nine ACE power converters. This converter also provides ±7.5 VDC (referenced to the secondary ground), which is used to drive the magnetic torque bars. A forward converter supplies the +5 VDC and ±15 VDC (both referenced to the secondary ground) for most of the ACE circuitry. There are post-regulators on the ±15 VDC outputs to improve the stability over line, load, and temperature (these voltages are used extensively in the sensitive gyro electronics). There are also current monitors provided on the +5, +15, and -15 Volt outputs for telemetry purposes (there is a complete complement of voltage and current monitors on all
supplies, except the +12 and -5 primary PWM supplies, which are spread among the ACE cards as space allowed).

**Reaction Wheel Power Supply**

The Reaction Wheel Power Supply design is an energy recovering switching power supply with a forward-mode Buck topology and recovery-mode Boost topology that operates at 125 kHz. The output is a variable voltage (between 0 V and the power bus voltage) referenced to the primary ground, and adjusted to provide a commanded current.

The card contains an inner voltage feedback loop, with an outer current control loop to maintain the commanded reaction wheel current (±2.2 A) as long as possible (the output voltage is limited to a range between the two primary power rails). In addition, the card has an active current limit, an overcurrent shutdown, and an ON/OFF circuit.

The ON/OFF circuit can be configured (by installation of corresponding passive components) to operate in a normal fashion or in a repetitive restart mode. This allowed all four wheels (one of which required an automatic reset of the over-current shutdown, and three of which did not) to be built using a single design. In addition, splitting the four supplies into four cards allowed savings in required test equipment and debug time (the four cards are identical except for the jumper configuration).

This was a fresh design for SWAS. A number of problems were encountered and fixed in this unusual design, mostly relating to thermal issues and EMI. The results of these design problems caused the circuit to go through two separate incarnations before the flight build: a breadboard, an ETU, and then a complete relayout for flight.

An additional system problem was encountered, in that the intentional ability to return power to the spacecraft power bus (during deceleration of the wheel) could lead to over-voltage conditions on the spacecraft power bus during testing. This led to careful restrictions during testing to ensure that no such destructive event would occur (it didn’t).

**Gyro Motor Power Supply**

This power supply also operates at 125kHz, and is a forward converter topology. The outputs are ±18-36 VDC with a floating reference (connected to the gyro pack ground). The design was duplicated for three separate cards to supply the three gyro's.

Schedule shortage required acceptance of several anomalies in the performance of this card. The main core is susceptible to overheating in the event of a short-circuit, and was protected using the ACE software. In addition, susceptibility to load transients inherent in commutating the gyro motor led to a higher voltage ripple than desired.

**The Gyro Pack**

The Gyro Pack (see figure 4) is a mechanical enclosure that houses three two-axis Tuned-Restraint Inertial Gyros (TRIGs) and six electronic assemblies. The electronic assemblies are three Servo Cards, one Gyro Commutation Card, one Gyro Excitation Card and one (Gyro) Motherboard (that is, a total of five 5 in. x 5 in. cards, and a motherboard). All of these cards were fresh designs for SWAS (although they are based upon experience from prior spacecraft); thus, they predictably encountered minor design problems that impacted schedule and budget.

The gyros are mounted such that each spin axis is aligned to a different spacecraft axis. Since each gyro provides two axes of information, this means that a single gyro failure will not prevent acquisition of full gyro rate information for science control. In order to save power, only two gyros are powered at a time (except for early orbit checkout before the instrument is turned on). The substitution of a failed gyro with the redundant unit would be performed only by ground command.

For the maneuver profile of the SWAS mission (nominally rapid maneuvers of up to three degrees separated by forty-five second pauses, with a few large angle maneuvers thrown in), the scaling error becomes the most critical gyro error. Drift will be reset at every target; scaling errors accumulate much faster during maneuvers, and may lead to missed targets (and associated invocation of safing modes).

Fine gyro temperature control is critical to reducing the scaling error; it is accomplished using a non-linear integrating control law built into the ACE software. This control law proved to be a difficult task due to the combination of noisy measurements, large time constants in the gyro response, and the desire for better
than 1 LSB control of the results; however, it was accomplished within the available 8085 (integer) processor, and the restricted code space available.

