Transiting Exoplanet Survey Satellite

Critical Design Review

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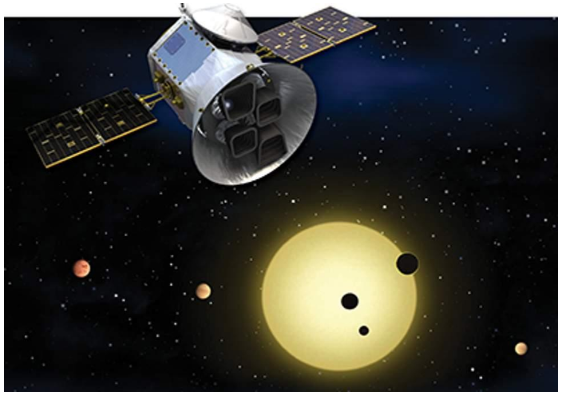
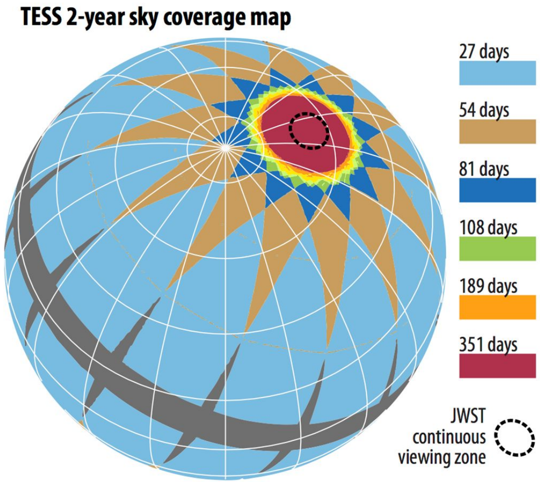
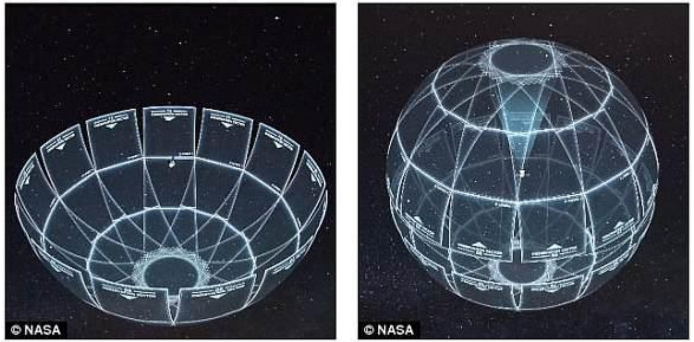
TESS




TESS 2-year sky coverage map
27 days
54 days
81 days
108 days
189 days
351 days
JWST continuous viewing zone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WHAT we’re doing and WHY we’re doing it

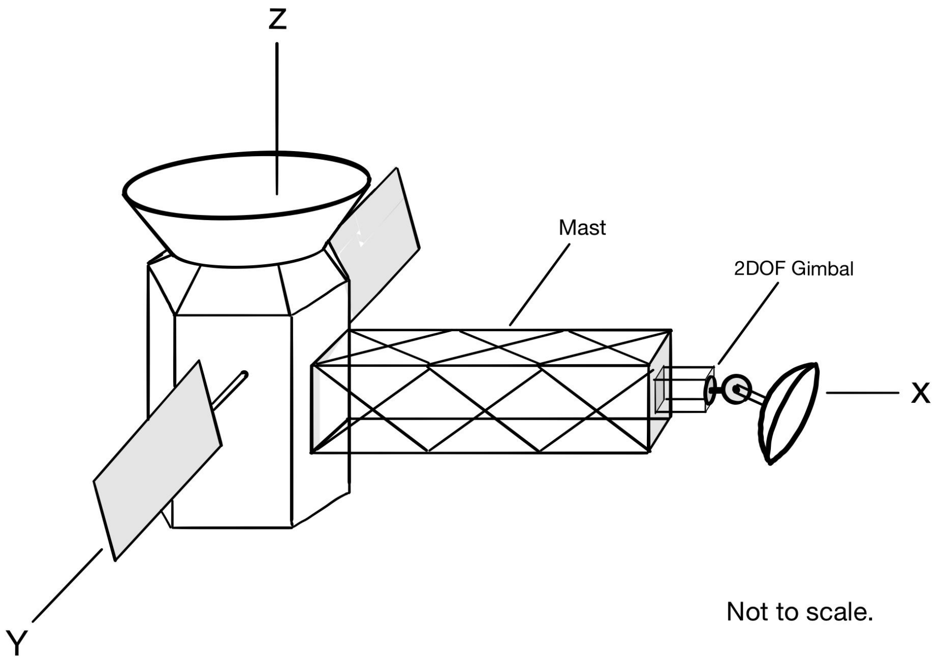
Antenna Positioning Mechanism:

- Increase sky coverage without altering mission time

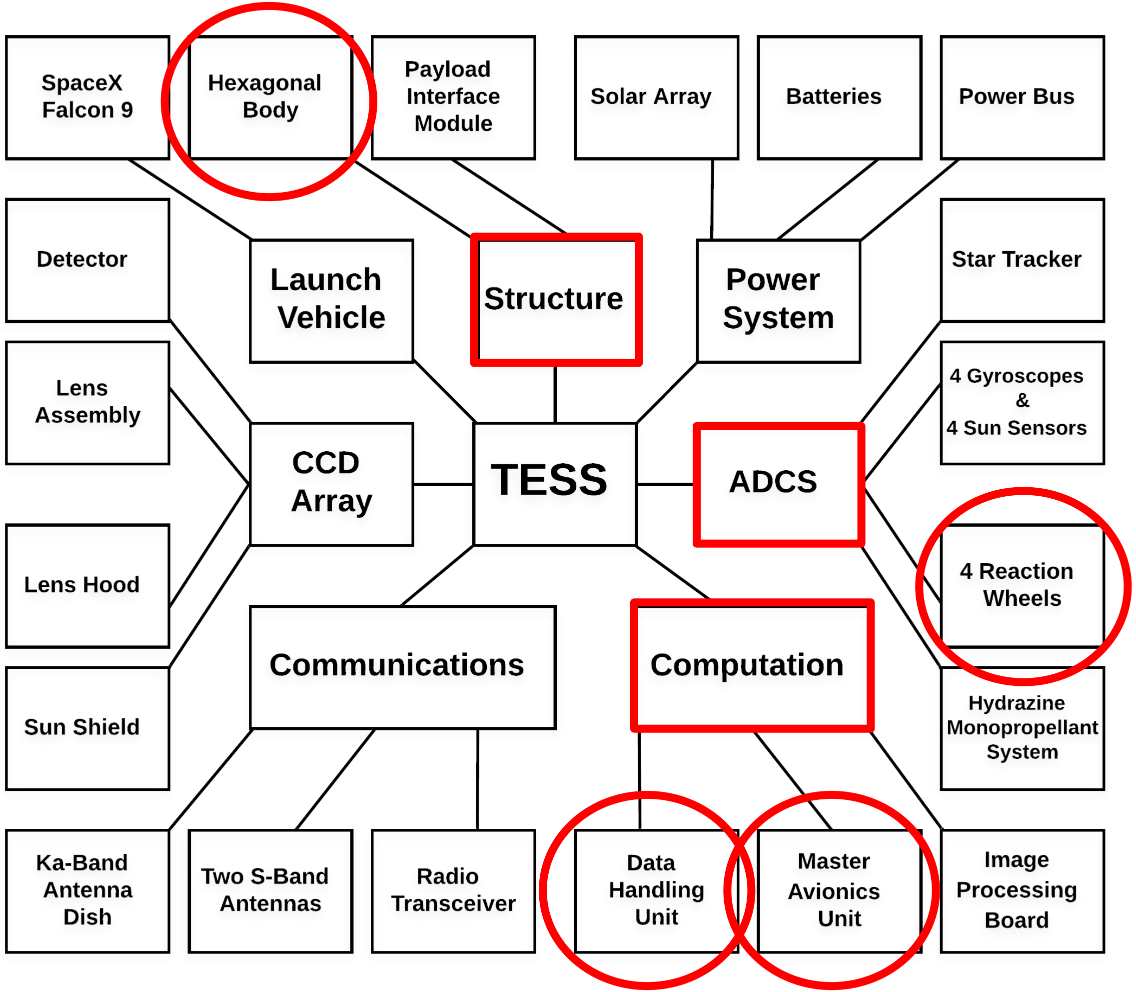
Piezoelectric ACS:

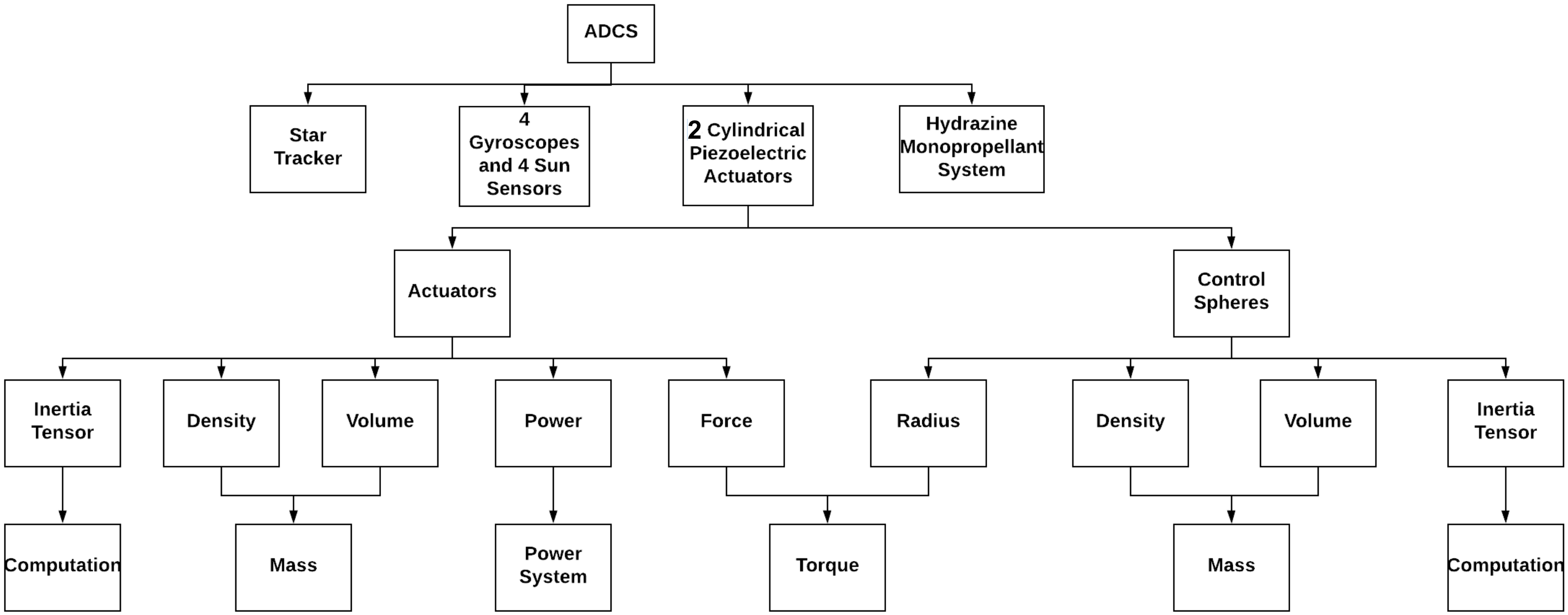
- Save space inside TESS
- Save mass → Save $$$
- More precise attitude control (10x)

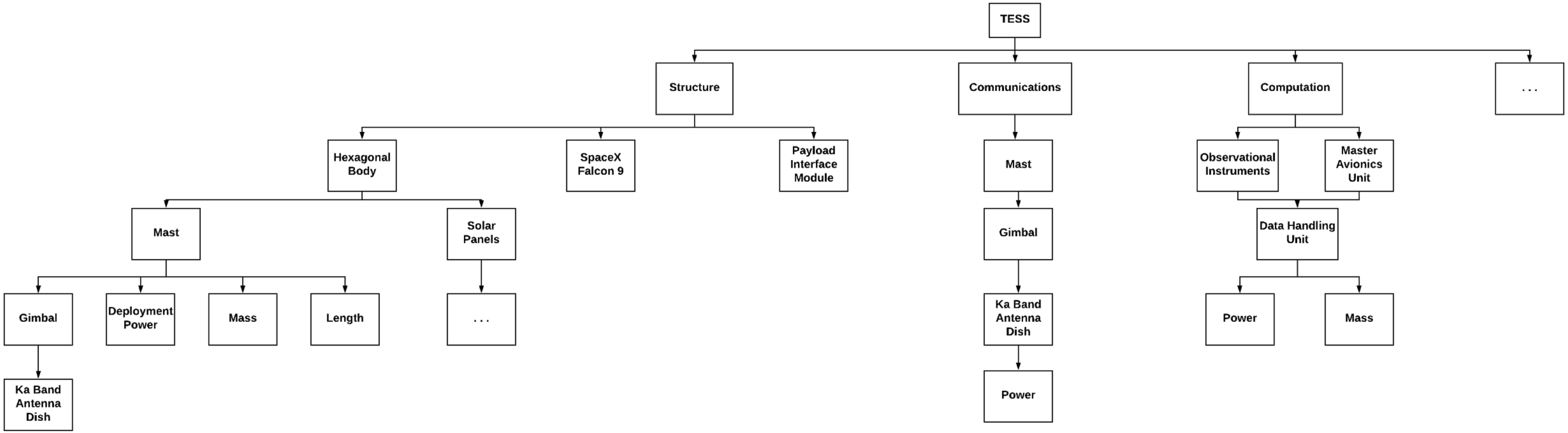
What TESS will look like after adding the mods

