Attitude Determination and Control

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Dan Hegel - Intro

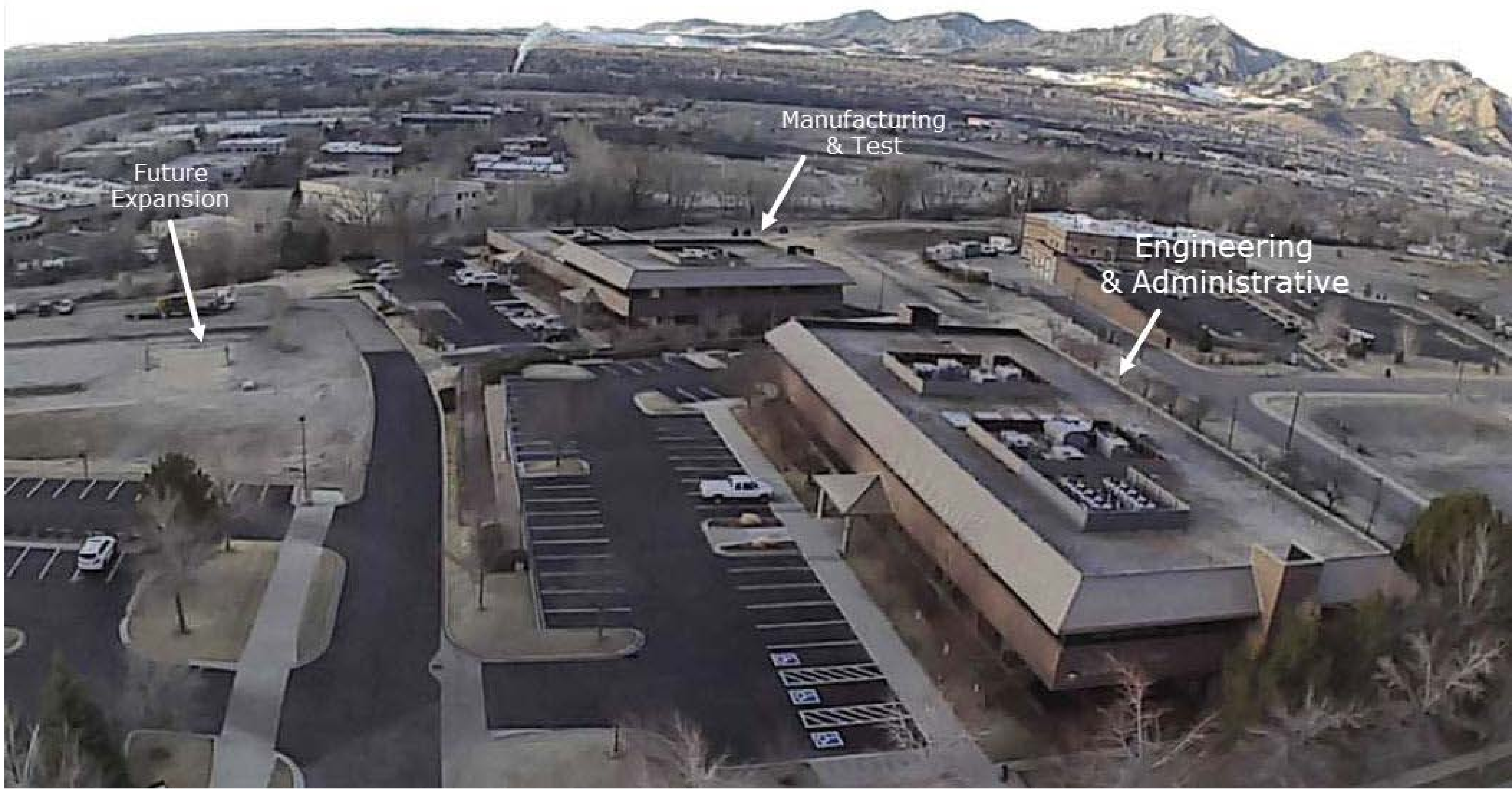
- Director of Advanced Development at Blue Canyon Technologies
  - Advanced mission concepts and new technology
  - Business development
- Helped start Blue Canyon Technologies as ADCS and simulation lead
  - Over 30 years' experience in ADCS
  - Chief architect of the XACT cubesat attitude control system
  - Star tracker primary developer
  - Primary developer of high-fidelity simulation and flight software auto-code system
- Prior companies include: Ball Aerospace, Motorola, and Lockheed
- Held lead GNC role, or had significant involvement, in over 15 spacecraft programs, including: Hubble Space Telescope, Gravity Probe-B, Iridium, QuikSCAT, SUOMI NPP, and the QuickBird and WorldView imaging spacecraft
- Education:
  - Bachelor's in Aerospace Engineering from Arizona State University
  - Master's in Aeronautics and Astronautics from Stanford University.