**Gyro Servo Card**

There are three Gyro Servo Cards; each card contains two servo loops. Each card supports one two-axis gyro unit. Extensive experimentation went into the simplification of the servo circuitry to reduce potential error sources. Although the resulting circuits were derived from existing SPARTAN servo circuit designs, the results are sufficiently different to present different problems.

Significant time and manpower were lost in the debug and trimming of these cards due to inadequate test equipment (which was still on order at the time) and poorly developed test procedures (the experienced personnel were tied up solving more urgent problems). This sort of shortage of equipment and experienced manpower is inherent in any low-cost program where extensive new designs are attempted.

Again, building three identical copies of the circuit reduced cost and risk. However, some noise problems were encountered due to the inability of the output stage to adequately follow the back EMF of the gyro torquers.

**Gyro Commutation Card**

This card separately commutates 2-phase Gyro Motor Power for the operation of each of the three gyros. The two 400 Hz control signals from the Gyro Excitation Card are common to all three output circuits. Mistaken layout of FETs (the layout had the FETs right side up, when they needed to be upside down to allow for heat sinks) led to the need for relayout of this card (the FETs would only fit on the one side of the card, and they could not be heat-sunk unless upside down); otherwise, the design was straightforward.

**Gyro Excitation Card**

This card provides assorted common functions required for the gyro circuitry. This includes three 48 kHz sine wave generators for driving the gyro pickoff sensors, two 400 Hz square wave control signals (with a 90° phase difference) for the Gyro Commutation Card, and ±2.5 VDC voltages for Gyro Servo power. Both frequencies are derived from a single crystal oscillator to achieve the required stability.

**Gyro Motherboard**

This card contains five 56 pin Airborne connectors (with three different keyed pinouts). Signals are carried on redundant pins to reduce risk of backplane and connector failures. This analog backplane was designed so that the grounding point for the Gyro Pack can be jumper configured to the lowest noise configuration.

The Reaction Wheels

The SWAS Reaction Wheels (see figure 5) were built in-house due to a lack of suitable wheels available on the commercial market within the SMEX price range at the time of the initial SWAS design.

Each of the four SWAS Reaction Wheel assemblies includes a motor, a spinning mass (flywheel), and associated drive electronics for the motor. The motors used are three-phase brushless DC motors, commutated on the basis of redundant hall effect devices built into the motors. These same hall effect devices are used to provide speed and direction measurements. Rad-hard hall effect devices were provided to the motor vendor to substitute during their manufacturing process. The units are sealed to avoid problems with outgassing lubricants from the motor bearings.

Each Reaction Wheel contains one Reaction Wheel Commutation Card (a card in the shape of an annular ring built to fit the housing), which provides a hall effect decoder, a three-phase motor commutator, a pressure sensor, a thermistor, and some power filtering. Commutation is supported in either direction. Thus, the ACE software can control the commutation and current setting to allow full four-quadrant operation of the wheel. In addition, the wheel supports use of either hall effect set which allows switching by ground command in the event of a hall effect failure.

SWAS ACS Hardware Development Effort

The design and development of the SWAS ACS hardware clearly demonstrated a number of points concerning the economical development of space hardware. Rating the circuit designs by the time, money, and manpower they required, fresh designs cost more than design modifications, which cost more than relayouts of existing designs; and, obviously, re-builds of existing designs cost the least. The surprising thing about this is that it remained true regardless of the relative complexity and difficulty of the functions: fresh designs of simple circuit functions cost more than modifications of existing circuits for complex functions.
Breadboard Development
As experienced in the SWAS ACS hardware design and development, breadboard experimentation remains far more critical and accurate than simulation. There were a number of SWAS circuit designs which benefited during the breadboard process either because design failures were corrected, or because the circuits were simplified greatly.

