MODULAR ATTITUDE DETERMINATION AND CONTROL SYSTEM FOR SMALL SATELLITES

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In order to meet the cost goals of small satellites, attitude determination and control problems must be solved using standardized components. Small satellite attitude control systems must feature performance, versatility, and above all, low cost. Large, custom designed, high cost attitude control systems have no place in the small satellite community. A modular concept of attitude control is presented which will allow ambitious performance and cost goals to be attained. Basic building blocks allow mission specific goals to be reached with a minimum of effort and expense. Several basic modules are described and applied to a number of representative mission requirements. The concept illustrates a philosophy of modularity, flexibility, and manufacturability so necessary to the small satellite community.

INTRODUCTION

The current interest in small satellite technology is being driven by economic limitations that restrict large national asset types to a limited number of programs of limited scope. Small satellites offer a way to accomplish significant tasks without the burden of large expensive programs with the inherent built in risks associated with "once in a lifetime" flight opportunities.

One of the major subsystems, on most spacecraft, is the attitude control system. That system is required to maintain the orientation of the spacecraft within prescribed limits so that the power and thermal systems can function and the payload can perform its mission. The Attitude Control System (ACS) is also usually called upon to supply sufficient information so that its performance can be assessed and thus the attitude of the spacecraft can be determined either in real time on board or after the fact during ground processing.

The type of attitude control system used depends upon the specific mission. They range from none at all for programs like GLOMAR and VANGUARD through treasures of mankind programs such as the HUBBLE SPACE TELESCOPE where it is assumed to be reasonable and appropriate to fly redundant sets of the best of everything. It is obviously not cost effective to utilize the latter on small single mission spacecraft. An adequate ACS must be tailored to the specific mission.

The Attitude Determination and Control System discussed in this paper is not a single system or even a multiple system, but more of a philosophy dedicated to providing attitude control solutions for a variety of missions. Instead of one large, expensive, one design does all for all systems, a versatile, flexible, cost effective approach that is easy to tailor to specific tasks is presented.

ACS TASKS

If an attitude control system is required at all, and it usually is, it will be required to either orient the spacecraft relative to a fixed reference or maintain the spacecraft angular momentum vector within prescribed limits. In other words the spacecraft will either be spinning or not.

Spin stabilization may range from simple rate limiting to precision orientation of the spacecraft spin axis and precise phasing of the spin about that axis. In the simplest case, the spacecraft is simply placed into orbit and allowed to drift with the assumption that it will seek a gravity gradient, aerodynamic and magnetic null. In more interesting cases, it will be desirable to limit the spin rate, aim the spin axis toward the Sun or toward some other target or even a variety of target orientations.

Three axis stabilization requires that the spacecraft rotation be stopped and the spacecraft be oriented and held in some manner relative to a reference frame. The reference frame may in turn be fixed inertially or fixed relative to some celestial body such as the Earth. In either case, active muscles of some type act to control the orientation of the spacecraft and endeavor to keep it aligned with the reference. The reference orientation may be changed from time to time implying that an agile control system is required. Small satellites may fit in anywhere. It is the ACS engineer's problem to determine the ACS requirements and recommend an economical viable solution for each mission. It is the goal of the Modular Attitude Determination and Control System (MADACS) concept to make the decisions easier and minimize the mission and program costs.

MADACS PHILOSOPHY

The task of the ACS engineer is then to meet a set of mission requirements in the most cost effective manner possible. The MADACS philosophy is to use a set of simple instruments in a bus structured system which can be added to as required in order to accomplish a given mission. Instruments which feature good performance, simplicity, and above all low cost are preferred over custom designed or multipurpose instruments which are not cost effective. Simply stated, begin with a basic structure and add to it as necessary. A simple instrument is preferable to a complex instrument.

This approach is similar to the modern office environment. In the simplest case, a modest desktop computer interfaces with a low cost printer. As the office grows and the requirements increase, laser printers, color printers, modems, card, tape, and various magnetic storage media are added along with networking. A branch office in a new city can begin operations with a subset and grow in similar and different ways as the situation dictates. The same basic building block approach is the heart of the MADACS concept.

For the small spacecraft ACS designer then, the goal is to evolve a set of reliable instruments to solve various ACS problems. Mission unique instruments are to be avoided if at all possible. The advantage is that simple instruments should be easy to build, easy to test, and can be built in moderate quantities where advantages of scale begin to influence costs. The disadvantage is that the weight of a set of simple instruments is likely to be more than the weight of a dedicated custom designed instrument. Furthermore, it may not be immediately obvious that there is a cost benefit since suppliers often charge more for building and testing two simple instruments than they do for building and testing one complex instrument. As production volumes increase, the advantages of multiple simple instruments should lower costs significantly compared to lower volume production of more complex instruments. Instruments priced so that two simple versions cost significantly more than one complex version should be viewed with considerable skepticism.

