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The Inertial Stellar Compass:
A New Direction in Spacecraft Attitude Determination

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Abstract. The Inertial Stellar Compass (ISC) is a real-time, miniature, low power stellar inertial attitude determination system, composed of a wide field-of-view active pixel star camera and a microelectromechanical system (MEMS) gyro assembly, with associated processing and power electronics. The integrated technologies enable an attitude determination system with an accuracy of 0.1 degree (1 sigma) to be realized at very low power and volume. The attitude knowledge provided by the ISC is applicable to a wide range of space and earth science missions that may include the use of highly maneuverable, stabilized, tumbling, or lost spacecraft. Under the guidance of NASA's New Millennium ST-6 project, Draper Laboratory is currently developing the Inertial Stellar Compass. Its completion and flight validation will represent a breakthrough in real-time miniature attitude determination sensors. This paper describes system design, development, and validation activities currently underway at Draper.

Introduction

The combination of a star tracker and gyros on board a spacecraft is an old and widely accepted method of solving the attitude determination problem. With an ever-wider range of small spacecraft missions becoming practical, the need for sub-degree attitude determination performance in a compact, low-power package is emerging as one of the significant technical hurdles that stand in the way of miniaturization. Fitting a star tracker and gyro attitude determination system within the cost, size and mass constraints of small satellite missions is only now becoming feasible thanks to new sensor technologies such as Micro-Electro-Mechanical (MEMS) gyroscopes and Active Pixel Sensor (APS) imaging devices.

Draper Laboratory's Inertial Stellar Compass (ISC) is an innovative attitude determination instrument that combines these emerging sensor technologies into an integrated package to be space-validated in 2004. The ISC has the following key performance features:

- 0.1° (1-sigma) accuracy in each axis
- High-rate maneuver capability
- Self-initializing
- Mass ~ 2.5 kg
- Power ~ 3.5 W

A key advantage of the ISC is the simple and flexible integration with the host spacecraft. The output of the ISC consists simply of an Earth Centered Inertial (ECI) attitude quaternion and attitude rates, a data set that amounts to "bolt-on" attitude determination.

The ISC reduces the cost, schedule and risk impacts of sensor integration. Traditionally, in a star tracker and gyro attitude determination system, the spacecraft's flight computer performs the fusion of sensor data using custom mission-specific software. This requires the spacecraft designer to have detailed knowledge and understanding of each sensor's behavior, down to the intricacies of how changes might occur over time, temperature, or other environmental factors. Unnecessary design risk is introduced when the engineers integrating the sensor outputs in software are not the same engineers who designed, and best understand, the sensor hardware. Additionally, performing the integration of the sensor suite externally (at the spacecraft level) prevents a form of "total integration" where performance can be gained through the low-level exchange of information between the different sensors.

As a smart sensor, the ISC hides the technical complexity of the attitude sensors (MEMS gyros and APS star camera) from the end user, provides "total integration" of the sensor suite, and guarantees that the software used to fuse sensor outputs into an integrated attitude solution is optimally tailored to the sensor hardware.

ISC Operating Principles and Capabilities

Under typical operating conditions, the MEMS gyroscopes drive the ISC output attitude. The gyros sense inertial rates at a high sample frequency (100 Hz). The raw gyro data is processed through a Kalman filter to produce the output quaternion, which is communicated to the host spacecraft in real time, at a frequency of 5 Hz. The star camera is used periodically (every few minutes) to obtain a camera quaternion, whose main purpose is to compensate the inherent drift of the gyros. A simple system data flow is shown in Figure 1.