Several potential circuits were shown to work well by simulation; and, then, failed at the breadboard stage. The prime two examples of this experience were the early designs for control loops for the Gyro Motor Power Supply (where simulation used the wrong style of magnetics model, and therefore failed to detect instability), and the Reaction Wheel Power Supply (where simulation ignored motor generated disturbances that led to instability in practice). In both cases, the designs could have been produced more cheaply and worked better, if there had been less reliance on simulation (and more on breadboard experimentation) in the early design development.

Several other potential circuits, which simulation had ‘proven’ necessary, turned out to be detrimental as demonstrated by the breadboards (for example, the 200 Hz ‘notch’ filter in the gyro servo circuit). In addition, sometimes, adequate simulation models were simply unavailable (that is, anyone who had done good enough testing to get a good simulation model, in the region of concern, was not talking about it).

By breadboarding all the new circuit designs, and testing them thoroughly, most of the major design problems were eliminated at an early (cheap) stage of the design flow.

ETU Development
After breadboards, the SWAS ACS hardware design and development proceeded to the Engineering Test Unit (ETU) phase. During this phase, a complete prototype system was built up, and subjected to testing (without much regard to the possibility of circuit damage caused by the testing). This ability to perform ‘high risk’ tests allowed the detection and correction of a number of problems (such as subtle software timing issues), which otherwise might have gone undetected until late in the flight test sequence.

Some design and layout problems were found that required major circuit changes to meet requirements. The most notable of these was the reaction wheel power supply, where changes in personnel had led to misunderstanding of the requirements, and of the existing incomplete design.

In the ideal world, there should be no need for a separate prototype (from the flight unit); however, the SWAS ACS hardware definitely benefited enormously from this ETU stage. In addition, the later TRACE and WIRE work benefited from having the SWAS ETU available as a test-bed.

Flight Unit Development
Even with the flight unit being the ‘third build’ of the new circuit designs, there were many significant design problems uncovered during the flight build. The presence of the ETU (which was form, fit, and function compatible with the flight unit) allowed for correction of these problems with less major impact on the flight schedule. Once a problem was known and a solution selected, the ETU could be fixed, and changed out for the flight unit; then, the flight unit could be fixed, and returned to the spacecraft. During this process, the time spent fixing either box could generally be used by other sub-systems for their debugging in parallel; if there had been no ETU, this would not have been possible.

To give a fair impression of this testing process, thorough testing of the flight ACS hardware revealed over 50 different anomalies that were accepted. In several cases, these anomalies required ACS software changes to prevent them from causing problems in orbit. By finding these anomalies on the ground, the team was able to pin them down quickly using intrusive methods unavailable in orbit, test their adaptations without risk to the SWAS mission, and then apply more thorough fixes to the TRACE and WIRE builds from the start.

The TRACE and WIRE Hardware Designs
The Phase A/B design of the TRACE and WIRE missions yielded two different ACS systems (which were also different from the SWAS ACS). When the TRACE design was handed off to the development team, the team realized that the design and fabrication of the TRACE system would call for a lot of manpower that was not available, and would probably cost more money than the SMEX project could spend. Comparing the requirements of the WIRE mission with SWAS, the team concluded that they were almost identical; as a result, it was decided to rebuild the SWAS ACS for WIRE. The team also felt that it would save time and money to rebuild the SWAS ACS for TRACE (including components which were not strictly required for the TRACE mission).

In this fashion, all of the requirements would be met for both missions. Although there would be more weight and power than originally budgeted for the TRACE ACS, the total spacecraft budget could still handle this system. With this philosophy TRACE would always have a board (or box) available to be used in case of a major problem that could impact the schedule.

Table 1 shows the differences in sensors and actuators.

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required by each mission; figures 6 and 7 show the placement of the ACS System components for each mission. The TRACE mission uses a Guide Telescope, which is provided by the instrument team, like the SWAS Star Tracker, for its fine pointing. Likewise, the WIRE ACS requires a Star Tracker for precise instrument pointing. More about the use of these items and the associated accuracies can be found in the references.

**Modifications to Meet Mission Requirements**

The WIRE ACS needed additional protection for the instrument to cover the analog safehold mode. The eventual design required a new sensor for this purpose, as well as additional software algorithms (in both the ACE and SCS), and changes to electronic circuitry in the ACE (addition of 3 analog signal inputs). The software and electronic modifications are implemented in both the TRACE and WIRE ACE builds to maintain compatibility. See reference 3 for a more complete description of the WIRE safehold mode design.