MADACS PHILOSOPHY (Continued)

Our small satellite systems are rarely redundant. A "no single point failure" or complete redundancy requirement on a program takes it out of the low cost arena although the spacecraft may still be small. However, there is no reason not to take opportunities for graceful degradation or redundancy where it is available with limited or no extra expense. Often a given mission requirement dictates a set of instruments. In order to meet the requirements, a basic ACS is augmented with perhaps an inertial reference unit or additional sun sensors. A degraded mission, should one of these instruments fail, is often available then with little or no effort. A MADACS system recognizes opportunities for degraded missions and makes them available. However, no significant effort is applied other than to be sure that they can be turned on or uploaded in flight should the failure be encountered. Thus the cost of the redundancy opportunity is nearly zero.

In summary then, a MADACS system uses a bus structured concept. Simple instruments are used to accomplish the various tasks and are added to as necessary for enhanced capabilities. Redundancy is generally not available although when an opportunity is available to salvage a degraded mission, the capability is provided without significant advanced effort or testing.

MISSION DEVELOPMENT

The development of a given spacecraft and mission obviously begins with someone proposing a specific set of experiments and tasks which eventually become funded so that the mission can go ahead. The ACS designer should shortly get involved. The first task is to determine the performance necessary to meet the mission requirements.

So often, the ACS engineer is ignored in the early stages of mission planning. Later, he is given a set of requirements to meet. The desired pointing and rate requirements are specified along with a weight and power budget. It is very discouraging to eventually learn that the experimenter specified a sub ARC second pointing requirement simply because he thought it was easy. What he really wanted to do was monitor the Canadian wheat crop with a wide angle camera and a few degrees of accuracy would have been sufficient. The project cost differential is enormous. The really solid designs involve the ACS engineer from the start of the project. This allows interaction with all phases of the spacecraft design.

Once the mission requirements are understood, the ACS designer then has to make several ACS decisions. First is whether or not the system should be momentum biased or zero momentum. In almost every case, the cost effective choice is momentum bias. The elegance of the technique, the solution of the yaw control problem essentially for free, and the limited amount of hardware required, all make momentum bias almost always the technique of choice for any serious performance requirements. Having stated this, later in this paper are several cases where momentum bias is not the cost effective choice. However, momentum bias should always be considered first and abandoned only with good reason.

Next we must determine how to store momentum. There are only two choices, wheels and vehicle motion. In most cases, some wheel(s) will be required. The elegance of momentum bias techniques comes into play when wheels are used since one wheel yields 3-axis control versus three wheels for a zero momentum spacecraft. The economies of momentum bias techniques are obvious.

As momentum accumulates, some means must be provided to dump the momentum. The truly clever ACS engineer will attempt to avoid fighting with environmental disturbances if at all possible. In a low orbit, perhaps aerodynamic drag can assist in momentum management. It is always nice if the spacecraft is gravity gradient stable, not unstable. Involving the ACS engineer early in the program can help. Usually some active muscles will be required in addition to passive spacecraft design techniques. For a small spacecraft, electromagnets are a preferred choice. The advantages of magnetic momentum management are safety, low cost, and reliability.

MISSION DEVELOPMENT (Continued)

No expendables are required, thus the spacecraft lifetime is not limited by consumables. Mass expulsion techniques are also available, but should be adopted only for specific cases and with good reason. It is doubtful that exotic techniques like solar sails will find applicability to small satellites.

The choice of attitude sensor or sensors rounds out the basic ACS. Generally the choice is obvious from the mission concept. A sun sensor is an obvious choice for a sun pointer and a horizon sensor or sensors is obvious for a nadir pointer. A vector magnetometer is useful if magnetic momentum management is employed. Rate gyro(s) may be used for rate stabilization and enhancing the performance of the horizon sensors or propagating the output from other sensors. Star trackers will be useful for ultrahigh accuracy missions or for random inertial orientations.

In summary the ACS designer should work with the experimenter and the spacecraft designer throughout the mission development in order to optimize the cost effectiveness of the spacecraft. The selection of sensor suites and the momentum management techniques round out the tasks. The MADACS concept attempts to address the sensor suite and momentum management issues in a structured, cost effective manner.

EXAMPLES

The best way to illustrate the MADACS concept is to briefly outline the concept for a variety of missions ranging from simple to high performance. The simplest of all is no ACS at all. Obviously the result is the most cost effective system, but the least interesting.