Agenda

- Quick BCT overview
- Basic attitude control loop
  - Sensors
  - Actuators
  - Control compensator
- Orbit determination and propagation
- Momentum Control

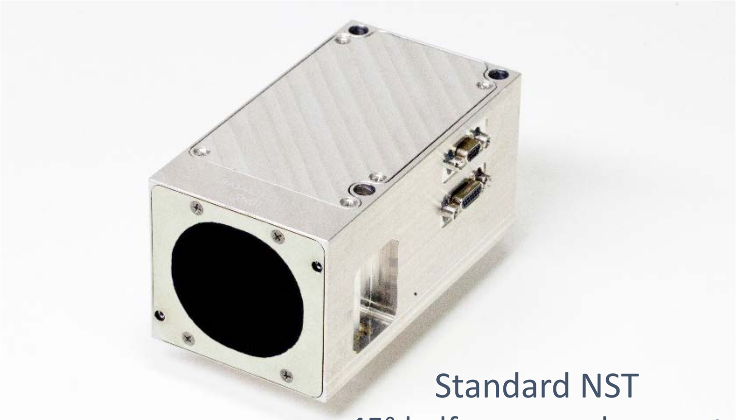
BCT Overview

- Founded in 2008
- Experienced team of space industry veterans
- Agile small satellites:
  - Spacecraft
    - Cubesats (3U, 6U, 12U)
    - Microsats to ~200kg
  - Components
    - Star Trackers
    - Reaction Wheels
    - RF Communication
- Staff & Facility:
  - 100+ people
  - 45,000 square feet



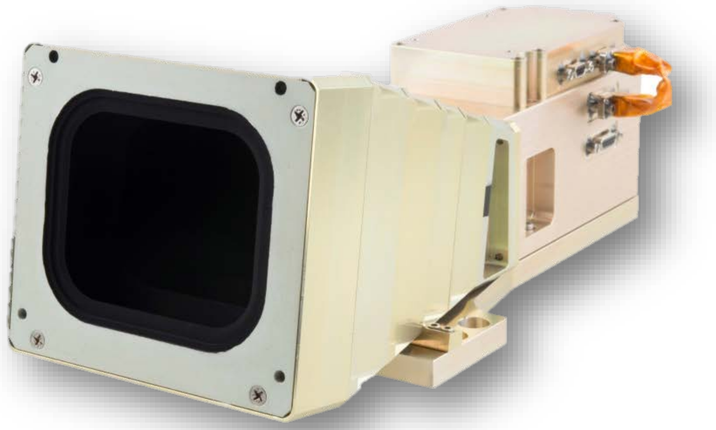
Nano Star Trackers

- The Blue Canyon Technologies Nano Star Tracker is a reliable, high performance design, compatible with a variety of SmallSat configurations and missions. Features include:
  - Tracks stars down to 7.5 magnitude
  - On-board star catalog (>23,000 stars) and lost-in-space star ID
  - Easy to integrate digital interface electronics
  - Compact packaging (CubeSat compatible)



