# A Stellar Gyroscope for CubeSat Attitude Determination

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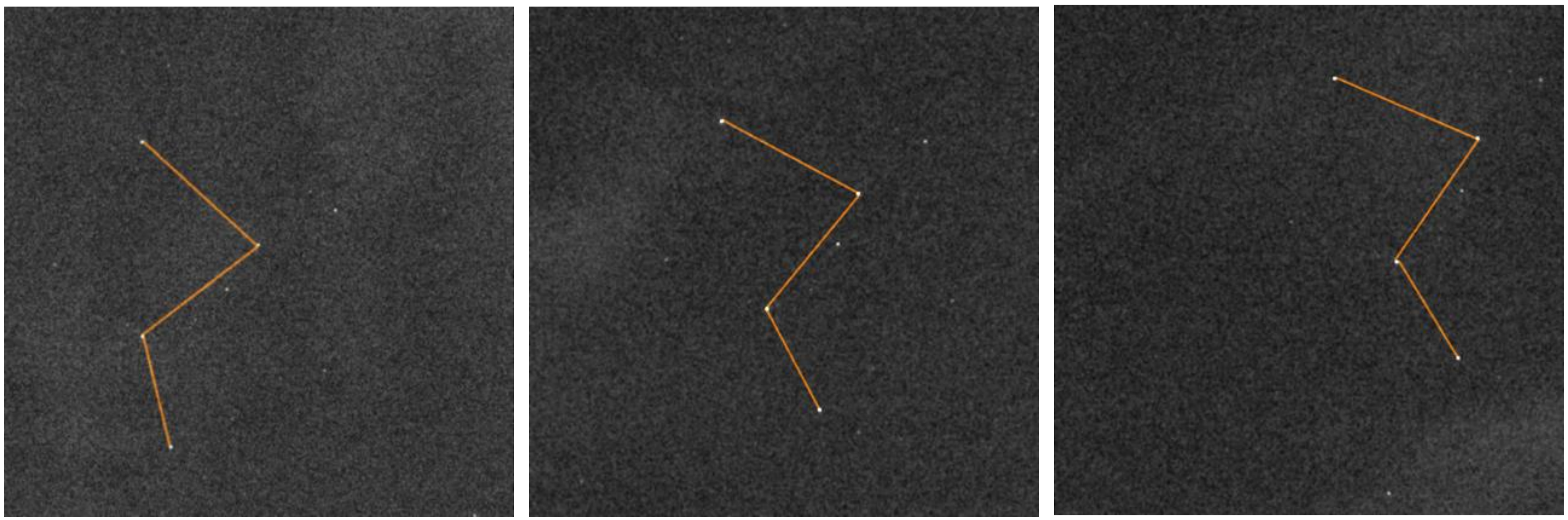
# Presentation Overview

- Stellar Gyroscope Concept
- Motivation
  - CubeSat ADCS
  - Attitude knowledge in eclipse
- How the Stellar Gyroscope Works
- Flight Experiment

# Concept of Stellar Gyroscope

Observe the motion of stars in camera's field of view to infer changes in satellite's attitude.



- Measures relative attitude between exposures with common stars
- Tolerates large amount of noise, allowing low cost assembly and small form factor

# CubeSat Attitude Determination Challenge

<u>In Sun Light</u>

- Magnetic Field Vector
- Sun vector
- Earth Sensor
- Star Tracker: *needs baffle*

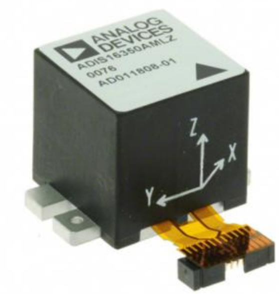

<u>In Eclipse</u>

- Magnetic Field Vector
- *No* Sun Vector
- Earth *not lit* for Earth Sensor
- Star Tracker
- Rate Gyroscope integration *with drift*

SSBV CubeSat Solution:
Sun: Sun Sensors & Magnetometer + GPS
Eclipse: MEMS Gyros + ***Stellar Gyro***