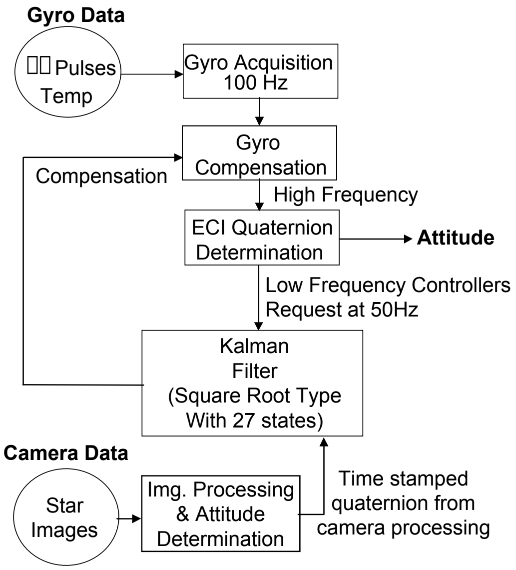

Figure 1: ISC System Data Flow

A typical profile of attitude error, computed by simulation, is shown in Figure 2. The 1-sigma error bounds are shown in bold, while the actual attitude error from one simulated run is shown as a thin line. Since the error bounds are 1-sigma, the error can be expected to go outside of the bound for 32% of the time. Every five minutes, the gyros are compensated with a fresh camera quaternion, as evidenced by the sudden narrowing of the error bounds.

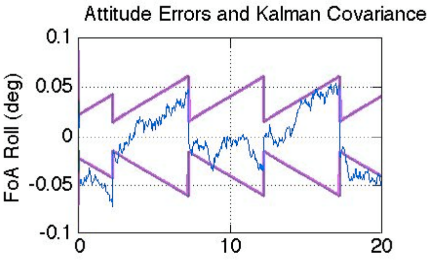

Figure 2: Typical Single-Axis Attitude Error Profile

Used together as a tightly integrated sensor suite, the gyros and camera enhance each other's capabilities, resulting in a more robust attitude determination system than could be achieved by integrating separate star tracker and gyro units.

To provide a camera quaternion, the ISC must first process a star image, identify the stars in the image, and calculate the resulting attitude. The star identification process is computationally more intensive (the so-called "lost in space" problem) if no prior knowledge of attitude is available. After the ISC is initialized, the gyros can provide this prior knowledge, thus making star identification a straightforward process. Unlike conventional star trackers, the ISC therefore has no need for tracking individual stars in the camera field-of-view. All the stars in one star image can drift out of the FOV before the next image is processed several minutes later. This greatly reduces the computational burden from frequent, repeated image processing using windows centered on a few guide stars; in the ISC, the gyros do the tracking for the camera.

As for any attitude determination instrument used in an attitude control feedback loop, the instrument output is desired in as close as possible to real-time. Unlike a star tracker, the ISC does not have a requirement for fast processing of camera images to achieve near real-time performance. The gyros provide this capability, and do so with a relatively small computational expense, thus allowing the ISC processor to run at a slower, power-saving clock rate. Camera images can be processed a posteriori and still ensure full instrument accuracy even if a few tens of seconds elapse between image exposure, image processing, and the computation of the corresponding camera quaternion.

When the attitude rate exceeds the camera's optical tracking limit (where the camera can no longer resolve enough stars because of image blurring from the motion), the ISC can continue to provide an accurate attitude for a period of several minutes, provided that the motion later returns to an acceptable range for camera imaging (0.25°/sec). During the period when the ISC "rides the gyros", the limiting factor is the total rotation accumulated in each axis, which causes the attitude error due to gyro scale factor uncertainty to dominate. To keep accuracy within specifications, the ISC needs a camera update after five minutes or one full revolution (360 degrees) in each axis, whichever comes first. The ISC can thus maintain full attitude accuracy for most conceivable 3-axis spacecraft maneuver profiles, regardless of rate. This high-rate maneuver capability requires no additional processing by the host spacecraft: the ISC simply continues to output a 5 Hz quaternion.

The ability to "ride the gyros" is also desirable when the camera FOV is occluded by the sun, moon or earth. As long as this occlusion does not last for more than five minutes, full accuracy is maintained. If the occlusion continues after five minutes, the accuracy of the output quaternion is gradually degraded by gyro drift. However, this degradation is well understood since the error bounds of the attitude are estimated in the ISC and communicated to the host spacecraft. The real time estimate of the attitude error accumulation will be provided to the host spacecraft.

The ISC itself benefits from the real time knowledge of the error bounds for its output quaternion. The ISC can decide internally when a camera update is necessary (when the gyro error bounds grow beyond a threshold) and when a camera update is possible (when the rates are below the camera's optical tracking limit). This intelligent use of the camera avoids a situation where a useless, motion-blurred camera frame is acquired and processed for attitude information.

Finally, without use of the camera, the ISC gyros can provide attitude rate data with sufficient accuracy that a spacecraft can recover from a tumbling state and bring its rates to well within the ISC camera's optical tracking limit. This capability makes the ISC suitable for initial attitude acquisition without the need for additional attitude sensors.

