Abstract: Draper’s 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 sensor (APS) star camera and a microelectromechanical system (MEMS) gyro assembly, with associated processing and power electronics. The integrated APS and MEMS gyro technologies provide a 3-axis attitude determination system with accuracy better than 0.1 degree at very low power and mass. The attitude knowledge provided by the ISC is applicable to a wide range of space missions that may include the use of highly maneuverable, stabilized, or even tumbling spacecraft. Under the guidance of NASA’s New Millennium Program’s ST-6 project, Draper has developed and now flight validated the ISC. Its completion via flight validation represents a breakthrough in real-time, miniature attitude determination sensors. This paper describes the space validation component and initial on-orbit results of the ISC.
Inertial Stellar Compass
Achieves 0.1° attitude determination in a small, low power, bolt-on package

- NASA New Millennium Program ST6:
  - Develop and validate a low-power, low mass attitude determination system
  - Flight validation necessary component

- Complementary technologies used in the design: MEMS gyros and an active pixel sensor star camera
  - Gyros provide continuous attitude information
  - Star camera periodically provides attitude “truth” which bounds gyro error (bias and scale factor) growth
  - Kalman filter combines the data and outputs quaternions at 5Hz

- “Lost-in-Space” initialization capability

- Key Specs:
  - Power: 3.6 W
  - Mass: 2.9 kg
  - Accuracy: 0.1°, 1 sigma in 3 axes
  - Slew Rates: up to 40°/sec

- The success of the ISC marks for the first time the successful use of MEMS gyros in space
  - Demonstrates that MEMS devices have a promising future in space given their inherent low power and low mass qualities.

- ISC composed of two assemblies:
  - Data Processing Assembly (DPA)
  - Camera Gyro Assembly (CGA)
The Inertial Stellar Compass is an Integrated Attitude Determination Solution

Fusion of Camera and Gyro Data

Camera Gyro Assembly

Data Processing Assembly

Attitude to spacecraft

Functional Block Diagram

Active Pixel Camera

Image Processing

Periodically Processed Star Image

Star ID Algorithm & LSF

Known Star Positions

Star Catalog

MEMS Gyros

Gyro Compensation

Gyro Parameter Tuning Update

Continuous Rate

Kalman Filter

3-axis orientation (truth)

Synthesized attitude solution

Periodically Processed Star Image

Gyro Parameter Tuning Update

Known Star Positions

3-axis orientation (truth)

Synthesized attitude solution
The Camera Gyro Assembly

- Integrated for sensor alignment
- Small package
- Low-power controller board
  - No data processing
  - Digital I/F
**ISC Star Camera Design**

- 21° square FOV
- 35mm f/1.2 Lens
- 512 x 512 pixels
- Sees 1500 brightest stars in sky
- 0.4 W
- 37” in roll and 18” in pitch and yaw (1 sigma)
- Capable of taking raw images on demand
ISC Gyro Design

- Maximum Input Scaling: 40°/s
- Board Power = 0.90 W
- Sampling rate: 320 Hz
- Measured Performance
  - Bias Drift Rate = 3.3°/hr
  - Angle Random Walk = 0.16 °/rt-hr
  - Scale Factor Error = 100 PPM
**The Data Processing Assembly**

- **Power conditioning**
- **Low-power processor**
  - Processor clocked down to 4Mhz
  - Sparc7 on a chip
  - 32 bits
- >50K Radiation tolerant, SEL immune, SEU tolerant
Flight Validation of ISC on TACSAT-2 Spacecraft

• TACSAT-2 Spacecraft
  – 350kg Air Force TACSAT-2 (RoadRunner) spacecraft, launched December 16th, 2006
  – Concept Baseline to Launch Ready in 14 months
  – Storage to On-Orbit Functionality in 7 Days
  – Autonomous On-Orbit Commissioning in 24 Hours
  – In-Field Tactical C3 of Satellite
  – Visible Imagery Under 1 Meter GSD
  – Geolocate RF Targets and Image in Same Pass
  – Demonstrate Additional Advanced Technologies

• Primary mission is to obtain 1m visible imagery coupled with RF geolocation

• Inertial Stellar Compass validation
  – Power, Commands, Telemetry
  – Point (low angular rate)
  – Slew (high angular rate)
  – Sky coverage > 90%
TACSAT-2 Successfully Inserted in 407km x 410km orbit

Note: These pictures are not mine, not sure who took them, but they certainly deserve credit!
The ISC is on-orbit and looking GREAT!

- **Initial turn-on 12/27/06**
  - Normally remains powered-on in background mode

- **ISC Demonstrating Exceptional Performance**
  - Camera reporting valid quaternions
  - MEMS gyros reporting valid body rate information
  - Integrated attitude meeting 0.1° requirement

- **Operation time (as of 6/4/2007):**
  - ~150 days
  - 29 power cycles during S/C safe modes

- **Temperatures between 5°C to 28°C**

- **Data Collection (as of 6/4/2007)**
  - >31 MByte of dedicated Diagnostic Data
  - Approx 430 background orbits > 1.7 GByte of data

- **ISC software**
  - No patches or changes to ISC software needed while on-orbit

- **Communication**
  - **Commands**
    - Commands accepted normally by the ISC (tens of thousands)
  - **Telemetry**
    - Normal, except for occasional TacSat-2 carrier spacecraft -to-AFRL-ground station drop outs (unrelated to ISC operations)
Run 11 Data Details

- **Dedicated ISC Operation on 12/28/2006**
  - A dedicated ISC slew run on RR that occurred at 19:10z, to an inertial hold, then a slew back to the sun at 19:50z.
  - The ISC was initially in BKG mode, then switched to DIAG mode at 19:42z
Body Rates during Slew Up (Run 11)

ISC sees body rates imparted by RR to do slew at correct magnitudes.
ISC Camera Stars and Centroids (Run 11)
First Light Star Camera
Raw Image

Some bright stars
First Light Star Camera
Overlay ISC Reported RA/DEC w/Magnitudes

![First Light Star Camera Image]
R11: ISC Integrated Attitude, Self Score

Data is converged!