# Motivation - Alternatives for Eclipse

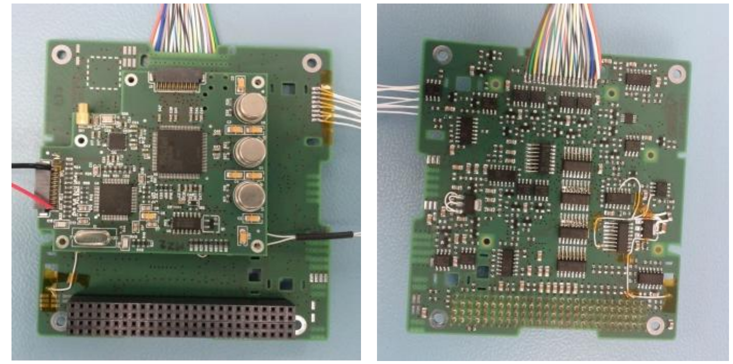
- Attitude measurement challenging (Earth sensor in InfraRed, Star Tracker)
- Laser Ring Gyros: Highly accurate, Large, Expensive
- MEMS Gyroscopes:
  - Compact, and Affordable
  - Small Satellites almost exclusively use MEMS
  - Noisy: drift ~0.5 degrees per minute

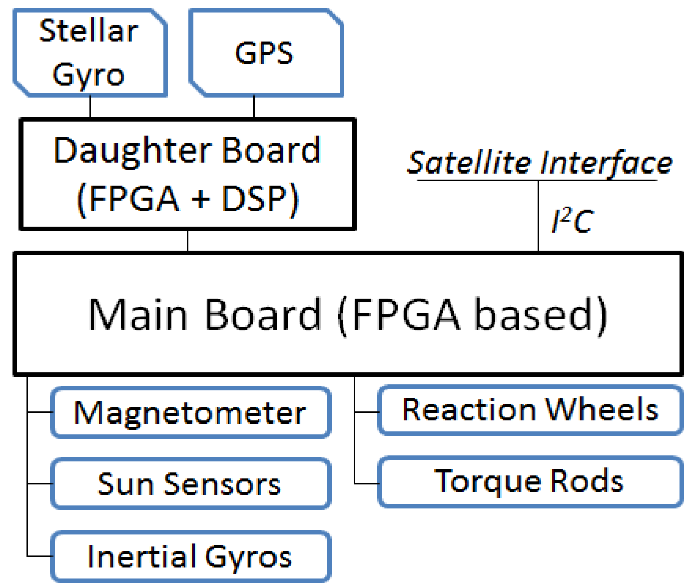



- Image-based Approach (stellar gyro):
  - Comparable volume and cost
  - Added computational requirements
  - Can assist MEMS gyros by limiting drift

# ADCS System

- In Sun light:
  - Magnetometer, with magnetic model and GPS position knowledge
  - Sun Sensors, using Position Sensitive Detector (not photodiodes)
- In Eclipse:
  - MEMS inertial gyroscopes
  - Assisted by stellar gyroscope to reset drift

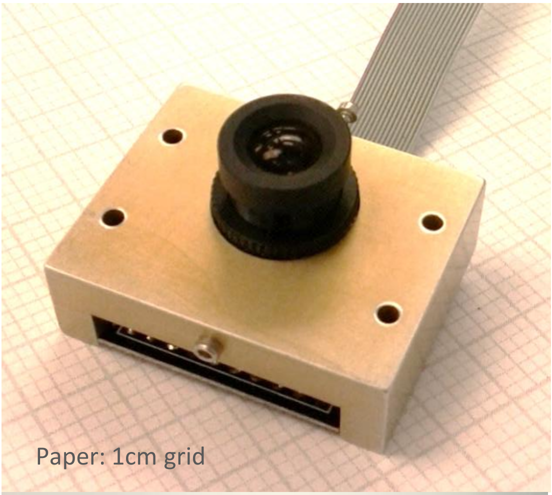


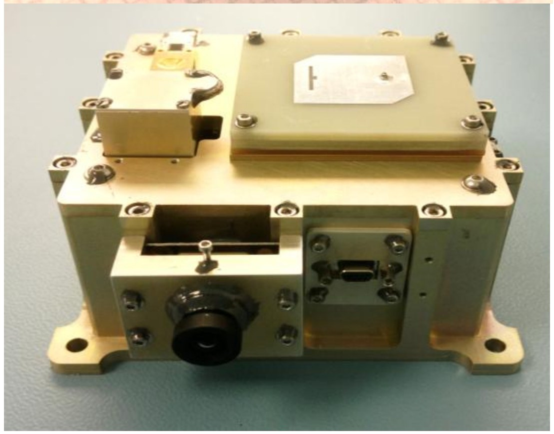


# Camera Specifications

- CMOS Sensor with S-Mount Lens
- Designed to capture Star Magnitude 4 and brighter
- At least 3 stars in Field of View in 99% of the sky.