The ISC Design

The ISC instrument consists of two separate units, connected by a cable: the Camera Gyro Assembly (CGA), which contains the sensors, and the Data Processing Assembly (DPA) that contains the instrument's embedded computer. The two-unit design facilitates integration with the host spacecraft. Only the CGA need be precisely aligned with the host spacecraft, with the aid of a reference cube.

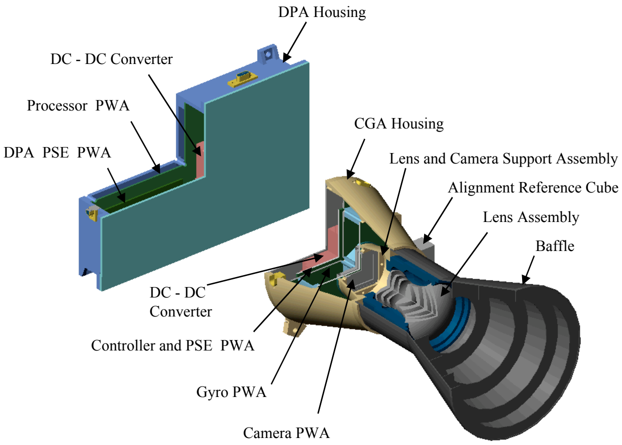

Figure 3: CGA and DPA Cutaway View

The CGA and DPA communicate across a serial data link. The CGA collects raw sensor data as commanded and returns it to the DPA for processing. A conceptual view of the two units is shown in Figure 3.

Camera Gyro Assembly (CGA)

The CGA consists of a wide field-of-view Active Pixel Sensor (APS) star camera and a Micro-Electro-Mechanical System (MEMS) gyro assembly, which are controlled by an FPGA controller within the DPA.

The CGA (see Figure 4) is comprised of five functional blocks known as the Controller, Power

System Electronics (PSE), Analog Data Acquisition Module (ADAM), MEMS Gyro, and Camera. The Controller block is the glue between the camera electronics and the gyro electronics and provides an interface to the DPA. The PSE provides all the internal voltages necessary for the CGA functional blocks. The PSE power is derived from the primary DPA +28V interface. The ADAM digitizes both the MEMS gyro data and CGA housekeeping data and then passes this along to the controller for inclusion in the CGA serial data stream. The camera block contains the optics, image sensor and electronics for acquiring star images. The MEMS gyro functional block senses angular rate with a 3-axis Draper MEMS gyro and passes along an analog representation of the sensed rate to the ADAM for digitization.

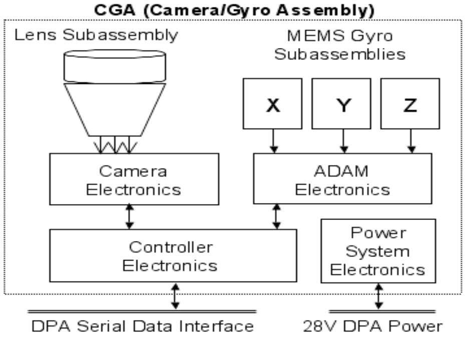

Figure 4: CGA Block Diagram

APS Camera

In the last decade, a new family of imaging arrays called active pixel sensors has emerged, mostly from industrial applications, and are suitable for use in a star camera role.[1] The APS is an array of photosensors, each with a local amplifier plus row and column addressing capability. While they do not rival the performance of the best CCDs, active pixel sensors have advantages that make them suitable for the star camera application. Size and weight can be reduced significantly since the required control and driving electronics are fewer than for CCDs. In particular, APS imagers can integrate analog and digital functions on the same die. Compared to the highly capacitive CCD, power can also be reduced since APS imagers typically use standard 5-Vdc and 3.3-Vdc power supplies. APS imagers used in space applications are typically radiation-hard since they can be manufactured with processes such as silicon-on-insulator. One key difference between a CCD and an APS imager is that the CCD transfers image charge to one or more output amplifiers, while the APS places a sampling amplifier within each pixel. This further contributes to radiation tolerance since the APS is not sensitive to charge transfer efficiency effects commonly associated with radiation-damaged CCDs.[2]

The disadvantages of an APS with respect to CCD imagers include poorer noise performance and lower fill factors.[3] This effectively limits the sensitivity of the system resulting in longer exposure times for the same scene. For the ISC, sensitivity determines how many stars can be imaged in a scene. To compensate for the reduced sensitivity, the ISC is equipped with wide-FOV, large aperture optics to allow more stars of a sufficiently bright magnitude to be imaged. The design benefits from the advantages of the APS imager in power and weight savings, radiation tolerance, and simplified electronics, while achieving sensitivity better than star magnitude 5, which gives a reliable attitude solution over 99.5% of the sky.