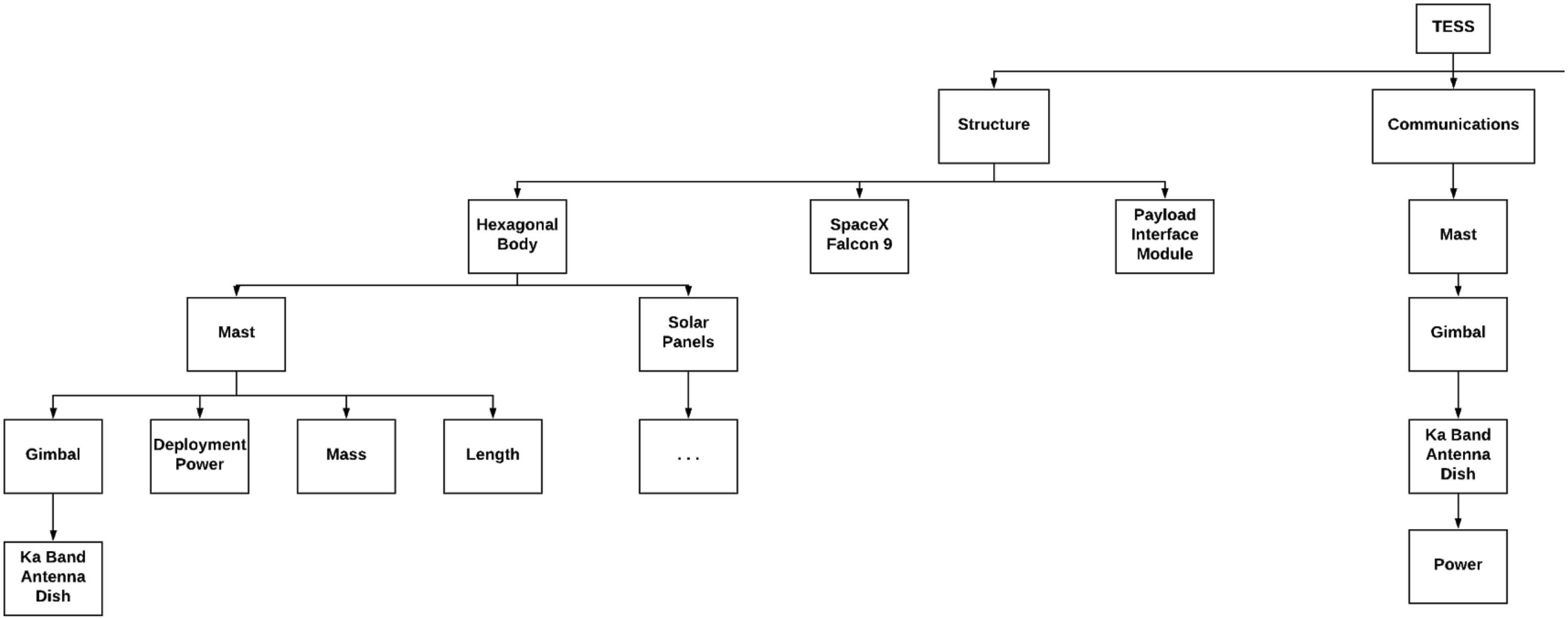


Not to scale.


SpaceX Falcon 9
Hexagonal Body
Payload Interface Module
Solar Array
Batteries
Power Bus
Detector
Launch Vehicle
Structure
Power System
Star Tracker
Lens Assembly
4 Gyroscopes & 4 Sun Sensors
CCD Array
TESS
ADCS
Lens Hood
4 Reaction Wheels
Communications
Computation
Sun Shield
Hydrazine Monopropellant System
Ka-Band Antenna Dish
Two S-Band Antennas
Radio Transceiver
Data Handling Unit
Master Avionics Unit
Image Processing Board


ADCS
Star Tracker
4 Gyroscopes and 4 Sun Sensors
2 Cylindrical Piezoelectric Actuators
Hydrazine Monopropellant System
Actuators
Control Spheres
Inertia Tensor
Density
Volume
Power
Force
Radius
Density
Volume
Inertia Tensor
Computation
Mass
Power System
Torque
Mass
Computation