Rate Reduction

The requirements for this type of ACS are that the spacecraft spin rates be reduced to a low level of a few degrees per minute. Some of the Shuttle deployed SPARTAN spacecraft rely upon this type of ACS. The spacecraft is released with some arbitrary reasonable tip-off rate of a few degrees per second. Several days later, the spacecraft is retrieved. In order to retrieve the spacecraft, the rates must be low enough so that the shuttle can grapple the spacecraft with its arm. LDEF of course used gravity gradient and relied upon passive damping for stabilization. The subject mission does not last several years, so more effective damping is required.

The MADACS ACS can and has been realized in analog. The three axis version has been built and flown. The simpler two axis version has been proposed for a new program.

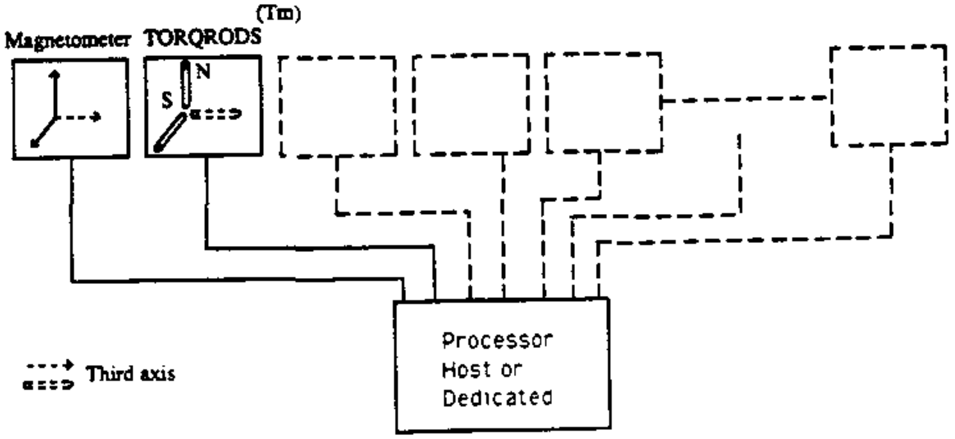


Figure 1
Rate Reduction

Maximum Autonomy/Minimum Hardware/3-Axis

ITHACO has published work on two concepts, Magnetic Navigation (MAGNAV)* and Magnetic Attitude Control (MAGACS)**. These concepts rely upon Kalman filtering techniques with vector and scalar magnetic field measurements to determine the spacecraft orbit elements and the attitude matrix. In principle these techniques can be combined in one MADACS. The spacecraft could be built and then launched upon any available booster to any arbitrary low Earth orbit and left with moderate initial rates. Standard rate reduction algorithms would slow the vehicle rates while MAGNAV determined the orbit elements. Once these are known, MAGNAV continues to run while MAGACS solves for the attitude matrix. The electromagnets then reduce the rates to zero and drive the attitude to its proper orientation. The navigation capability has been shown to be several kilometers while the attitude control and determination capability is likely of the order of a couple of degrees. The spacecraft would gather its data and transmit only when it determined that it was in range of its ground station. NO COMMAND RECEIVER would be necessary resulting in the world's <u>most</u> <u>secure uplink!</u>

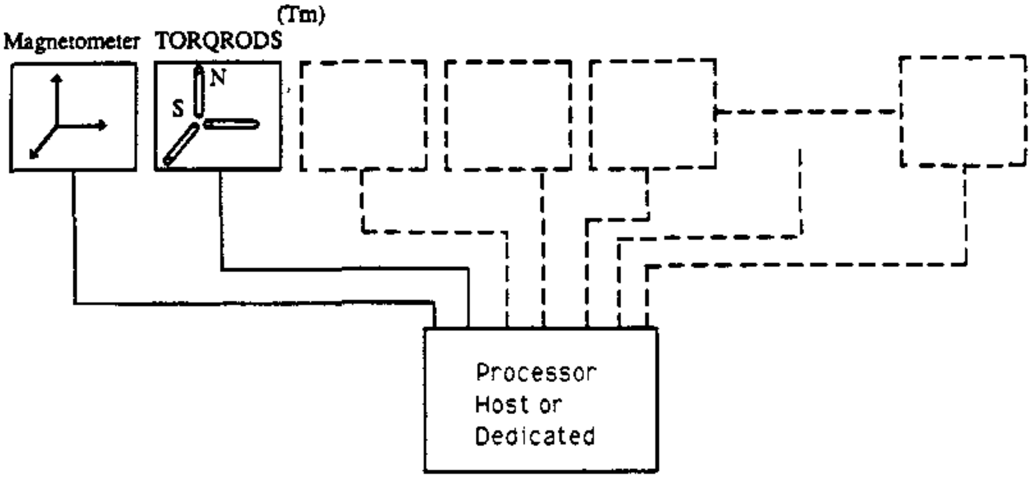


Figure 2
Minimum Hardware, 3-Axis

* Magnetometer-Based Autonomous Satellite Navigation (MAGNAV)," S. M. Fox, P. K. Pal, M. Psaiki, 13'th Annual AAS Guidance and Control Conference, Feb 3-7, 1990, Keystone, Colorado