| Parameter | Value |
|---|---|
| **Sensor** | OmniVision OV7725 CMOS VGA Sensor (640 x 480 pixels) |
| **Optics** | 6 mm focal length, Aperture F/2.0 |
| **Field of View** | 27.6° by 36.7° |
| **Sensitivity** | 3.8 V/(Lux · s) |
| **S/N Ratio** | 50 dB |
| **Dark Current** | 40 mV/s |
| **Pixel Size** | 6 x 6 μm |



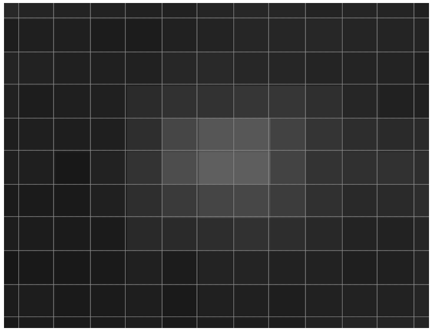
Camera assembly as experiment on TDS-1.
Further miniaturization is possible.

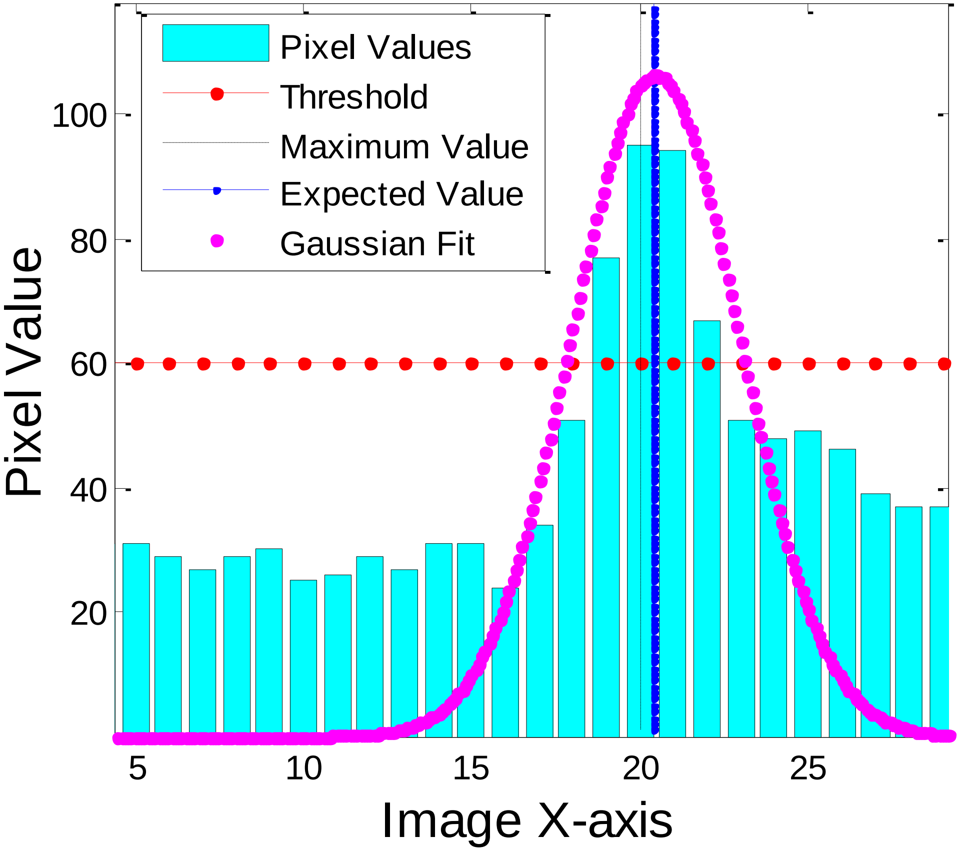
# Star Detection

- "Centroiding", aka Expected Value

$$E(x) = \sum x \cdot f_x(x)$$

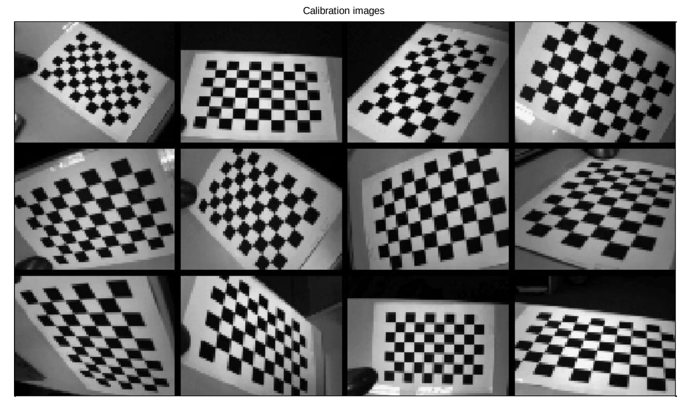
$$f_x(x) = \sum_y f_{xy}(x,y)$$

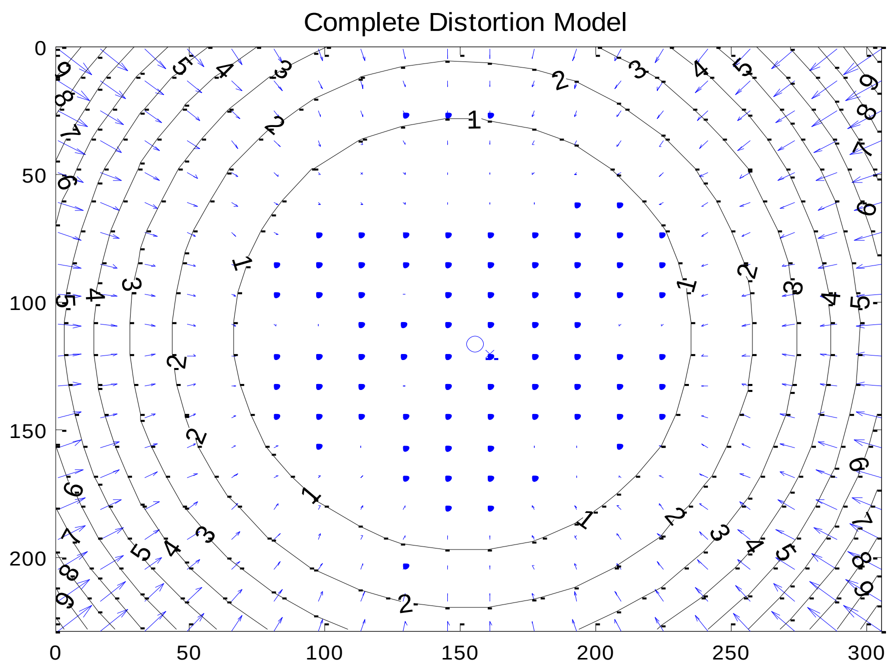