Standard NST
45° half cone sun keep out

19 Star Trackers On Orbit



Extended Baffle NST
(+28V option, 17.5° half cone sun keep out zone)

Nano Star Tracker Capability

Specification	Performance
Attitude solution update rate	5 Hz
Bore-sight accuracy	3 arcsec (1-sigma)
Roll axis accuracy	20 arcsec (1-sigma)
Lost in space solution time	4 seconds
Field of view	10 x 12 degrees
Spacecraft lifetime	>5 Years (LEO)
Sky coverage	>99% sky coverage
Mass	0.35 kg (with baffle)
Volume	10 x 6.73 x 5 cm (with baffle)
Nominal power consumption	0.75W
Peak power	≤1.0W
Idle mode	0.5W
Operating voltage	5 +/- 0.1V
Data interface	RS-422

Reaction Wheels

- BCT Reaction Wheels provide an efficient, high performance solution for spacecraft attitude control
- Available in a range of sizes, providing a wide combination of torque and momentum storage
- Control electronics can be included internally to the reaction wheel, or in a separate unit
    - *Any size wheel* can be used with BCT attitude determination systems
      – Only table values in flight software need to change

48 RWp015 On Orbit

3 RWp500 On Orbit

	(MicroWheel) RWP015	RWP050	RWP100	RWP500	RW1	RW4	RW8
Momentum	0.015 Nms	0.050 Nms	0.10 Nms	0.50 Nms	1.5 Nms	4.0 Nms	8.0 Nms
Max Torque *	0.004 Nm	0.007 Nm	0.007 Nm	0.025 Nm	0.1 Nm	0.3 Nm	0.3 Nm
Mass	0.130 kg	0.24 kg	0.35 Kg	0.75 kg	1.6 kg	3.0 kg	4.1 kg
Volume	42 x 42 x 19 mm	58 x 58 x 25 mm	70 x 70 x 25 mm	11 x 11 x 3.8 cm	15 x 15 x 6.5 cm	17 x 17 x 7 cm	19 x 19 x 9 cm
Voltage	12 VDC	12 VDC	12 VDC	28 VDC	28 VDC	28 VDC	28 VDC
Power @ 1/2 Momentum	< 0.6 W	< 0.5 W	< 0.5 W	< 3.0 W	< 3.0 W	< 4.0 W	< 5.0 W
Power @ Full Momentum	< 1.0 W	< 1.0 W	< 1.0 W	< 6.0 W	< 7.0 W	< 8.0 W	< 10.0 W
Design Life	> 5 years	> 5 years	> 5 years	> 10 years	> 10 years	> 10 years	> 10 years
Static Unbalance * (Fine)	< 1.2 g-mm (0.25 g-mm)	< 1.2 g-mm (0.35 g-mm)	< 1.5 g-mm (0.5 g-mm)	< 3 g-mm (1 g-mm)	< 4 g-mm (1.8 g-mm)	< 6 g-mm (2 g-mm)	< 8 g-mm (2.8 g-mm)
Dynamic Unbalance * (Fine)	< 20 g-mm^2 (2.5 g-mm^2)	< 20 g-mm^2 (2.5 g-mm^2)	< 20 g-mm^2 (5 g-mm^2)	< 25 g-mm^2 (10 g-mm^2)	< 100 g-mm^2 (50 g-mm^2)	< 150 g-mm^2 (75 g-mm^2)	< 200 g-mm^2 (100 g-mm^2)

XACT / XB1 ADCS Module

- XB1 ADCS/C&DH is similar to stand-alone XACT
  - Nano Star Tracker for precise attitude determination (Integrated stray light baffle)
  - Three micro sized (or larger) reaction wheels enabling precise 3-axis control
  - Three torque rods
  - MEMS IMU
  - MEMS Magnetometer
  - Sun sensors
- Multiple pointing reference frames, such as:
  - Inertial
  - LVLH
  - Earth-fixed target
  - Solar
  - Other spacecraft
- Highly-integrated architecture with powerful, robust processing core

8 Units On Orbit.
Dozens more to go.

2 on their way to Mars!