TESS
Structure
Communications
Computation
. . .
Hexagonal Body
SpaceX Falcon 9
Payload Interface Module
Mast
Observational Instruments
Master Avionics Unit
Mast
Solar Panels
Gimbal
Data Handling Unit
Gimbal
Deployment Power
Mass
Length
. . .
Ka Band Antenna Dish
Power
Mass
Ka Band Antenna Dish
Power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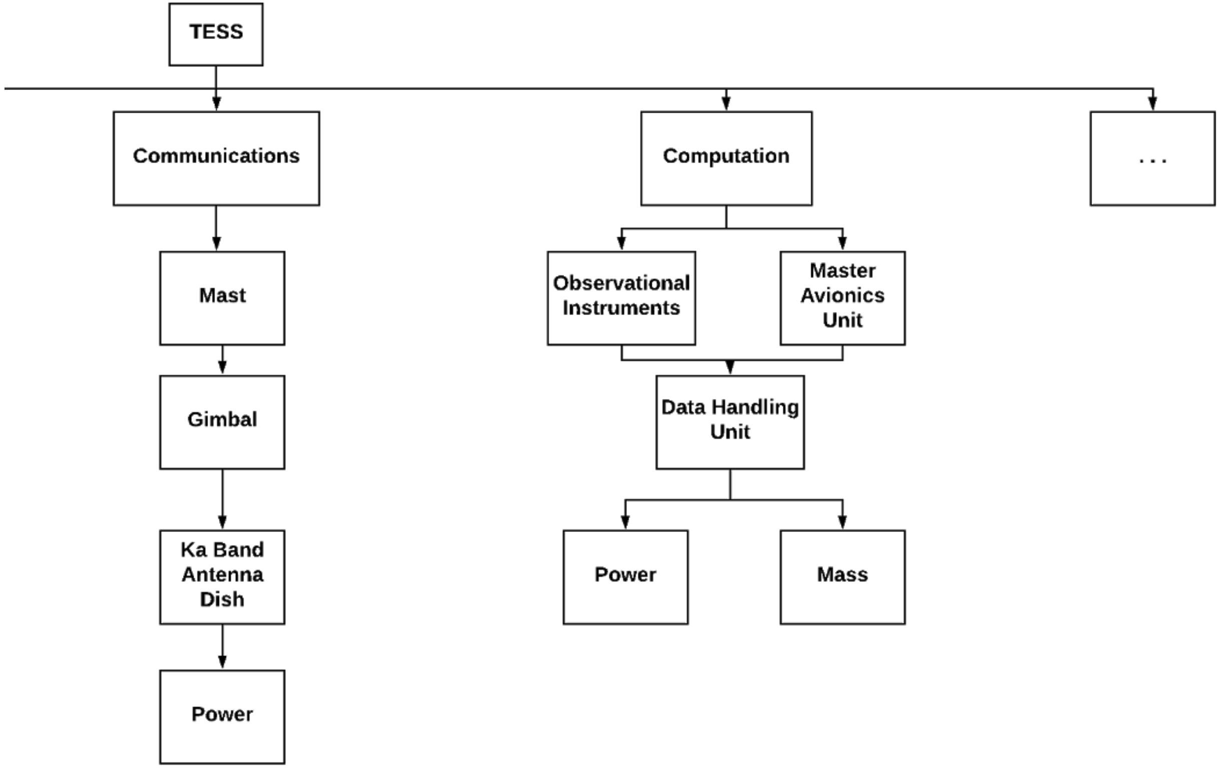
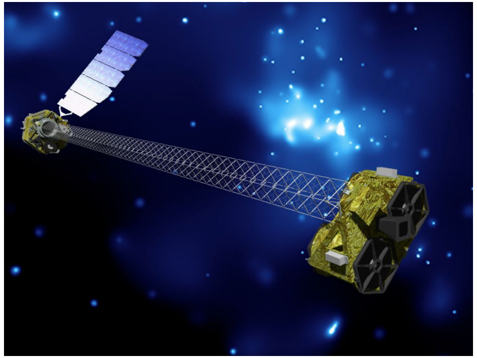
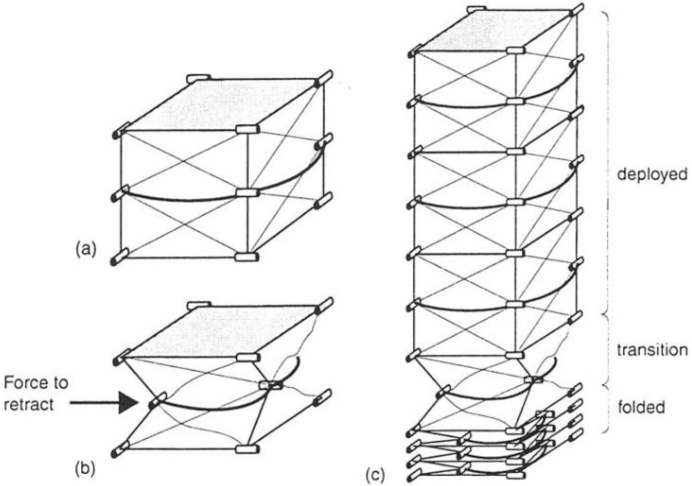
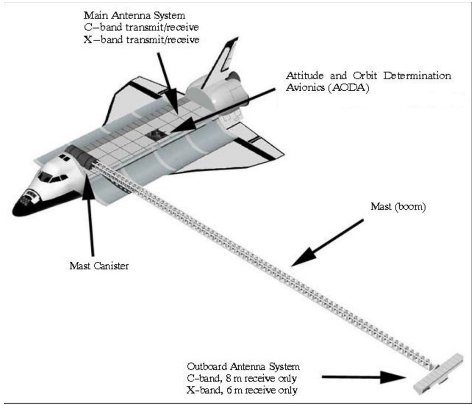

TESS
Communications
Computation
. . .
Mast
Gimbal
Ka Band Antenna Dish
Power
Observational Instruments
Master Avionics Unit
Data Handling Unit
Power
Mass

Major Analysis:
Antenna Positioning Mechanism





FAST Deployable Mast



Shuttle Radar Topography Mission

Antenna Positioning Mechanism Assumptions

- Previous to modification, the spacecraft was of uniform density, and all objects added are of uniform density.
- Is a rigid body
- No magnetic forces influence the spacecraft.
- Solar Radiation Pressure is constant.
- Aerodynamic Drag is negligible.
- Observatory will always be antisolar.
- It is in its final orbit.

The Analysis Step By Step

1. Establish reference frame
2. Find ideal mast length
3. Simplify the satellite into smaller generalized shapes
4. Find the inertia of the spacecraft about its new center of mass
5. Formulate the forces at work on the spacecraft (gravity gradient, SRP, etc.)
6. Divide the spacecraft into three planes and set up an equilibrium problem.
7. Simulate the torques on the craft over the orbit on MATLAB.

Inertia and Force Equations

$$I_{zz} = \frac{1}{2}mr^2 \; ; \; I_{xx} = I_{yy} = \frac{1}{4}mr^2 + \frac{1}{12}ml^2$$

Equation Moment of Inertia for a cylinder

$$I_{xx} = \frac{1}{12}m(h^2 + w^2) \; ; \; I_{yy} = \frac{1}{12}m(l^2 + h^2) \; ; \; I_{zz} = \frac{1}{12}m(l^2 + w^2)$$