Each spacecraft has different inertial properties, and requires a different level of momentum storage for the safehold mode of operation. Because of this, all three missions have different safehold speeds for the Y-axis reaction wheel. The required safehold moments are 2.84 N·m·s (SWAS), 0.91 N·m·s (TRACE), and 1.84 N·m·s (WIRE) and the respective reaction wheel speeds are 236 rad/s (SWAS), 82.9 rad/s (TRACE), and 153.4 rad/s (WIRE). Using configurable jumpers on the Torque Rod Card made the requirement for different values of spacecraft momentum easy to handle. Other changes due to safehold requirements for different torque rod limits and control gains only resulted in changes in resistor values on the Acquisition/Safehold card.

There is an additional requirement for the WIRE safehold because of the possibility of the WIRE instrument becoming inoperative due to prolonged exposure to any heat source, such as the Sun or the Earth. The WIRE ACE safehold mode incorporates zenith instrument pointing (WIRE calls it 'Earth Avoidance Safehold', or software safehold), and is controlled by the ACE 8085 microprocessor with inputs from the Wide Angle Earth Sensor (WAES). This mode incorporates the capability to use the three remaining reaction wheels, in the case of a failure of the +Y axis reaction wheel.

Incorporation of the software safehold mode required modifications to the safehold timer scheme as well, since the SWAS design used a hardware timer to lock out all processor control during analog safehold. To provide for this intermediate mode, the existing SWAS timers were split (using white wires) to provide a separate hardware timeout for the software safehold and for the hardware safehold (in event of an ACE processor problem). This required a change in the timing of one of the timers (performed using jumpers provided for the purpose).

Another change in the ACS system design for TRACE and WIRE is the maximum spacecraft slew rate. SWAS required maneuvers of large angles in a short period of time, so the maximum slew rate was designed for 3°/sec. Both TRACE and WIRE require lower slew rates, so the maximum rate was reduced to 1°/sec. This lower rate allows for better resolution and lower noise in the TRACE and WIRE gyro rate measurements. The only hardware modifications required for this were value changes in resistors and capacitors (some on the GYRO ADC card, and some on the Gyro Servo Cards).

The original layout for the SAMPEX Microprocessor PCB allowed for larger PROMs which are used on the TRACE and WIRE missions. The change consisted of installing 2 jumpers per chip to accommodate the larger memory chip; it was required to accommodate the ACE software safehold controller needed for WIRE.

The microprocessor watchdog timer for SWAS has selectable times of 1.0, 2.1, and 4.2 seconds. The desired time is selected by a wire jumper. Unfortunately it turned out that a time of 0.25 seconds was needed to support the software safehold for the WIRE mission. Due to the design having selectable times, the simple addition of an external wire was used to make the modification.
Modifications to Improve Performance
When the SWAS Gyro ADC card was originally tested, it possessed several quirks that were not easily fixed. These quirks were accepted for SWAS, but fixed for TRACE and WIRE. In the process of the resulting re-layout, the performance was also substantially improved. The only price was the requirement for lower noise op-amps (which increased power consumption about ¾ W); the mechanical and electrical interfaces did not change.

The SWAS Gyro Power Supply design is a forward
converter topology, which lacks adequate short-circuit protection, and stability margins at low voltage settings. This card was redesigned for TRACE and WIRE as a flyback converter topology that is inherently current limited. The new circuitry is better compensated to provide stability at the low output settings. In addition, the voltage ripple was reduced, and the efficiency was improved to be greater than 86% at all output voltages. The change required a new transformer, and a new PCB layout. The mechanical and electrical interfaces to this card also did not change.

The TRACE and WIRE missions required the addition of an alignment cube on the Gyro Pack. This was necessary so that the misalignment between the gyro axes and the guide telescope/star tracker axes could be measured with ground-based equipment; this misalignment is needed by the ACS when computing the attitude (for SWAS it is determined through on orbit maneuvers, due to the lack of an alignment mirror on the star tracker).