** "Three Axis Attitude Determination via Kalman Filtering of Magnetometer Data," M. L. Psaiki, F. Martel, P. K. Pal, Journal of Guidance, Control, and Dynamics, Vol. 13, Number 3, May-June 1990

THREE-AXIS NADIR POINTING

The three axis nadir pointing configuration has been built and flown several times. The HCMM and SAGE spacecraft first used autonomous magnetic momentum management and a modular concept. These highly successful spacecraft operated well beyond their design life. The baseline MADACS system for a circular orbit is shown below. Dotted in components provide increased accuracy and ease of operation in elliptical orbits along with additional availability of degraded backup modes.

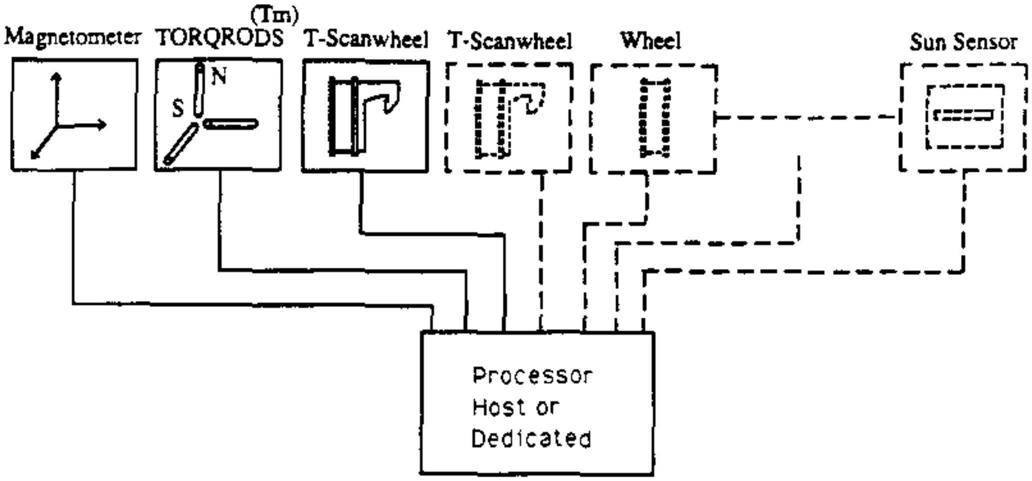


Figure 3
3-Axis Nadir Pointing

COMBINED 3-AXIS/SPIN STABILIZED

The conventional approach to a spin stabilized spacecraft which has an Earth centered reference uses horizon crossing indicator(s) for attitude determination. MADACS supports that type of ACS of course using the HCI portion of the T-SCANWHEEL®. (SCANWHEEL® is a registered trade mark of ITHACO Inc., Ithaca, N.Y.) The following alternate approach was proposed for a program which desired highly modular spacecraft and which may on rare occasion require spin stabilization. The only difference between this ACS and the previous ACS is the control algorithm that drives the SCANWHEELs. The pitch loop is closed about the pitch rate rather than the pitch position.

The ACS proved to have significant advantages over the conventional approach. Initialization of the mission using a conventional momentum bias acquisition of the orbit normal proceeds as if the spacecraft is a nadir pointer. Indeed, an experiment requiring nadir pointing and an experiment requiring spin stabilization can share the same spacecraft provided that they are willing to take turns. Software developed for acquisition is identical. Software developed for nadir pointing is easily modified for spin stabilization. Nutation damping is facilitated by the wide bandwidth data provided by the spinning SCANWHEEL, thus solving a sometimes difficult problem for spinning spacecraft.