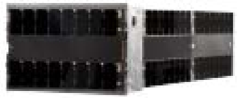
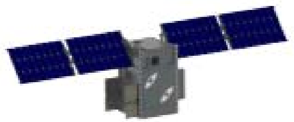
0.5U module
(15 mNms wheels)

***XACT** Single tracker pointing accuracy:*
0.001 deg, RMS, 2 axes,
0.004 deg, RMS, 3rd axis,

***XB1** Power module contains 2nd tracker.*
Resulting 2-tracker pointing accuracy:
0.001 deg, RMS, all 3 axes,

BCT Family of Buses

Delivering over 50 spacecraft, from 3U to ESPA-class and ESPA to 200kg

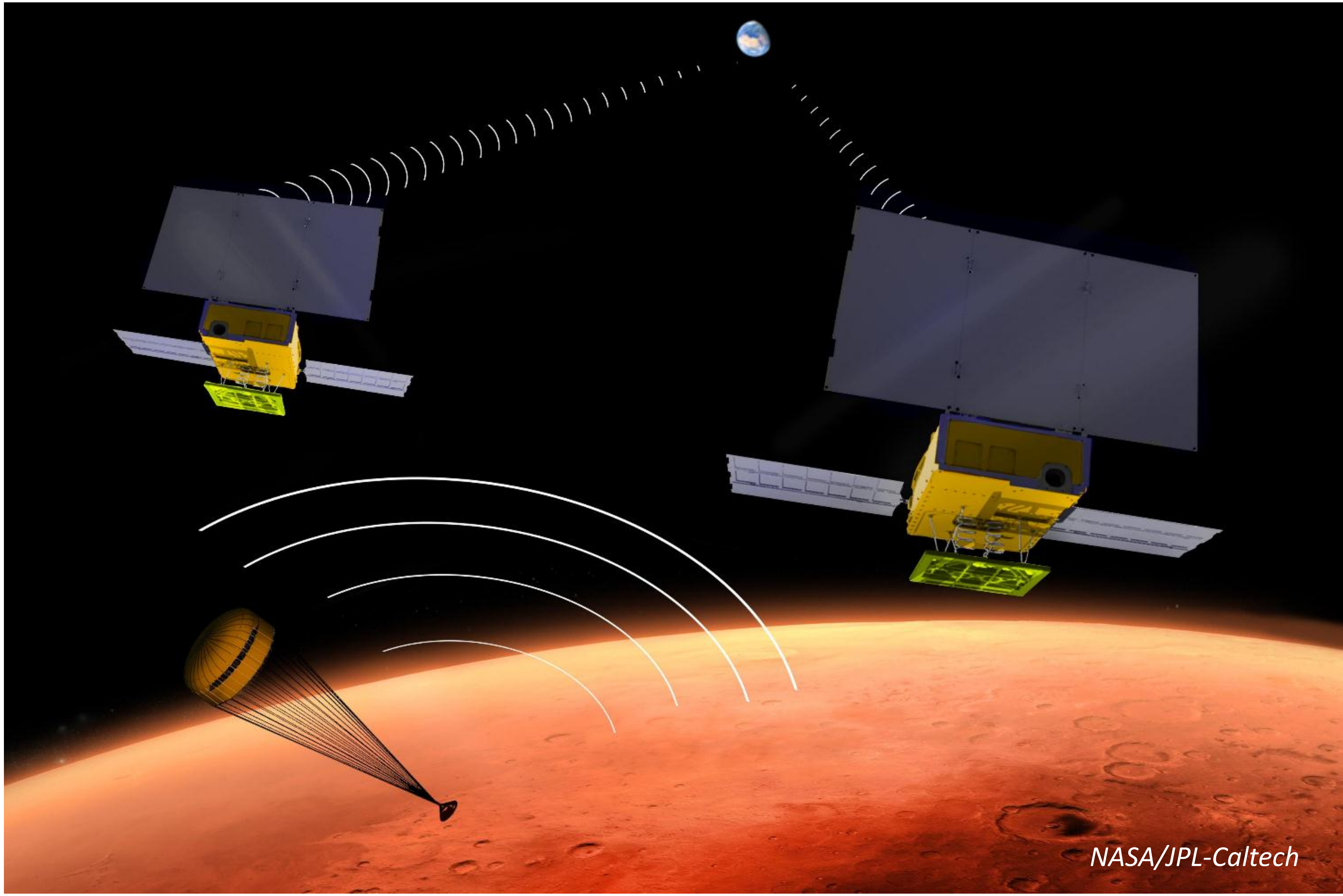

	XB3	XB6	XB12	XB Microsat
Class	3U	6U	12U	Up to 75 kg
Available Payload Volume	2U	5U	11U	45 x 45 x 80 cm
Pointing Accuracy	±0.002° (1-sigma), 3 axes, 2 Trackers			
Pointing Stability	1 arc-sec over 1 sec			
Maneuver rate	10 deg/sec (typical 3U)	3 deg/sec (typical)	3 deg/sec (typical)	5 deg/sec (typical)
Orbit knowledge	4m, 0.05m/s	4m, 0.05m/s	4m, 0.05m/s	4m, 0.05m/s
Data Interfaces	Serial, LVDS, Spacewire, HDLC, I2C or SPI available			
Onboard Data Storage	16 Gbytes	16 Gbytes	16 Gbytes	128 Gbytes (1 TB option)