One last modification was done to the Power Filter card. The SWAS Power Filter exhibited a resonance with the reaction wheel commutation at around 400Hz (and its harmonics). The addition of an RC circuit on the power return from the Main Power Converter lowers this resonant peak to a more acceptable level.

These three changes (power filter, gyro power supply, and gyro ADC) would have been performed for SWAS except for the limitations of funding and schedule. Obviously, even the third iteration of a design still has room for significant improvements.

Modifications to GSE

An additional change made for TRACE and WIRE was the development of a new board test GSE to support automated testing. The cost-benefit of this change was less beneficial than expected; however, it allowed optimal use of the experienced personnel available (otherwise, the schedule could not have been maintained, and the net costs would have been higher).

Further, there was a new addition developed for the spacecraft GSE (called the ‘Clean Room GSE’). This addition allowed increased automation for spacecraft level ACS testing; the results were decreased down time for re-configuration during testing, and almost complete elimination of erroneous ACS test configurations.

In addition, all three ACS GSE’s (board level, box level, and spacecraft level) required the modification of hardware and software to support the addition of Earth Sensor signals for WIRE. Further, the requirements for simultaneous testing of multiple boxes demanded construction of additional copies of GSE to go with the additional flight hardware (SWAS, TRACE, and WIRE were being tested simultaneously, with TRACE and WIRE performing identical tests at the same time).

The Savings of Re-Using Hardware Designs

As table 2 clearly shows, the savings associated with re-use of designs are enormous. Over half the costs associated with SWAS ACS were non-recurring costs, which were not required for TRACE ACS and WIRE ACS, even though the SWAS ACS itself incorporated significant re-use of designs. The TRACE and WIRE savings from this could potentially have been even higher, if no attempt had been made to fix the known problems in the SWAS hardware design.

The numbers in table 2 also clearly demonstrate the savings from building two identical units simultaneously. Despite the costs associated with building additional GSE, the cost of building the TRACE and WIRE ACS Hardware was less than twice the recurring cost of building the SWAS Hardware.

An added benefit was the reduced cost of the associated software, analysis, telemetry database and test procedures. In many cases, TRACE and WIRE were able to re-use SWAS ACS software, ground system, documentation, and analysis components without change, since the hardware had not changed in any way significant to these components.

An additional hidden benefit was also achieved: the resulting ACS hardware and software for TRACE and WIRE is much more robust and reliable, since anything which had appeared questionable after extensive SWAS testing was fixed at the start of the TRACE and WIRE builds. If the SWAS baseline were not available to build upon, there would be no way that the TRACE and WIRE missions could have achieved their enhancements within the current funding and schedule.

The Problems of Re-Using Hardware Designs

There are, however, hidden costs to this level of re-use. Obviously, a design which is continually re-used becomes frozen, and cannot advance or improve. In addition, an ACS design cannot generally be re-used unless it was originally designed for re-use. Planned re-use of designs will usually result in decreased performance on each unique mission.
Table 2: SWAS, TRACE, and WIRE ACS Cost Figures

<table>
<thead>
<tr>
<th>Cost Item</th>
<th>SWAS</th>
<th>TRACE</th>
<th>WIRE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breadboard &amp; ETU Development</td>
<td>2,100</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>GSE Development</td>
<td>600</td>
<td>850</td>
<td></td>
</tr>
<tr>
<td>Flight Hardware Fab. and Test</td>
<td>2,125</td>
<td>3,580</td>
<td>2,290</td>
</tr>
<tr>
<td>Hardware Sub-total</td>
<td>4,825</td>
<td>2,290</td>
<td>2,290</td>
</tr>
<tr>
<td>ACS Analysis</td>
<td>1,890</td>
<td>910</td>
<td>1,230</td>
</tr>
<tr>
<td>Flight S/W Coding and Testing</td>
<td>1,240</td>
<td>700</td>
<td>690</td>
</tr>
<tr>
<td>ACS User Documentation</td>
<td>240</td>
<td>150</td>
<td>200</td>
</tr>
<tr>
<td>Sensor and Actuator Procurements</td>
<td>2,050</td>
<td>825</td>
<td>2,625</td>
</tr>
<tr>
<td>Total ACS Cost</td>
<td>10,245</td>
<td>4,875</td>
<td>7,035</td>
</tr>
</tbody>
</table>