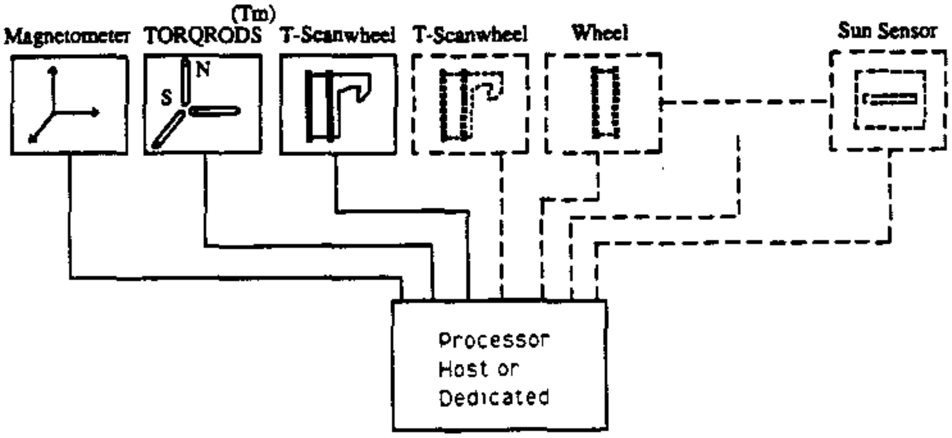


Figure 4
Combined 3-Axis/Spin Stabilized

ENHANCEMENTS

Obviously there are many more possible combinations that can be accommodated by using the MADACS system. Two SCANWHEELs offset in the roll/pitch plane using momentum bias allows yaw/pitch slewing and active nutation damping for aiming instruments such as telescopes or cameras. Sun sensors can be added to the basic system for enhanced yaw knowledge or sun pointing missions. Rate gyros allow increased rate stability and gyro compassing for enhanced accuracy and stability. A star tracker can add significantly to the accuracy obtained if desired.

SOFTWARE

The MADACS software concept follows the same approach. A modular software system is envisioned that will allow basic systems to be documented and then maintained. Modifications would be by addition of device drivers as they come on line. By modularizing the software, the software is easily tailored to specific missions.

Software modifications are expensive, no matter how well designed the basic system is. The Combined Spin/ 3-axis System discussed above would appear to have two extra wheels if it were used only as a spinner. It was originally proposed for a multiple spacecraft program which would have already flown several 3-axis spacecraft before the spinner was to be built. In that case, the extra costs of the two wheels is more than offset since so much of the software remains the same. The few changes are much less risky and less expensive compared with the expenses of rewriting for a pure dedicated spinner. On the other hand, if a number of spin stabilized spacecraft were envisioned, then the software would be worth pursuing. The MADACS concept says to begin with what you have now and build upon it as a base.

COMPONENT STATUS

There are many building blocks for the MADACS system. Some exist, some are in development, some have only recently been identified as possible candidates, and no doubt some have not even been thought of yet. The following list of components is not complete. Indeed it is difficult to complete MADACS. Modularity of the system allows it to be modified and added to as needed for each succeeding task. The tasks are unique enough so that the list cannot ever be complete. What we can hope to do though is narrow the obvious choices and avoid duplication of effort as much as possible. Equipment specifications cited are typical and subject to change by the vendors, contact vendors for complete data.

Software

Current industry wide practice has each prime contractor writing their own ACS software for their own particular environment. No sharing or commonality is known. Software efforts then tend to be written in a variety of languages and are closely guarded properties of the prime contractors. New jobs are fed to the internal software groups rather than to subcontractors where results could be shared. The small satellite community must break out of that mold. Unless good ACS software becomes available at minimal costs, no one will realize the total benefits of digital techniques applied to small satellites. MADACS software must be produced in an intelligent, well structured, and well documented manner. It must be controlled and maintained with the same rigor and attention to detail that is given to good hardware components of a MADAC S system. Development of MADACS software has recently been proposed under a Small Business Innovative Research (SBIR) initiative, but it will be several months before any possible award is announced.

Processor

Most prime contractors today have their own processor. For all spacecraft, the choice of using a dedicated ACS processor or hosting the software in a main spacecraft computer is faced by the prime contractor. Defense Systems Inc., McLean, Va., and Southwest Research Corporation, San Antonio, Texas, may be willing to offer a small computer for ACS applications.

TORQRODs™

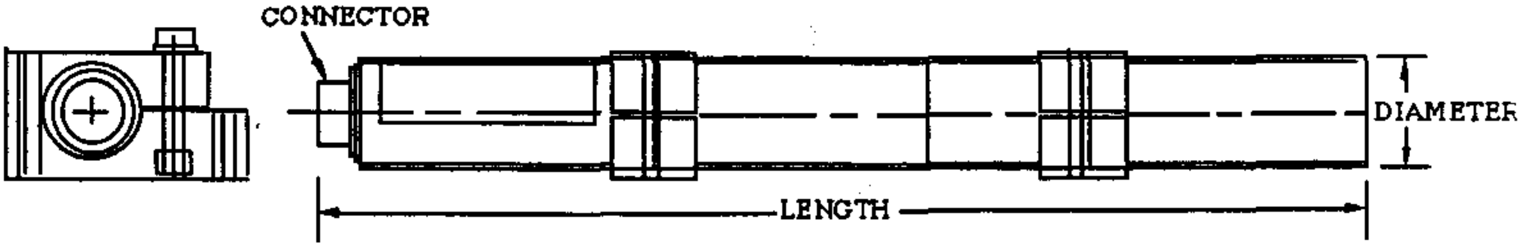
Electromagnets sold under the trade name TORQRODs by ITHACO Incorporated are the most mature component of MADACS available today. They have been manufactured in a variety of sizes for the past 20 years. In order to control costs, order several TORQRODs at a time from the standard catalog choices with standard or reduced testing. MADACS' goal is to eventually manage to place many of the MADACS components into the same catalog category. A standard product, built in moderate batches to standard specifications and standard assembly and test procedures yields optimum costs for the user and profit for the vendor.