After extensive design trades that included the cost of the flight experiment, an APS camera was chosen with the properties listed in Table 1.

Table 1: ISC Star Camera Design

Focal plane	Lens
512 x 512 pixels	21 x 21 deg FOV
25-μm pixels	35-mm focal length
Quantum efficiency > 0.2	F# 1.2
Noise <100 electrons	Lens efficiency > 0.8

Similar magnitude-sensitive WFOV and medium field of view (MFOV) star cameras have been flown in space with great success, but without an APS imager. [4,5,6,7,8] Fundamental to the ISC design is the STAR250 APS designed and built by Fill Factory of Mechelen, Belgium for the European Space Agency's ASCoSS (Attitude Sensor Concepts for Small Satellites) project.[9] This existing design was chosen for the ISC star camera based on the sensor's specifications and its ability to detect stars of magnitude 5 or brighter for ISC specific integration times.

The ISC uses a 21-deg FOV lens with a 35-mm focal length and an F# of 1.2. The star images are defocused to 1.5 pixels Full-Width Half Maximum (FWHM) to allow for interpolation of star centroids to approximately 1/10th of a pixel. A Zeiss lens, based on a design used in motion-picture applications, will be modified by the manufacturer to make it suitable for space flight. The variation of the lens back focal distance over the range of operating temperatures is expected to be very low given the heritage of the lenses under consideration.[10] A lightweight custom carbon fiber outer baffle is baselined within the ISC design to reduce stray light effects.

MEMS Gyros

The ISC MEMS gyro assembly incorporates Draper's latest tuning-fork gyro sensors and ASIC-based electronics designs. The MEMS device is a TFG14-R3, 20-μm thick sensor fabricated in a silicon-on-insulator process that incorporates novel features for high performance. Gyro electronics are the latest mixed signal Application-Specific Integrated Circuit (ASIC), Gyro ASIC 4, designed to operate with approximately 12 off-chip components at a power draw of 75 mW. Inertial systems fabricated from these components have been used in guided ballistic munitions, autonomous vehicles, and space applications. The systems feature factory-type temperature compensated in-run performance of 1 to 10 deg/h bias and 100 to 300 ppm scale factor over temperature ranges of -40°C to +85°C. In-run performance improves to levels of <1 deg/h and <100 ppm over smaller temperature variations of 10°C to 20°C and can be improved further using dynamic calibration techniques that feed back scale factor and bias corrections via Kalman filtering. Angle Random Walk (ARW) is typically 0.1 to 0.3 deg/ h for gyros with input scaling to 1000 deg/s and can be reduced via optimization of sensor scale factor by varying operating parameters. For the ISC effort, the gyro design will be optimized for noise performance, resulting in ARWs in the range of 0.05 to 0.1 deg/ h. The combination of low ARW and dynamic calibration will enable greater attitude accuracy to be obtained.

The ISC MEMS gyro assembly (Figure 5) will adapt an existing 3-axis assembly design using TFG14-R3 sensors and Gyro ASIC 4 electronics and scale the instruments to the ±150 deg/s levels more compatible with intended space applications. This improves resolution and noise performance by minimizing susceptibility to additive noise in the data acquisition electronics. The gyro assembly will include data acquisition electronics to provide 16-bit angular rate, temperature, and health and status data to the processor at 100 Hz. Advantages of using MEMS-based spacecraft components include small volume (<30 cm^3), mass (<60 grams), and high resistance to radiation and vibration.[11]

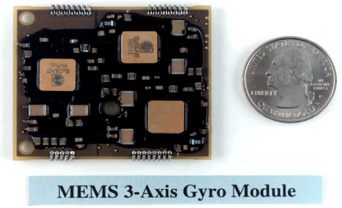

Figure 5: ISC MEMS 3-Axis Gyro Model

Power and Data

The CGA has three primary external interfaces: data, power, and debug. Communication to the DPA is via a custom synchronous serial stream. The power interface necessary for the CGA is derived from +28V sourced from the DPA. The CGA debug interface is provided for testing the CGA without disassembly or demating. It provides a digital parallel interface used to checkout the CGA.