Notes on Table 2:
- all figures are in $1000 units
- SWAS figures include star tracker provided by instrument budget
- TRACE figures include guide telescope provided by instrument budget
- WIRE figures are based on projected costs
- WIRE figures include costs of sensors and actuators used from inventory and not replaced
- TRACE and WIRE hardware costs are split 50-50 as agreed
- TRACE and WIRE documentation costs are estimates, since their bookkeeping merges them with analysis
- figures include costs of environmental testing at the box level
- figures include approximate civil service manpower (using $100K/man year)
- figures exclude IEEE parts costs

The SWAS ACS hardware design could have been marginally improved by ignoring potential future re-use requirements (the partition of the design into boards would have been more optimal, and the documentation requirements less stringent). In addition, the SWAS design could have been technically improved by using fresh designs for the microprocessor card (which would then have had more memory, and an improved magnetometer trim) and acquisition/safehold card (which would have incorporated an improved timer scheme, a sixth CSS threshold circuit, and probably some attempt at zenith pointing the instrument in safehold). Any of these changes would have required re-layout, and prevented meeting the SWAS budget or schedule.

The TRACE ACS hardware design could have been substantially lighter and lower power (and required a lower expenditure for sensors and actuators), if it had not incorporated extra hardware required for SWAS and WIRE. It also could have been minutely more reliable, if safehold timer changes required for WIRE were not incorporated. However, this would have been more than offset by the additional costs of building a non-duplicate design.

Similarly, the WIRE ACS hardware design could have benefited from a more integral (hardware) design of the Earth avoidance for its safehold. Again, this would have increased costs significantly by preventing re-use.

A unique problem with reusing the SWAS hardware on the WIRE mission is the fact that WIRE uses a composite structure to meet its weight budget, rather than the traditional aluminum frame. This changes the grounding scheme of the spacecraft. Past SMEX missions used the spacecraft chassis for grounding between boxes, but now external grounding wires are used between boxes and subsystems where grounding is important. This is the case with the ACE and Gyro Box, where the issue is still being resolved.

An additional problem with re-use is the need for more thorough documentation to cover loss of critical personnel. For a single mission with a quick build process, it is likely that most key personnel will remain throughout the build (and can maintain sloppy documentation, reinforced by their memories).

For a multiple build extending across multiple years (SWAS development started in early 1992, and is currently scheduled to be launched after WIRE - in 1999), key personnel will generally transfer to other jobs before the completion of the multiple build. This loss of personnel is certain, when tight budgets prevent maintenance of personnel during down times and gaps in the schedule. Several key personnel were lost this way, even before the completion of the SWAS hardware build.

In the present environment, it is virtually certain that rebuilds will be performed by new personnel, most of whom are previously unfamiliar with the design. This leads to mistakes, and a tendency to make unnecessary changes due to misunderstandings. Further, each new engineer seems to need to learn the same lessons as the
last one, particularly when these lessons reflect disagreement between practical observation of the hardware, and theoretical simulation of the hardware (this is called the 'learning curve').

In addition to thorough documentation (a cost of re-use), an approach to reducing the problem with personnel turnover is to automate test procedures. Automated testing only requires knowledgeable personnel when something goes wrong, which was often (due to the new nature of the equipment, and automated procedures) during the TRACE and WIRE builds. Thus, it allows an increased opportunity for personnel to learn the system without severely impacting the budget and schedule.

Despite these problems, re-use seems mandatory in the present budget environment. The problem remains how to mitigate the defects of re-use.

The SMEX Lite Hardware Design

In order to meet demand for a further substantial decrease in cost without loss of performance, the SMEX project has undertaken a new satellite bus design called 'SMEX-Lite.' This bus has an architecture derived from the collective experience of the prior five SMEX missions. The intention is to increase re-usability, while using surface-mount electronics technologies to reduce size and weight.