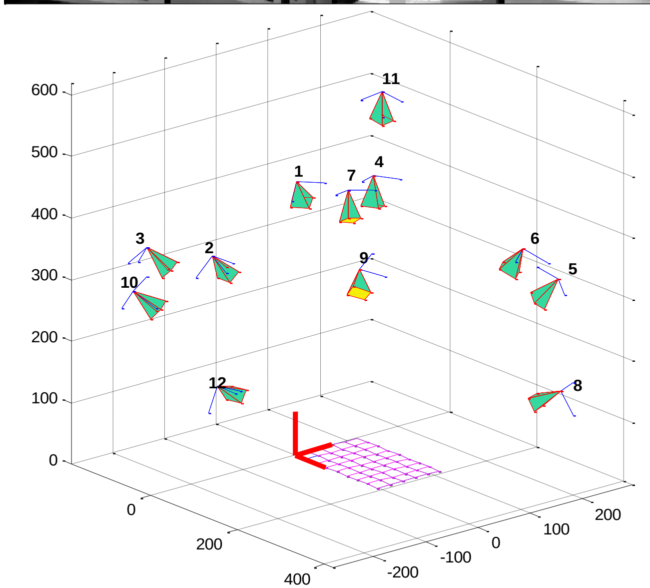


# Camera Model

- Camera Calibration to characterize:
  - Principal Point
  - Focal Length
  - Lens Radial and Tangential Distortion
- Used to acquire precise star vectors




Camera Calibration Toolbox – by Jean-Yves Bouguet
http://www.vision.caltech.edu/bouguetj/calib_doc/

# Solving the Relative Attitude Problem

- Using the Direction-Cosine-Matrix (DCM) notation, the attitude change between two frames satisfies:

$$\overrightarrow{\mathbf{v}^b} = C^{ba}\,\overrightarrow{\mathbf{v}^a}$$

- The goal is to find the rotation matrix ($C^{ba}$) that defines the rotation between frame *a* and frame *b*.