Equation Moment of Inertia for a rectangular prism

$$I_{xx} = \frac{2}{3}mr^2 \; ; \; I_{yy} = I_{zz} = \frac{5}{12}mr^2$$

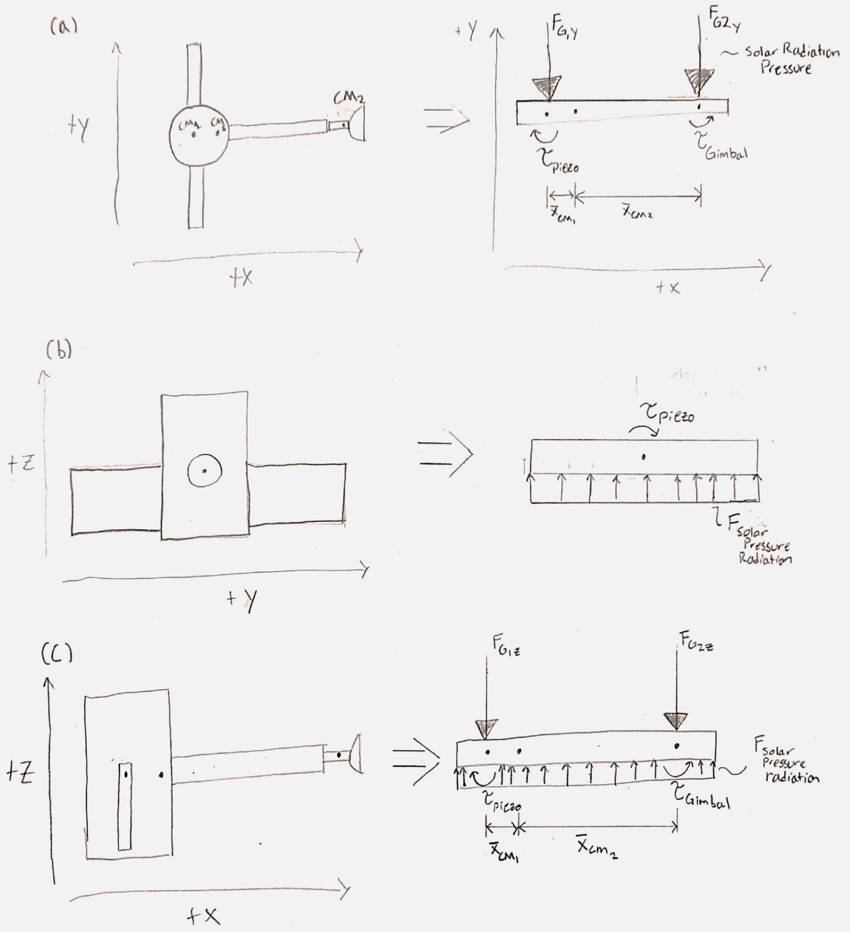
Equation Moment of Inertia for a hemispherical shell

$$I_O = I_i + m_i d_i^2$$

Equation Parallel Axis Theorem

$$F_{Gravity\ Gradient_i} = m_i \frac{(v^2(r+\bar{x}cos(\theta)) - \mu)}{(r+\bar{x}cos(\theta))^2}$$

Equation The Gravity gradient force equation



Equilibrium Equations

Sum Moment about Z-Axis;

$$\sum M_z = 0;\ \tau_{piezoelectricX} + \tau_{GimbalX} + (F_{Gravity\ Gradient\ Mass1Z}\bar{x}_{Mass1Z} - F_{Gravity\ Gradient\ Mass2Z}\bar{x}_{Mass2Z}) = 0$$

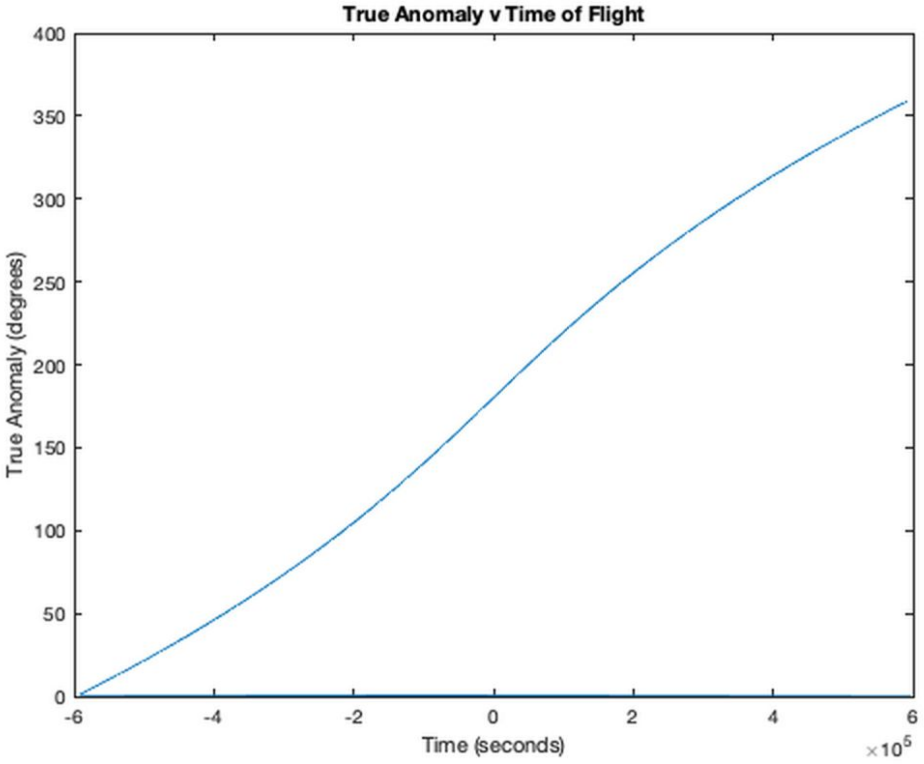
Sum Moment about X-Axis;

$$\sum M_x = 0;\ \tau_{piezoelectricX} + \tau_{Solar\ Radiation\ Pressure} = 0$$

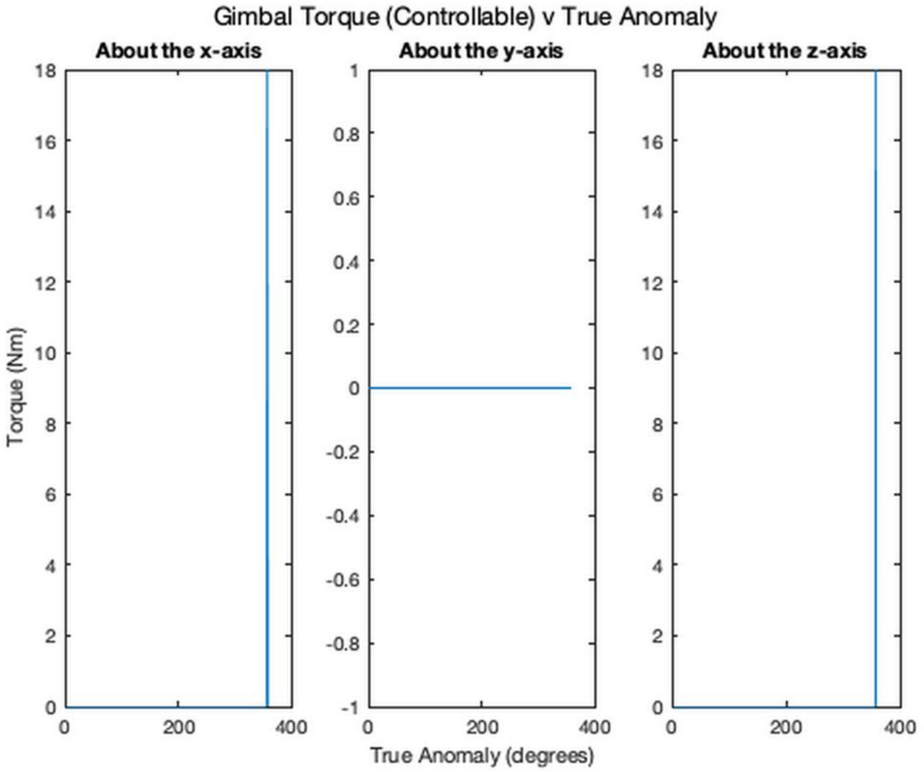
Sum Moment about Y-Axis;

$$\sum M_y = 0;\ \tau_{piezoelectricY} + \tau_{GimbalY} + (F_{GGM1Y}\bar{x}_{M1} - F_{GGM2Y}\bar{x}_{M2}) + \tau_{SRP} = 0$$