TORQRODs

Over 200 TORQRODs Have Been Built Or Are On Order

PROGRAM	SCSC	ETS-3	SME	MOS-1	GSTAR	SATCOM/ KU	ANIK-E	ACTS	GRO	HUBBLE SPACE TELESCOPE
MOMENT Am^2 AT SATURATION	1	15	30	80	140	350	600	1000	2700	4000
MASS Kgm (lbs)	.078 (0.2)	0.375 (0.83)	0.85 (1.87)	1.5 (3.4)	2.0 (4.5)	4.1 (9.1)	7.26 (16.0)	12.1 (26.6)	43.2 (95)	43.2 (95)
LENGTH Centimeters (inches)	12.7 (5.0)	39.4 (15.5)	49.5 (19.5)	63.5 (25)	83.3 (32.8)	91.4 (36)	127 (50)	139.7 (55)	146.1 (57.5)	248.9 (98)
MAX POWER (Watts)	0.146	1.0	3.2	4.4	3.9	11.4	9.1	13.4	40.6	14.3

Note: Residual Dipole ≤1% of Saturation Moment



Examples of TORQROD Characteristics

T-SCANWHEEL®

The T-SCANWHEEL best illustrates the MADACS concept. The small stackable wheel is a high efficiency, low cost unit using common materials such as aluminum and steel in a uniquely conceived versatile unit. The wheel itself is a high efficiency, low cost, reaction wheel. It is designed for efficient assembly and batch production.

The optical portion of the T-SCANWHEEL is a Horizon Crossing Indicator useable as such on spinning spacecraft. When combined with a T-Reaction Wheel or a dedicated mirror drive motor, a rotating mirror provides a scanning motion suitable for horizon sensing.

For use in a MADACS system requiring X number of wheels and Y number of SCANWHEELs, the off-the-shelf units readily combine to form a variety of useful combinations. First flight of the reaction wheel is set for 1991. The engineering model wheel is operating, first flight and life test wheels are nearing completion of production. A T-SCANWHEEL combination has been built up on the engineering wheel and briefly operated. Further development and qualification will proceed in the near future.