- Given at least two vector measurements (two stars before-and-after), The Q-Method is used to find the analytically optimal relative attitude estimate.

# Correspondence Across Frames

- False-positives: noise
- False-negatives: missed stars
- Entering and Leaving FOV.
- Correspondence Problem: identifying the same star across frames.
  - By brightness: highly susceptible to noise
  - By predicted location: susceptible to unexpected maneuvers and to false-stars and missed stars

Overlaid detected stars in 5 images that are 3 degrees apart

# Random Sample Consensus (RANSAC)

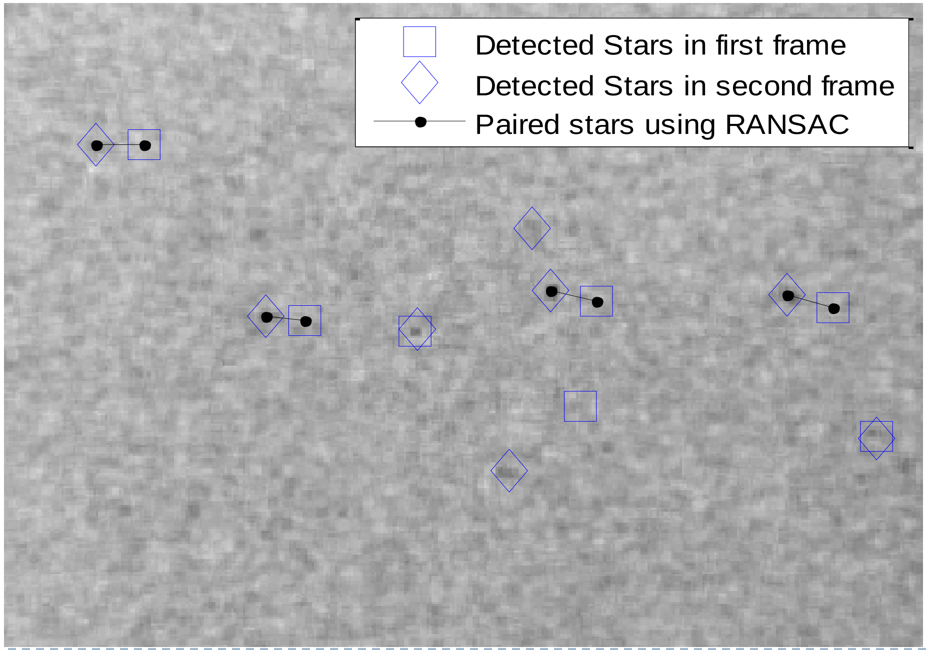
- RANSAC: iterative method to estimate parameters of a mathematical model from a set of observed data which is contaminated a large number of outliers that do not fit the model.
- The steps of RANSAC can be summarized as
  - **Hypothesize:** A hypothesis rotation is based on MEMS rate information, or calculated using randomly selected star pairs across frames.
  - **Test:** The estimated rotation matrix is tested against all the stars in the two frames. Stars that show consensus are counted towards the Consensus Set (CS).
  - **Iterate:** RANSAC iterates between the above two steps until a random hypothesis finds "enough" consensus to some selected threshold.