System Bus Voltage	9 – 23 V (battery and array dependent)	9 – 23 V (battery and array dependent)	9 – 23 V (battery and array dependent)	9 – 36 V (battery and array dependent)
Energy Storage	75Whr	75-185Whr	75-185Whr	300Whr
Solar Panels	Customer or BCT Provided Solar Panels (Details available per request)	Customer or BCT Provided Solar Panels (Details available per request)	Customer or BCT Provided Solar Panels (Details available per request)	Customer or BCT Provided Solar Panels (Up to 200W)
High Current Capability	Unregulated up to 60W	Unregulated up to 140W	Unregulated up to 140W	Sized for program specific needs
Frequency	UHF, Sband, Xband			
Uplink	CCSDS, SGLS, NSGLS			
Downlink	Up to 15 Mbps	Up to 15 Mbps	Up to 15 Mbps	150 Mbps option
Mass / Volume for Avionics	1.5 kg / 10 cm x 10 cm x 14 cm	1.5 kg / 10 cm x 10 cm x 14 cm	2.0 kg / 10 cm x 10 cm x 20 cm	25 kg / 40 cm x 40 cm x 20 cm
XACT-Bus Nominal Power	< 6.3W (Excluding RF Comm)	< 6.3W (Excluding RF Comm)	< 6.3W (Excluding RF Comm)	< 10W (Excluding RF Comm)
Orbit Altitude / Orbit Lifetime	LEO / > 5 years			