Data Processing Assembly (DPA)

Hardware Design

The processor consists of a Draper-developed single-board computer (SBC) built around the ERC32, a commercially available low-power embedded processor from Atmel Wireless and Microcontroller Corporation. The ERC32 is a single-chip solution for a SPARC V7 type microprocessor. It is an integrated 32/64-bit floating-point processor tolerant to very high radiation doses (300Krad), virtually immune to latch-up, and extremely robust to single-event upsets (SEUs).[12] The chip is a fully static design and typically consumes 0.4 W at 14 MIPS/3 Mflops when powered by a 3-Vdc supply.[13] This highly integrated high-performance chip, when combined with FPGA-based interface logic and external memory, provides all the Central Processor Unit (CPU) interfacing necessary for the ISC in a very small volume at low power, while still maintaining both computational ability and excellent radiation performance.

The development environment is very rich with commercially and freely available software tools, including a GNU compiler and GDB for debugging. Commercially available development boards are available at moderate cost allowing for concurrent hardware and software development.

The DPA interfaces with the host spacecraft via a 15-pin RS422 interface. Command and data handling functions for the ISC are handled within the DPA. Power for the ISC is supplied via a +28V line sourced from the host spacecraft.

Software Design

Implementing the attitude determination algorithms and controlling the stellar-inertial system requires a substantial software component. Software functions include gyro and camera data acquisition, image processing, star detection and identification, data fusion, Kalman filtering, command and data handling, and housekeeping.

The attitude determination function (see Figure 6) generates attitude with respect to celestial space for all three axes relying on information from *both* the MEMS gyro and star camera software. Fundamental to this approach is use of an extended Kalman filter that processes the slower, low frequency information from the star camera and estimates the gyro bias drift and delta quaternion from the high frequency compensated gyro acquisition data.

Gyro data are acquired at 100 Hz and compensated digitally using calibration data from thermal performance and noise models, suitably updated in real time based on observed performance. These high-frequency data are fed to the ECI quaternion determination software, which produces a 5-Hz attitude solution to the host spacecraft. At modulo 0.1 Hz, the quaternion determination software requests a quaternion from the star camera, which is time-synchronized with this data and fed to a square root type, 27-state Kalman filter. The filter computes a correction to the attitude quaternion and the bias compensation, that are fed back directly to the main quaternion determination and gyro compensation software, respectively. The camera provides this attitude data to correct the low-frequency drift of the gyro. The gyro can then maintain desired attitude determination accuracy between updates. Simulation has shown that 5-min updates will suffice for 0.1-deg accuracy and that more frequent updates will yield even better accuracy.

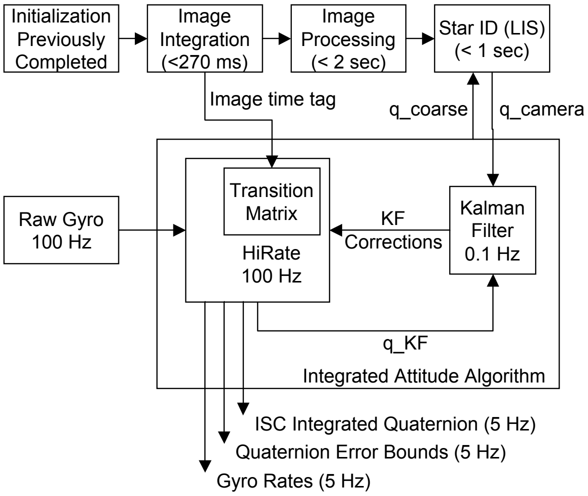

Figure 6: Attitude Determination Block Diagram

The net data products are the ECI attitude and an estimate of the three-axis angular rates. Other selectable data products include attitude error bounds, angular acceleration and raw time-tagged MEMS gyro or star camera data.