Green is Camera Attitude
Blue is Integrated Attitude
Red is 0.1 deg error bound

1-σ = 0.0371°
1-σ = 0.0363°
1-σ = 0.0384°

Within 0.1° Spec!
**R11: ISC Integrated Attitude vs. Spacecraft Attitude**

### Graph 1

- **δ \( Q_{isc} \) RA
- **δ \( Q_{isc} \) DEC
- **δ \( Q_{isc} \) Roll

**1-σ = 0.0594°**

**1-σ = 0.0523°**

**1-σ = 0.0335°**

*Within 0.1° Spec*
Camera Validation Example: R340 Images

Capella

Shaula

Aldebaran

Menkent

Antares

scorpius

Jupiter

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Multi-Slew Accuracy Validation Example: Run 407

- **ISC background dedicated slew on Mar 29th, 2007**
  - Approx 84 minutes dedicated to ISC slews
  - Approx 45 minutes of valid ISC data collected during S/C eclipse

- **11 slews to 5 different starfields then back to sun track**
  - Gacrux, Spica, Menkent, Shaula, Antares
  - Last 3 slews – camera occluded by Earth
R407: ISC Body Rates Output

Slew back to sun track

Gyro Rates

seconds

deg/sec

2500 3000 3500 4000 4500 5000 5500 6000 6500
R407: Integrated Attitude Output (Declination Only), Self Score

Self Score Accuracy
RA=0.063°
DEC=0.043°
ROLL=0.045°

Within 0.1° Spec

Blue line – ISC Integrated Attitude
Green dots – ISC Camera Attitude
Red dashed line – Camera Relative 0.1° 1σ Error Bound

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R407: ISC Integrated Attitude vs. Spacecraft Attitude

\[ \delta Q_{isc}(sc) \text{ RA} \]
\[ 1-\sigma = 0.0700^\circ \]

\[ \delta Q_{isc}(sc) \text{ DEC} \]
\[ 1-\sigma = 0.0747^\circ \]

\[ \delta Q_{isc}(sc) \text{ Roll} \]
\[ 1-\sigma = 0.0511^\circ \]
ISC Can Provide Backup Sensing for Spacecraft

- Small footprint, low power, highly integrated nature of the ISC allows for spacecraft designers to accommodate the additional attitude and rate determination functionality ISC offers
- Detumble device for contingency
  - Safe hold mode device
  - Unexpected tipoffs from launcher
  - Primary ADCS sign errors
- Secondary reference for attitude and for rates
  - Sanity check primary ADCS sensors
  - Backup in case of primary failure
- Secondary camera could be used for variety of reasons
  - Track other distant spacecraft
  - Image relative position and pose
  - Confirm any optical jamming
The ISC Enables Small MicroSatellites

Draper DSTAR
Detection Satellite Targeting Autonomous Rendezvous

Billingsley Magnetometer
- 3 axis sensing
- Digital output

Spectrolab Solar Arrays (18 panels)
- 2 Triple Junction GaAs
- 28% Efficiency
- 25 cm x 25 cm panel
- Large power margins at EOL
- Honeycomb Al structure

Teldix Miniature Reaction Wheels (3)
- 2N-m/s absorbs all disturbances torques
- Low bias rate eliminates zero-crossover disturbances

Ithaco TR10CFR Torque Rods (3)
- 10 Am² momentum dumping capacity
- 15 redundant windings

Power Electronics
- HETE EPS heritage, smaller scale
- Built in coulometry
- Power point tracker design
- Hardware load shedding
- 90% efficient

S-Band Transceiver
- Exact duplicate of HETE transceiver
- Uplink data rate = 31.25 kbps
- Downlink data rate = 250 kbps
- Ranging capable

Propulsion Options
- High ISP Thruster gets DSTAR to RSO

400mm ISC CGA Based Optical Camera
- Used to image RSO from a distance

SPIRE – Space Passive Imaging Ranging Element
- Uses only optical cameras to obtain target position
- NO ACTIVE LIDAR necessary to obtain range
- Low mass and power solution for target range and bearing
- Accuracy to better than 10% of true range

Inertial Stellar Compass
- 3.5 W, 2.5 Kg, bolt-on sensor
- Direct quaternion output
- Self initializing
- Sense rates up to 50 deg/sec
- 0.1 deg accuracy

ISC DPA Based C&DH
- 32 MHz ERC32 microprocessor
- Large IO capability
- Integrated, space proven GPS
- Low volume, mass, and power

Mass < 42 kg
Power < 44 W

ISC ENABLED SOLUTIONS

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The ISC Exceeds Customer Requirements

- **Status**
  - Flight unit complete
  - Ground validation complete
  - Flight validation complete

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<td>Mass</td>
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Successful combination of APS star camera and MEMS gyro package into single integrated instrument

Achieves 0.1° attitude determination in a small, low power, bolt-on package