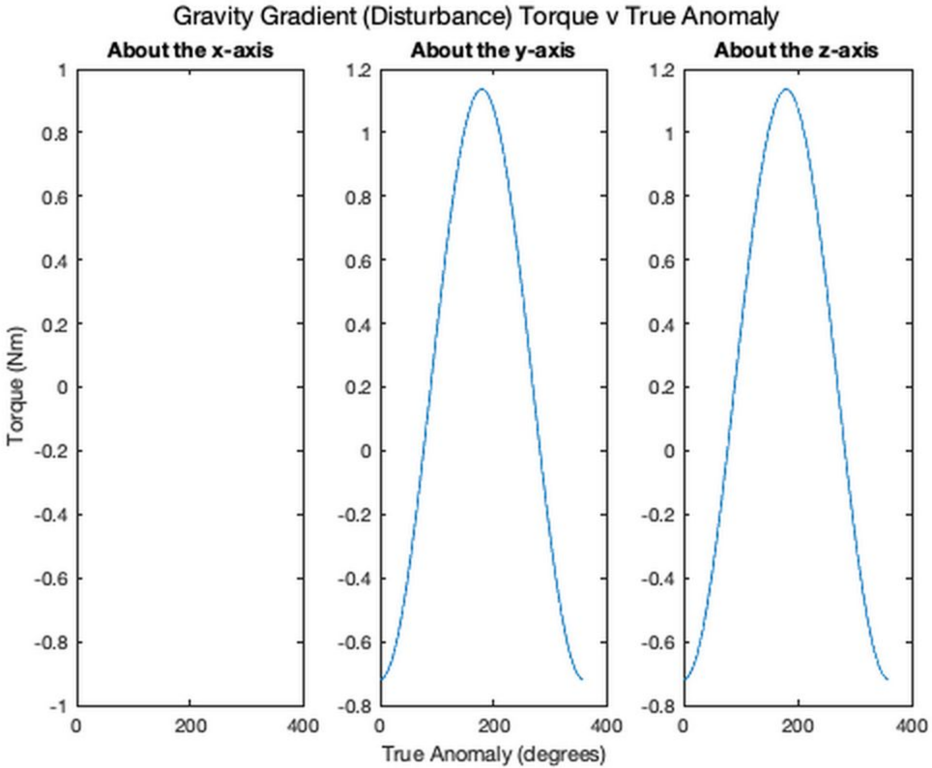
Major Analysis: Simulations



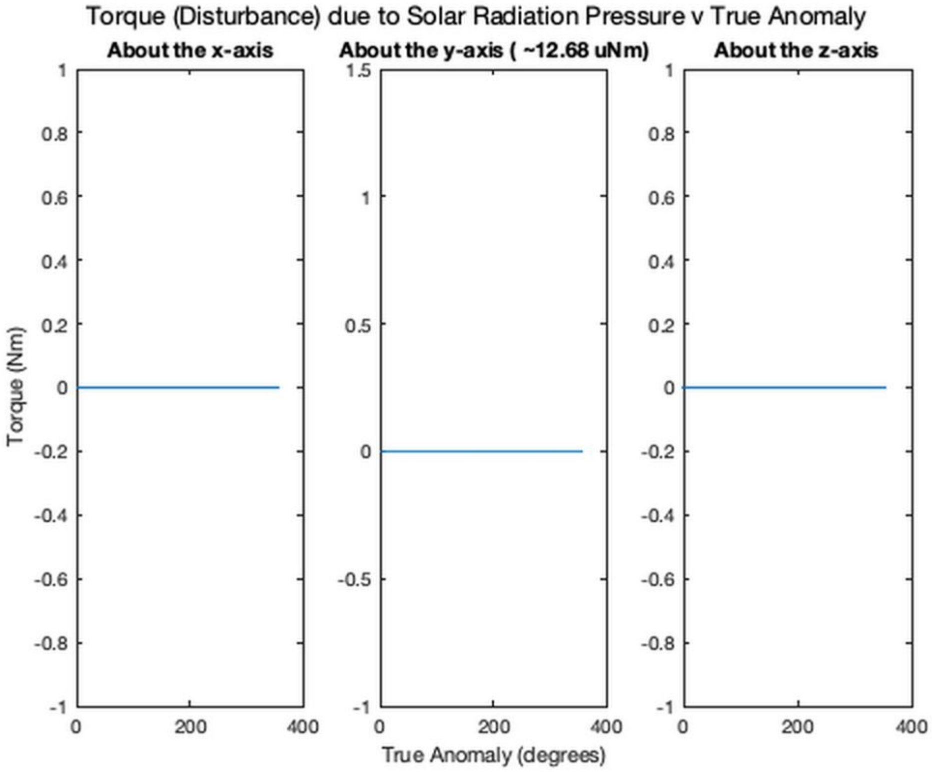
Major Analysis: Simulations



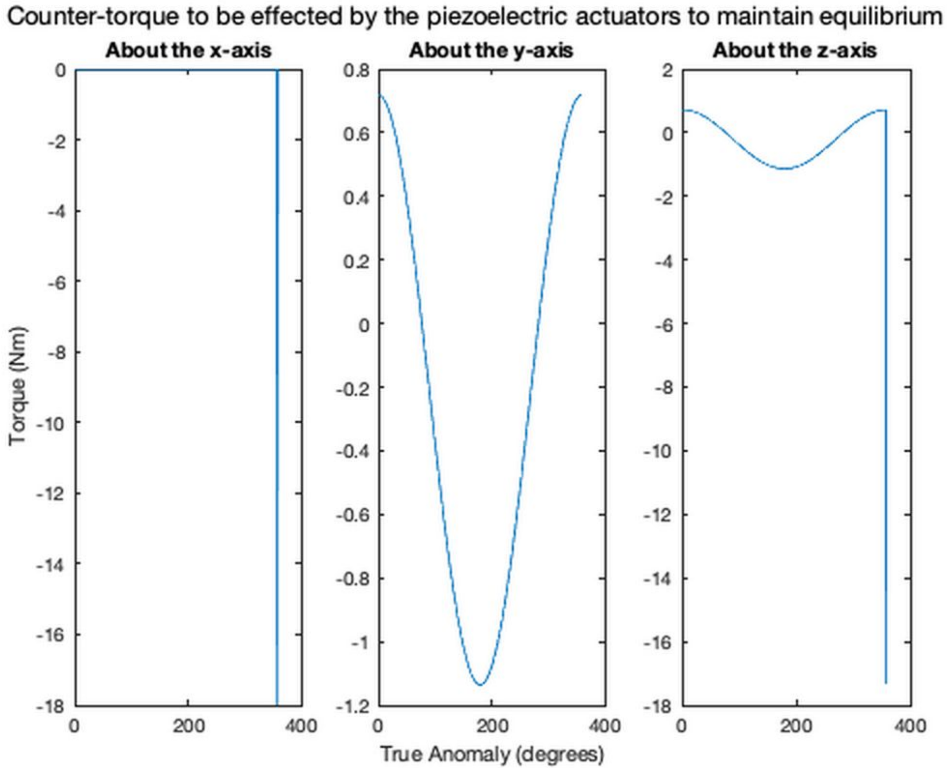
Major Analysis: Simulations



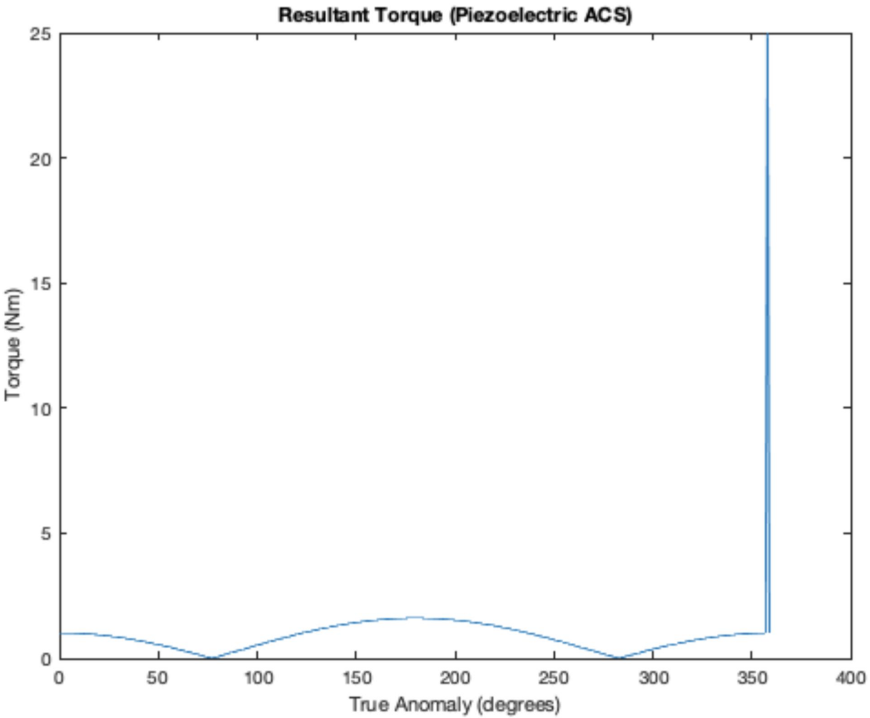
Major Analysis: Simulations



Major Analysis: Simulations



Major Analysis: Simulations



Major Analysis: Simulations

Based on these simulation results for the “worst-case” scenario, magnitude of max torque that the piezoelectric ACS needs to be able to handle:

24.9635 Nm

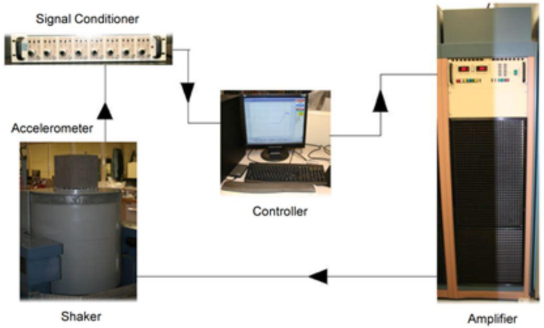
Can it handle it?
We’ll find out soon!