# RANSAC Performance

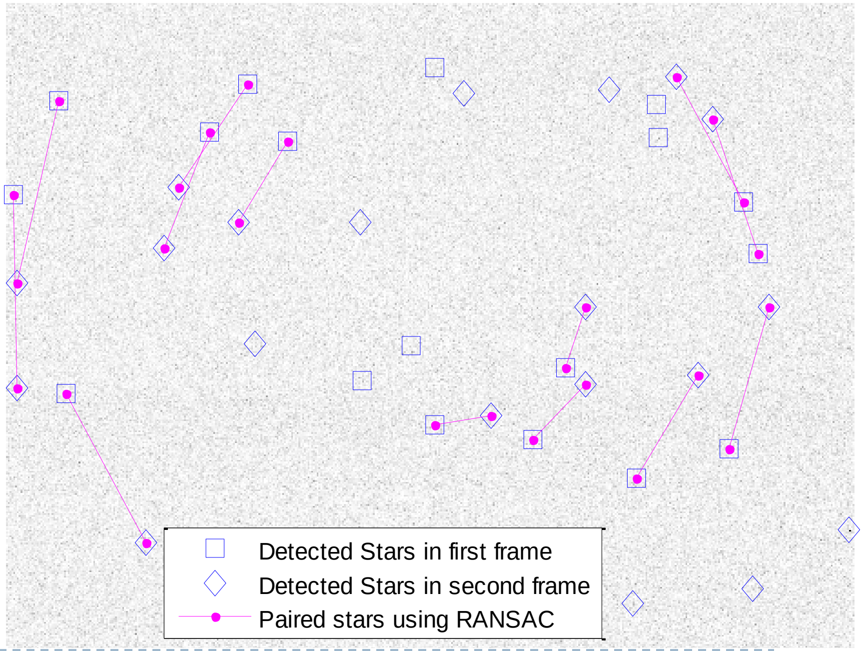
- Observe Motion of Earth
- 1 degree every 4 minutes
- Photos of the night sky at 0.25° increments, pointing arbitrarily up.
- Prototype Hardware

- Previous Work
- Photos of the night sky using Spin Table
- Canon G10

Rotation Estimate = 1.4495°, Actual Rotation = 1.5°

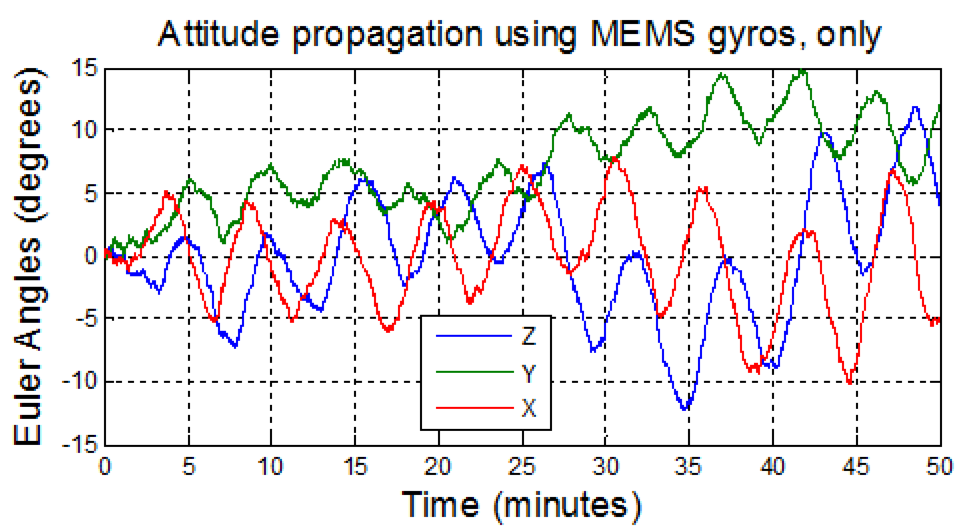



Angle Estimate = 25.0549°, Actual= 24.960975°



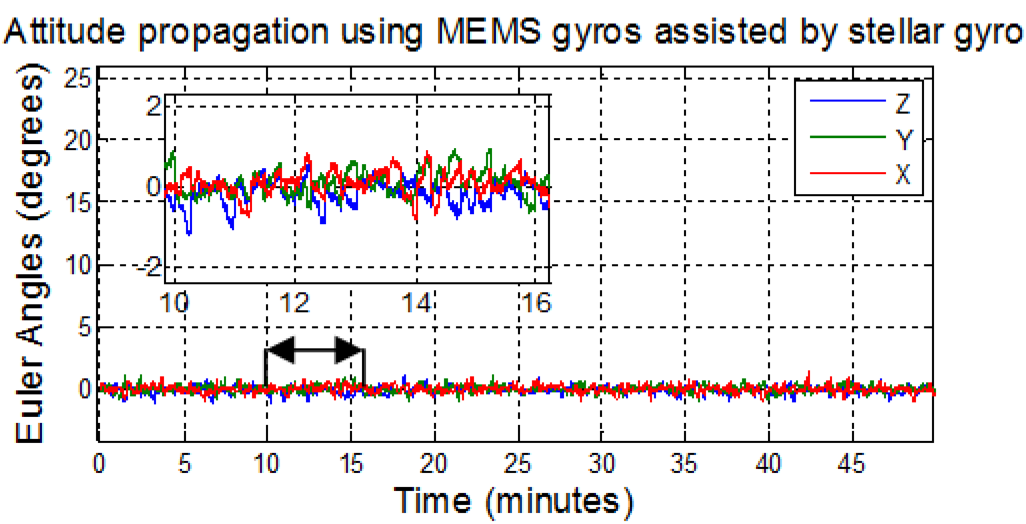
# Attitude Response in Eclipse: MEMS only