Lunar & Beyond Missions

- **Lunar IceCube**
  - **Customer:** Morehead State University;
  - **Destination:** Lunar Orbit; **Objectives:** Search for water ice on Moon;
  - **BCT Providing:** XACT
- **NEA Scout**
  - **Customer:** NASA MSFC;
  - **Destination:** Interplanetary; **Objectives:** Flyby of an asteroid with solar sail propulsion;
  - **BCT Providing:** 4 RWp015. Modified XACT, Solar Panels
- **BioSentinel**
  - **Customer:** NASA Ames;
  - **Destination:** Heliocentric; **Objectives:** Detect, measure, and correlate the impact of space radiation in living organisms;
  - **BCT Providing:** XACT
- **Lunar Flashlight**
  - **Customer:** NASA JPL;
  - **Destination:** Lunar Orbit; **Objectives:** Map lunar south pole for volatiles;
  - **BCT Providing:** XACT-50, Solar Panels
- **CuSP**
  - **Customer:** Southwest Research Institute;
  - **Destination:** Interplanetary; **Objectives:** Heliophysics;
  - **BCT Providing:** XACT
- **EQUULEUS**
  - **Customer:** University of Tokyo and JAXA;
  - **Destination:** Earth-Moon, L2; **Objectives:** Trajectory control experiment in cis-lunar region, Imaging of earth's plasmasphere, Lunar impact flash observation, measurement of dust environment in cis-lunar region;
  - **BCT Providing:** XACT-50
- **OMOTENASHI**
  - **Customer:** AeroAstro;
  - **Destination:** Lunar surface; **Objectives:** Demonstration of a nano-lander;
  - **BCT Providing:** XACT
- **ArgoMoon**
  - **Customer:** Argotec;
  - **Destination:** Earth (6 months); **Objectives:** Take historically significant photography of the EM-1 mission;
  - **BCT Providing:** XACT
- **LunaH-Map**
  - **Customer:** Arizona State University;
  - **Destination:** Lunar orbit; **Objectives:** Mapping of hydrogen around Lunar South Pole;
  - **BCT Providing:** XB1 avionics
- **Earth Escape Explorer (CU-E3)**
  - **Customer:** University of Colorado Boulder;
  - **Destination:** Deep space; **Objectives:** Demonstrate deep space communications from a 6U CubeSat as part of the NASA CubeQuest Challenge;
  - **BCT Providing:** XB1 avionics

ADCS for MarCO

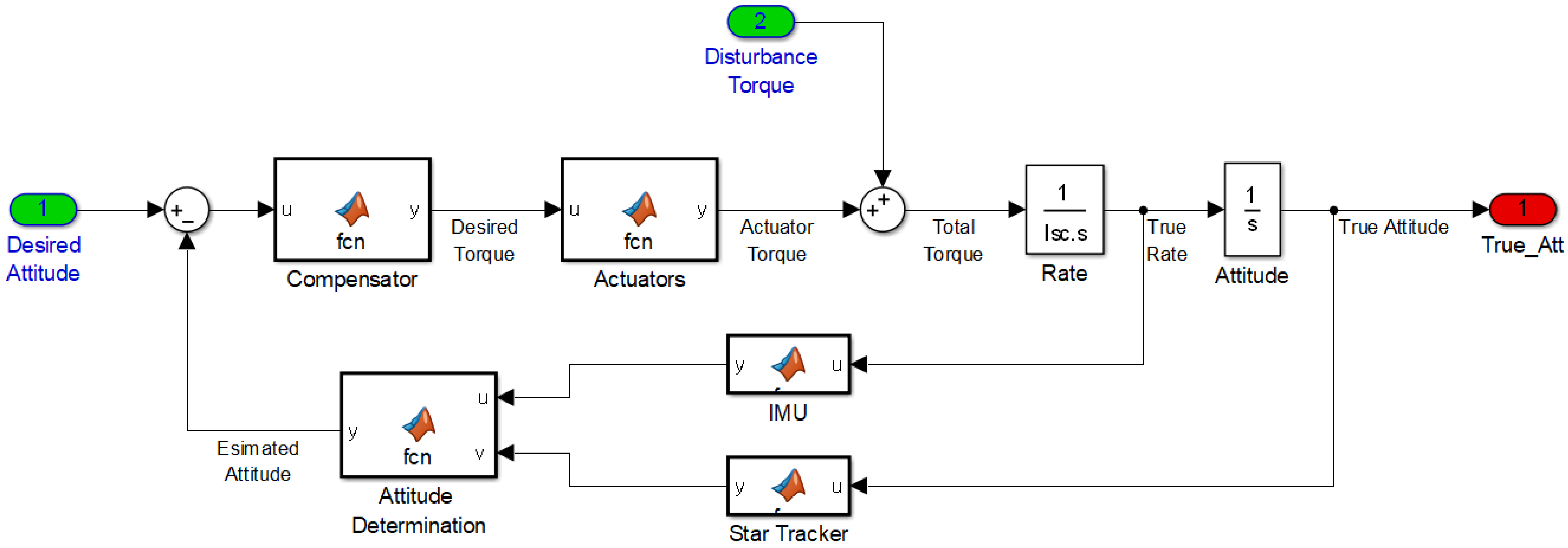
- **Customer:** NASA/JPL;
- **Destination:** Mars;
- **Objectives:** Data relay for INSIGHT lander during entry, descent, and landing phase;
- **BCT Providing:** XACT