Major Analysis: Antenna Positioning Mechanism Test Plan

Tests:

- Random Vibration Test
- Sine Sweep Vibration Test
- Acoustic Test
- Structural Functionality Testing

Major Analysis: Antenna Positioning Mechanism Test Plan



Kennedy Space Center Vibration Lab

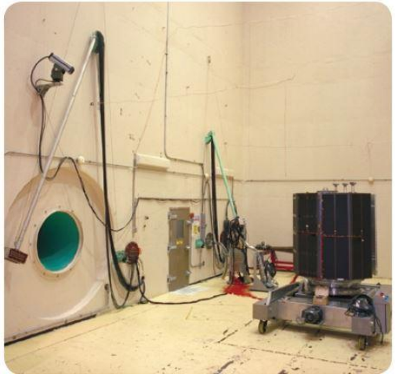
Kennedy Space Center Prototype Development Laboratory:

-machine shop

-3D digital scanning

-LabVIEW

-data acquisition



Goddard Space Flight Center Acoustic Test Facility

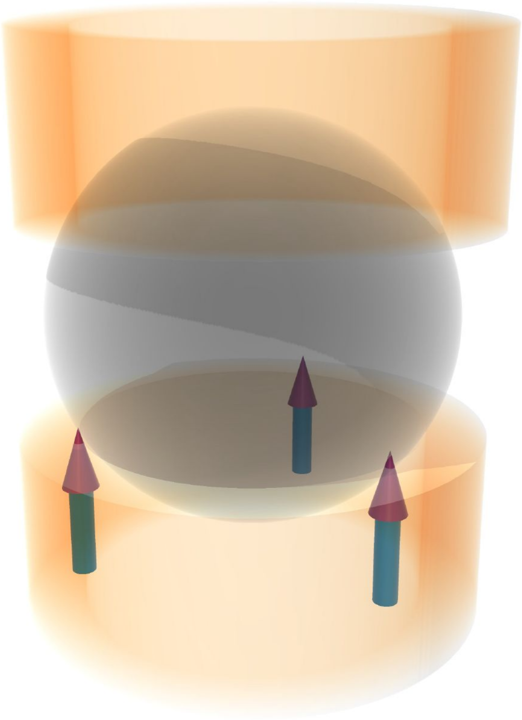
Minor Analysis 1:
Piezoelectric ACS

Minor Analysis 1: Piezoelectric ACS

What it is.

How it works.