- Assuming perfect attitude knowledge before entering eclipse
- MEMS rate gyro: 50Hz, ±80 °/second, 12-bit ADC, Noise 0.1 °/second RMS
- Attitude knowledge error increases up to 5 ° in the first 5 minutes and more than 10 ° after 35 minutes.



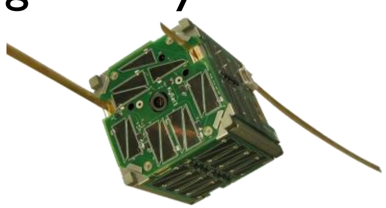
# MEMS assisted by Stellar Gyroscope

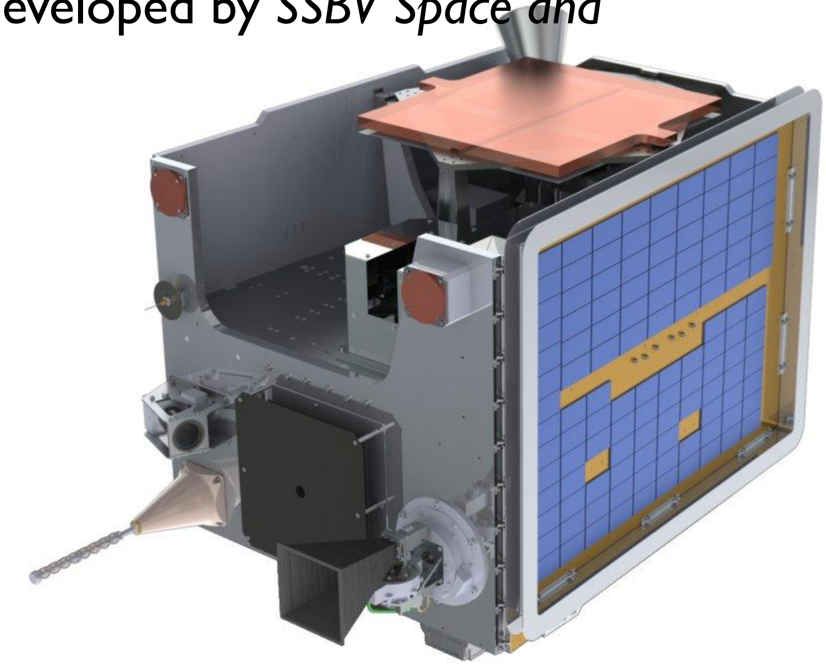
- Assuming perfect attitude knowledge before entering eclipse
- Stellar gyro generates attitude estimates (σ = 0.1°), at 15 second increments, relative to the first photo taken at the beginning of eclipse.
- Drift is maintained below 1°



# Flight Experiments

- TechDemoSat-1
  - Surrey Satellite Technology LTD, UK. Around 1-meter cubed, 150 kg.
  - No less than 8 technology demonstration payloads Maritime Suite, Space Environment Suite, Air and Land Monitoring Suite, Platform Technology Suite
  - TDS-1 will test CubeSat ACS payload developed by *SSBV Space and Ground Systems UK*
- KySat-2 (Kentucky Satellite-2)
  - Kentucky Space Consortium
  - 1-Unit CubeSat
  - Improved refight of KySat-1 mission objectives





# Conclusion

- Stellar Gyroscope finds relative attitude by tracking stars
- Correspondence (using RANSAC) can be done with large levels of noise, enabling implementation with low cost sensors and optics
- SSBV CubeSat ADCS system is designed to maintain high quality attitude knowledge throughout the orbit
- In Eclipse, it uses a Stellar Gyroscope to reset the drift of a MEMS attitude propagator.

# Thank You

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