This push has led in two different directions in different areas of the design. Some interface has been grouped across subsystems for design efficiencies; other hardware has been placed directly on the data bus for modularity (which increases re-usability).

The SMEX-Lite Reaction Wheels are each an integrated assembly which interfaces directly to the data bus. They contain re-packaged SWAS designs with several improvements. The bearings use a low outgassing grease which will allow un-pressurized housings. The tachometer makes full use of the motor hall sensors (including an added index sensor) to improve low speed performance. The design has also been improved to reduce EMI violations encountered with the SWAS design. In addition, circuitry will protect the spacecraft power bus from situations where the reaction wheel might return more instantaneous power than consumed by the remainder of the spacecraft.

The SMEX-Lite Magnetometer is also a stand-alone assembly. However, it produces analog signals which must be separately interfaced to the spacecraft bus. It is a miniaturization of the existing SAMPEX design (in turn, a copy of a design provided by Mario Acuña) to be compatible with the SMEX-Lite plans.

Sensors required solely for science pointing (such as gyros, and star trackers) will be the responsibility of the instrument team for SMEX-Lite. The assumption made is that they will interface directly to the data bus (or provide digital or analog outputs compatible with the Utility Hub mentioned below), and the data bus format used by SWAS to represent gyro data has been copied for system testing purposes.

For SMEX-Lite, the system design accepts the fact that the mission is now completely dependent upon the central spacecraft processor. As such, safehold control has been moved to software in the boot code of the main spacecraft processor.

The remaining Attitude Control hardware functions have been grouped with like functions of other spacecraft sub-systems in a common interface, called the Utility Hub. This interface includes the SWAS magnetic torquer driver; and Coarse Sun Sensor interface circuitry. In addition, it includes thermistors, generic analog I/O (16 bits for inputs; 12 bits for outputs), and generic digital I/O (5V logic). Modern electronic components have allowed this design to not require a backplane (a reliability benefit), as well as increasing the resolution of the analog interfaces.

Each of these re-packaged hardware designs uses the newer commercially available surface-mount components, including some integrated circuits which replace outdated parts that are no longer available for rebuilds.

Although the SMEX-Lite Attitude Control hardware is re-packaged in a smaller volume, upgraded to newer parts, and improved in performance, it still takes maximum advantage of re-use of existing designs. This combination should be an optimal compromise between the savings and costs involved in re-use.

Conclusion

The SWAS, TRACE, and WIRE builds represent a successful application of design re-use, with associated savings, to the construction of ACS hardware meeting unique scientific mission requirements. The lessons learned in this experience are currently being applied to increase the cost effectiveness of future ACS hardware designs, including that for the SMEX-Lite spacecraft bus.

Acknowledgements

The authors wish to thank Tom Budney, and Dr. Richard Freeman for reviewing this paper, as well as Jim Watzin for providing the outreach funding. Thanks also go to all the other designers involved with the three systems, including: Charles Clagett, Richard Schnurr, Dr. Darrell Zimbelman, Michael Fennell, and Thomas

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11th AIAA/USU Conference on Small Satellites
Quinn. The authors also wish to thank Giulio Rosanova, Pete Mule, and Eric Bentley for providing drawings and documentation used herein.

References


Author’s Biographies

Keith A. Chamberlin is the ACS Hardware Lead Engineer for the TRACE and WIRE spacecraft. He has a B.S. in E.E. from the University of Maryland. He has also worked on ACS for the Spartan program, and the SAMPEX, CRUX, and FAST spacecraft. He is a civil service employee of NASA’s Goddard Space Flight Center.

Thomas E. Correll is the ACS Hardware Lead Engineer for the SWAS spacecraft. He has a B.S. in E.E. (Mgmt. minor), and a M.E. in E.E. (spec. in controls), both from the Rensselaer Polytechnic Institute. He has also worked on ACS for the Spartan program, and the SAMPEX, CRUX, and SMEX-Lite spacecraft. He is a civil service employee of NASA’s Goddard Space Flight Center.