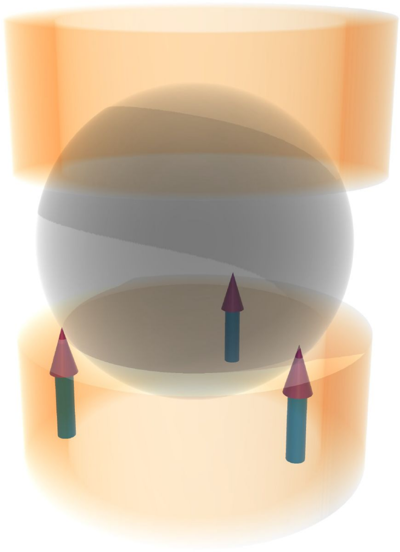
Why use it.



Minor Analysis 1: Piezoelectric ACS

$$F = (V/t)(-d_{31})/[(r_o/t - 0.5)\ ln(1 - t/r_o)]\ A\gamma^p$$

F = Piezoelectric Force
t = Thickness of Piezoelectric Shell
r_o = The Outer Radius of the Piezoelectric Shell
A = Area of the Piezoelectric Cross-Sectional Area
γ^p = Young's Modulus (superscript p refers to the piezoelectric material)
V = Input Voltage
d31 = Constant



Minor Analysis 1: Piezoelectric ACS

Requirements for 2 Piezoelectric Cylindrical Actuators and 1 Control Sphere

Max. Mass (kg)	Max. Volume (m^3)	Max. Voltage (V)	Max. Power per Piezo. Unit (W)	Max. System Power (W)	Min. Piezo. Force (N)	Min. Torque (N*m)
3.9 kg	3.5 $\times 10^{-2}$	28	77.5	155.0	352	25

Minor Analysis 1: Piezoelectric ACS

Trade Study: Piezoelectric Actuator Scaled to 6 cm Radius x 5 cm Height for a 6.5 cm Radius Control Sphere

Material	Type	Mass (kg)	Vol. (m^3)	F GLT (N)	Voltage (V)	Unit P (W)
Pz26	Ceramic	0.70	5.65 $\times 10^{-4}$	4040	28	72.3
PZT	Ceramic	0.69	5.65 $\times 10^{-4}$	4040	28	72.3
PVDT	Polymer	0.16	5.65 $\times 10^{-4}$	20.2	28	72.3

Minor Analysis 1: Piezoelectric ACS

Trade Study: Control Sphere Scaled to 6.5 cm Radius for 6 cm Radius x 5 cm Height Piezoelectric Actuator

Material	Density (kg/m^3)	Solid Mass (kg)	Shell Mass (kg)	I Sphere (kg*m^2)	I Shell (kg*m^2)	Volume (m^3)
Tungsten	19300	22.20	4.74	3.75×10^{-2}	1.33×10^{-2}	6.47×10^{-4}
Beryllium S 65 A	2000	2.30	0.49	3.89×10^{-3}	1.38×10^{-3}	6.47×10^{-4}
Magnesium A 31B	1700	1.96	0.42	3.30×10^{-3}	1.18×10^{-3}	6.47×10^{-4}

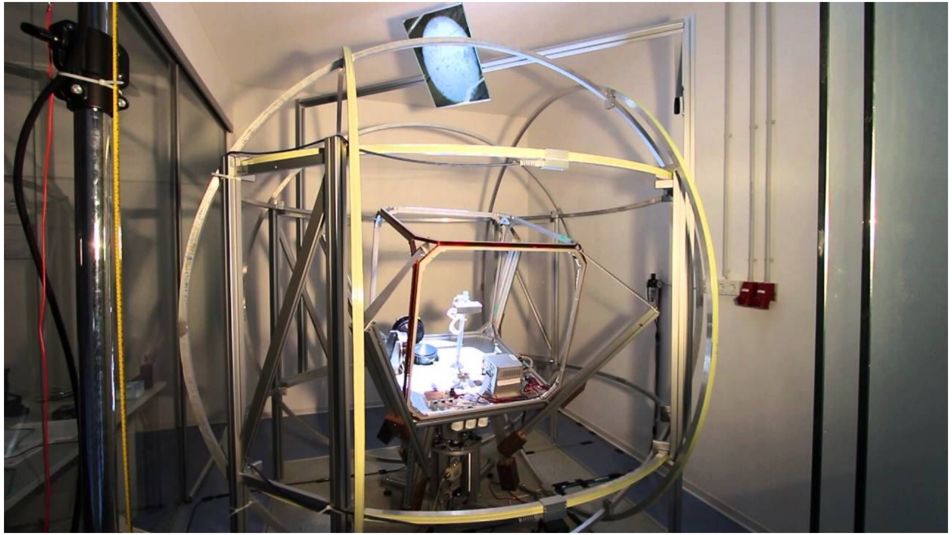
Minor Analysis 1: Piezoelectric ACS

Trade Study Results:

Piezo. Material	Control Sphere Material	Control Sphere Type	Total Mass (kg)	Vol. (m^3)	Voltage (V)	System Power (W)	Piezo. Force (N)	Torque (N*m)
PZT	Beryllium S 65 A	Solid Sphere	*3.68*	*1.78×10^{-3}*	*28*	*144.7*	*4040*	*262*
N/A	N/A	***Criteria:***	**< 3.9**	**$< 3.5 \times 10^{-2}$**	**≤ 28**	**< 155.0**	**> 352**	**> 25**

Minor Analysis 1: Piezoelectric ACS Test Plan

German Aerospace Center (DLR): Facility for Attitude Control Experiments (FACE)



Minor Analysis 2:
Power, Mass, Volume Changes

Minor Analysis 2: **Power**, Mass, Volume Changes

	+ Power	**- Power**	**Total**
Antenna Modification	37 W	---------------------------	+37 W
Piezoelectric	144.7 W	192 W	-47.3 W
Total Change	---------------------------	---------------------------	-10.3 W

Minor Analysis 2: Power, **Mass**, Volume Changes

	+ Mass	**- Mass**	**Total**
Antenna Modification	12.5 kg	---------------------------	+12.5 kg
Piezoelectric	+3.7 kg	-10.4 kg	-6.7 kg
Total Change	---------------------------	---------------------------	$\boxed{\text{+5.8 kg}}$

NOTE: Costs $20,200/kg to orbit
+5.8 kg → + **$117,160**

Minor Analysis 2: Power, Mass, **Volume** Changes

	+ Volume	**- Volume**	**Total**
Antenna Modification	7.81×10^{-2} m^3	---------------------------	$+7.81 \times 10^{-2}$ m^3
Piezoelectric	0	0	+0
Total Change	---------------------------	---------------------------	$\boxed{+7.81 \times 10^{-2} m^3}$

Note: Only external volume is considered

Minor Analysis 2: Power, Mass, Volume Changes Test Plan

Tests:

- Measurement of power consumption, mass, and volume
  - Compare to theoretical values
  - Test facilities

Verdict

	Met Requirements	Feasibility
Antenna Positioning Mechanism	✓	HIGH
Piezoelectric ACS	✓	LOW

Thank you

Questions?

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