What is Attitude Determination & Control

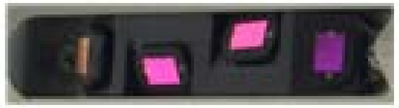
- The hardware (sensors and actuators) and software that control the orientation of the satellite
- Think of it as the auto-pilot
- A.K.A.:
  - ADCS: Attitude Determination & Control Subsystem
  - GN&C: Guidance Navigation & Control

Basic Control Loop



Attitude Determination (sensors)

Type	Comment	LEO	Deep Space
Star Tracker	Provides orientation relative to inertial space (**three** axes). The only option available for determining complete spacecraft orientation in deep space. Accuracy: <0.001 deg RMS	Yes	***Yes***
Sun sensor	Provides direction to the sun (**two** axes). Very safe method for getting the solar panels pointed at the sun to generate power. Accuracy: <2 deg	Yes	***Yes***
Horizon sensor	Provides roll and pitch orientation relative to the horizon (**two** axes). For high accuracy, atmospheric and oblateness information is required.	Yes	No
Magnetometer	Provides direction and magnitude of the local magnetic field (**two** axes)	Yes	No



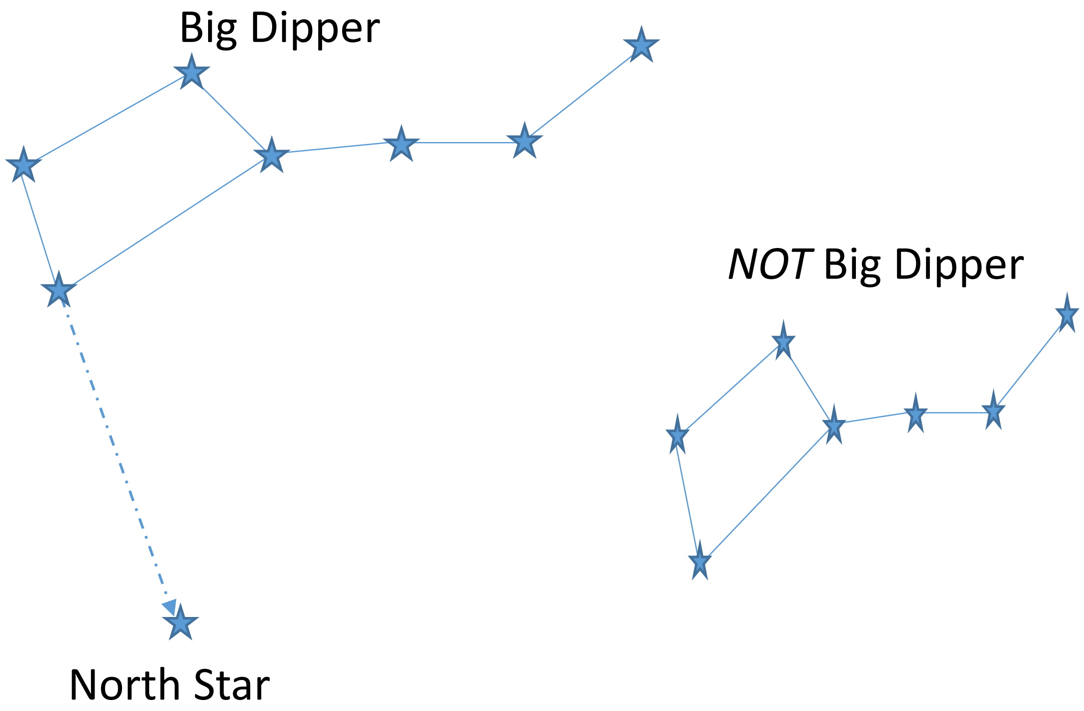
Note: An Inertial Measurement Unit (IMU) is a relative attitude sensor. IMU and sensors above are combined in filters to provide optimum attitude estimate.