Star identification can be accomplished in many different ways and is a widely accepted method for attitude determination onboard many types of spacecraft. The ISC software uses Mortari's Pyramid algorithm.[14] This algorithm presents a fast and robust star identification technique applicable to WFOV cameras that does not use a searching phase. The Pyramid algorithm is capable of identifying stars without any prior attitude knowledge in less than 1 minute on the ISC target processor running at 4 MHz. Furthermore, the algorithm is extremely tolerant of spikes. For the ISC application, four valid centroids will provide a false match frequency of only $5x10^{-5}$. The ISC software uses Mortari's ESOQ-2 algorithm to determine a star-camera quaternion from the identified stars. [15]

The Mortari Pyramid algorithm was further modified to use prior attitude knowledge provided by the gyros. Specifically, the K-vector method has been modified to trim the number of candidate star pairs that would normally be returned, according to the direction of the camera boresight. This filtering is especially important given the sizeable centroid errors, and hence the large sample of candidate star pairs associated with a WFOV design.

ISC Flight Validation

The Space Shuttle Hitchhiker (HH) carrier has been selected for ISC flight validation (see Figure 7). Given the ISC's small mass and volume, it is an excellent candidate for a HH mission. Multiple flight opportunities are likely to be available in the 2004 time frame. A tentative Shuttle/HH manifest date appears likely in February 2004, which matches well with the ISC schedule. The Shuttle will provide an attitude reference to assist in ISC validation, although the ISC will be capable of self-scoring without an external attitude reference. HH also provides all power, command and data interfaces required by the ISC. All experiment data, as well as Shuttle attitude reference data, will be time-tagged and downlinked during the mission.

The validation approach is to operate the ISC as much as possible in its intended operational environment, gathering attitude output data and raw data for ground analysis to validate the ISC's performance. The ISC will have the ability to self-score its performance by measuring gyro drift via frequent camera updates and providing raw image data for validation of camera attitude output.

The ground system for mission operations will consist of the ISC's Mission Operations Computer (MOC) connected to the HH payload operations control center (POCC). The software within the MOC will command and control the ISC while the Shuttle performs prearranged ISC attitude maneuvers at opportune times throughout its primary mission. Since all of the ISC data and commanding rates are within the allowable data rates of HH (38.4 Kbaud), the POCC and HH will serve as a direct communications feed between the ISC onboard the Shuttle and the ground-based MOC software. This simplifies the overall flight system and increases reliability since all the command, control, and situational awareness will be within the ISC team, with little or no intervention required from Shuttle personnel.

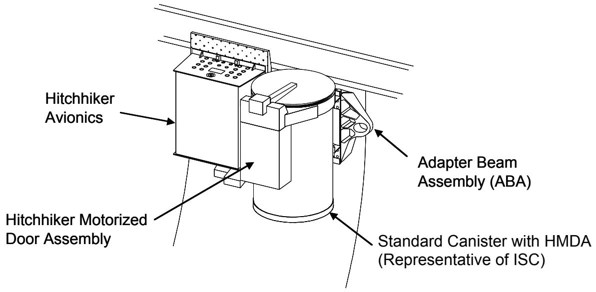

Figure 7: Typical HH Sidewall Payload Configuration

Mission operations will consist of continuous monitoring and control of the ISC instrument in its various configurations. The mission plan will consist of gathering performance data over the full operating range of the instrument, including sky coverage (driven by Shuttle attitude), rotation rates (accommodated by specific Shuttle maneuvers), and temperature profiles (using canister heaters).

ISC mission operations will be entirely scripted, qualified, and rehearsed through standard operating procedures established for any HH mission prior to flight. All data will be archived by the MOC and the POCC as they are received for analysis after the mission.

Conclusions

Draper Laboratory has developed and will soon flight validate the Inertial Stellar Compass (ISC), using the complementary technologies of an Active Pixel Sensor (APS) imager and Micro-Electro-Mechanical System (MEMS) gyros to demonstrate a real-time, miniature, smart spacecraft attitude determination sensor. The ISC is a self-initializing, integrated attitude determination system with 0.1-degree accuracy and high-rate maneuver capability, all in a 3.5 W, 2.5 kg package suitable for a wide range of microsatellite missions. Potential ISC missions may include the use of highly maneuverable, stabilized, tumbling, or lost spacecraft.

The ISC is planned to fly on the Shuttle in early 2004 and its flight validation will provide a viable technological path for its use on future spacecraft missions. The low power and low weight of the ISC will bring 0.1-degree attitude determination capability to a new class of small satellites, enabling the development of highly capable nano-satellite platforms.

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