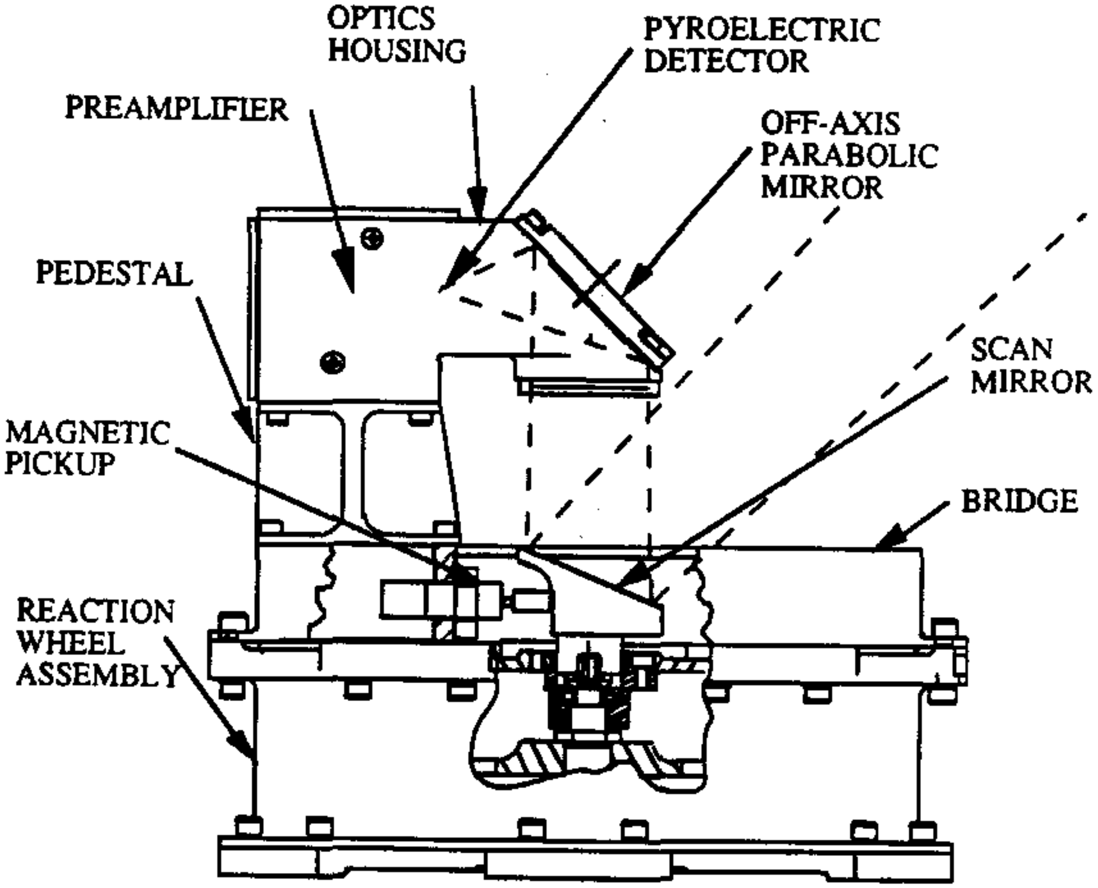


Figure 5
T-SCANWHEEL

T-WHEEL

- High Inertia to Weight Ratio With Ironless Armature
- Low Power - TiC Bearings/High Efficiency Motor and Driver
- Hall Sensor High Resolution Tachometer
- First Flight Will Be University of Bremen, FRG in 1991

		Type A Reaction/ Momentum Wheel
Operating Speed		0 to ±6000 RPM
Angular Momentum @ 2000 RPM		1.3 N-m-s (1 ft-lb-sec)
Angular Momentum @ 6000 RPM		4.0 N-m-s (3 ft-lb-sec)
Available Reaction Torque		20 mN-m (2.7 oz-in)
Weight	Unit Electronics	2.3 Kg (5 lbs) 1.3 Kg (2.9 lbs)
Outline	Height Diameter	63 mm (2.5 in) 203 mm (8 in)
Steady State Power @ 1000 RPM	Unit Electronics	0.5 Watt 1.0 Watts

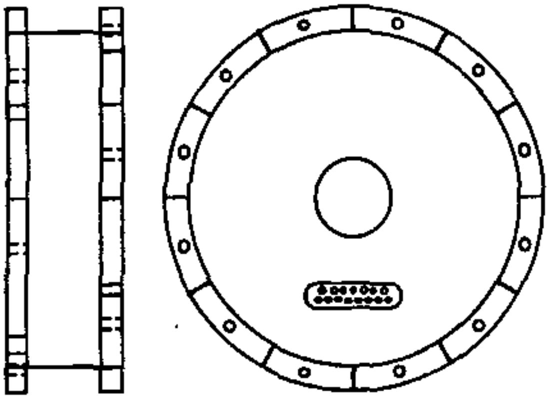


Figure 6
Typical T-Wheel Specifications

Vector Magnetometer

There are several excellent vendors of vector magnetometers. Schoenstedt Instruments and Develco for example have manufactured 3-axis vector magnetometers for spacecraft use. ITHACO recently developed a unique 2-axis magnetometer for use on a spin stabilized spacecraft where ultra low power was at a premium. The 2-axis unit fits very well with the MADACS concept of a simple instrument with multiple uses. If the cost is low enough, and the power is certainly very low, and the weight is not too high, then two 2-axis magnetometers will provide complete vector magnetic field data along with partial redundancy. The units can be mounted in such a manner that loss of a single axis can easily be accommodated without significant degradation. In fact, it is likely that loss of a single unit would not be too difficult to overcome with moderate performance loss. A single unit is sufficient for operation of a spin stabilized ACS. Thus the 2-axis magnetometer, built like the T-SCANWHEEL in batches, can provide a very nice alternative to a three axis unit.

MAGNETOMETER

Number of Axes	Two, orthogonal
Orthogonality	±1°, axis-to-axis and axes-to-reference surface
Linearity	<0.5% of full scale
Field Measurement Range	±100 mGauss to ±600 mGauss
Sensitivity	2 mV/mGauss to 100 mV/mGauss
Zero Field Bias	+2.5 V to +15 V (0.0 V with bipolar supply)
High Frequency Noise	<0.1% of full scale
Output Ripple	<5 mV RMS
Frequency Response	-3 dB at 80 Hz
Supply Voltage	+5 V to +40 V Bipolar ±2.5 V to ±7.5 V
Power Consumption	30 mW max at 5 V
Enclosure Dimensions	7.6 cm x 15.2 cm x 2.5 cm
Weight:	<350 grams