Star Tracker Basics

- Camera (lens & detector)
    - Acts like typical digital camera
    - Returns pixel amplitudes of stars on field of view (FOV)
- Sun keep-out baffle
    - Series of concentric rings that block the sun from blinding the detector
    - BCT sun keep-out angle +/- 45 deg. Also +/- 17 deg with extension
- Catalog
    - List of all visible star locations, used to compare against measured star locations
- Algorithms
    - Pattern matching (or Star Identification) used to determine which stars are on FOV
    - Typically QUEST used to calculate attitude, relative to catalog frame, using catalog and measured star locations

Pattern matching (or Star Identification)

- Variety of published algorithms for pattern matching
- Typically look for matches between measured and known (i.e. catalog) angles between stars



Where is this ?

Qt_wrt_i =
0.0000
0.0220
0.0000
0.9998

Attitude Control (actuators)

- Reaction wheels: Primary method of steering a satellite
  - Typically three wheels (roll, pitch, yaw)
  - Newton's 3rd law: Action-reaction principle.
  - Wheel rotates one way, the spacecraft rotates the opposite
  - Can use four wheels to avoid zero-speed crossings (null space control)



- Propulsion (thrusters)
  - Requires multiple thrusters or two-axis gimbal to generate torques
  - Can control attitude, instead of wheels. (Results in high fuel usage)
  - Typically used to dump excess momentum to keep wheels from 'saturating'
    - Tip-off rates from launch vehicle
    - Disturbances from solar pressure
  - Algorithms must convert 3-axis torque commands into thruster duty-cycles

Control Compensator

- Algorithms compare the estimated attitude to the desired attitude (e.g. point to Boulder, or point to Mars) and send correction signals to actuators that rotate the satellite into the correct orientation.
  - ‘Roll a little to the left; pitch a little lower; yaw to the right’
- Typical compensation is Proportional-Integral-Derivative (PID)
- Must account for structural-bending and fuel-slosh modes to avoid instability
- Must balance desired pointing performance with actuator demand (i.e. wheel power, or thruster fuel usage), given sensor noise input
- Must account for actuator limits and non-linearities
- BCT utilizes state-of-the-art controls synthesis techniques to optimize performance, given all constraints

Orbit Determination & Propagation

- GPS is not available much beyond GEO
- NASA/JPL Deep Space Network (DSN) provides ranging and doppler tracking to determine Helio-centric orbit (using radio such as IRIS)
- Celestial optical navigation (with camera or star tracker) is also a possibility, utilizing known planet locations, relative to the stars.

- Orbits must be propagated on-board, between determination updates
- BCT orbit propagation software is directly compatible with JPL DSN orbit determination output

Momentum Control

- Solar pressure is typically the dominant disturbance for deep space

 (Leaky thrusters and other out-gassing can also cause disturbances)

- Spacecraft geometry should be symmetric to minimize momentum build up, due to solar pressure
- Rolling periodically can average out the torques in inertial space
- Wheel momentum size will determine how often de-saturation needs to occur
  - Smaller wheels need more frequent de-saturation, but require less mass
  - The wheel size does not affect the amount of propellant needed over the mission life.