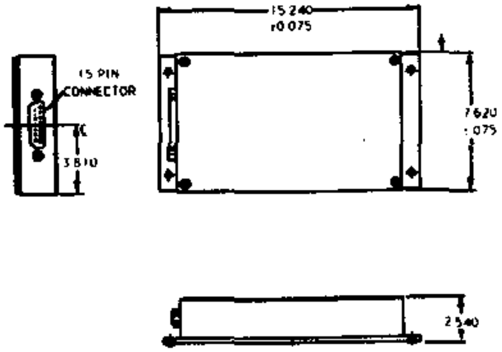


Figure 7
2-Axis Magnetometer

Sun Sensor

Sun sensors have traditionally been manufactured by Adcole Corp. They offer a wide variety of Sun sensors for many applications. Recently a Sun sensor has become available manufactured by Space Sciences Corp., Bronxville, N.Y., which appears to fit the MADACS concept. A simple instrument in either one or two-axis configurations is available. MADACS prefers the single axis model used twice, but for a given application pricing of a two-axis version may be advantageous.

Number of Axes	One (Two Optional)
Least Significant Bit	0.00625°
Output Format	Serial
Field-Of-View (FOV)	±64° Sensitive Axis ±64° Insensitive Axis
Accuracy	0.15° to 0.017° Options (3 sigma)
Power Consumption	1.00 Watt
Weight	0.455 kG (1.00 lb)
Dimensions	76.2 mm x 76.2 mm x 50.8 mm (3.0" x 3.0" x 2.0") Flange Mounted

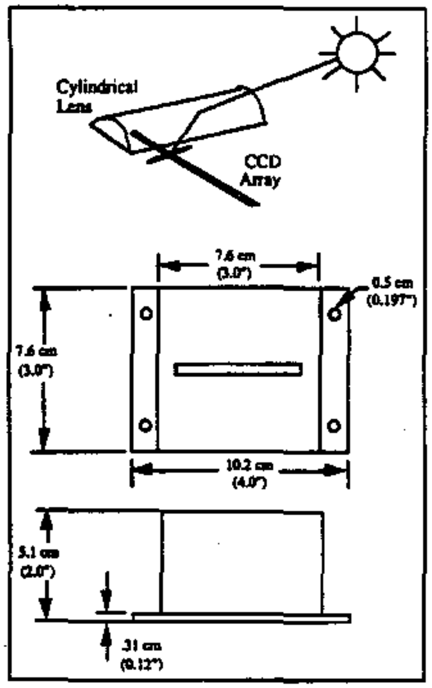


Figure 8
Typical Sun Sensor

Rate Gyro

There are several manufacturers of rate gyros. One that has been identified for MADACS consideration is manufactured by Bell INCOSYM TEXTRON in Westlake Village, California. Data for their Model III-T indicates that it should be adequate for moderate quality gyrocompassing and other applications.

Weight	12 oz.
Power	
Dual Voltage	
Start	8W
Run	1.5W
Run-up Time	8 Seconds
Single Voltage	
Start 5W	
Run	2.5W
Run-Up Tme	12 Seconds
Drifts	
Compensatable	
Non-G Sensitive	10 Deg/Hr
G Sensitive	10 Deg/Hr/g
Non-Compensatable	
Random	0.01 Deg/Hr (1 sigma)
Turn-On Repeatability	0.03 Deg/Hr (1 sigma)
G Squared Sensitivity	0.1 Deg/Hr/g Sq.
Magnetic Sensitivity	0.03 Deg/Hr/Gauss

Typical Rate Gyro Specifications

Star Trackers

Ball Aerospace Corporation has manufactured star trackers for spacecraft use. Recently, Applied Research Corporation in Landover, Maryland received an SBIR award to develop a low cost star tracker for small satellite applications. Development is scheduled to commence early in 1991. Assuming that a successful development follows, this unit can significantly enhance the performance and mission capabilities of MADACS.

Preliminary Star Tracker Specifications

Field-of-View	11 degrees by 8 degrees
Limiting Magnitude	10 (cooled) 4 (uncooled)
Accuracy	10 Arc Seconds
UpdateRatE	1 Hz nominal (adaptable)
Tracking Capacity	1-5 stars
Output	16 bit magnitude, 16 bit position each axis
Power	5 watts
Mass	4 Kg

Additional Components

The nature of MADACS is that it will never be complete. For example, larger or smaller wheels may be employed, depending upon the mission requirement. Other components and devices will be used for special purposes. The goal is to not solve all problems, but to share solutions, to standardize components, and to increase production volumes by eliminating redundant choices and thus reducing component costs. Above all, the goal is reduced ACS and thus spacecraft cost so that more missions can be flown, more science be done, more services be offered, and more profit be made by all.