MAGNETICALLY ENABLED STRUCTURES USING INTERACTING COILS

MAGESTIC

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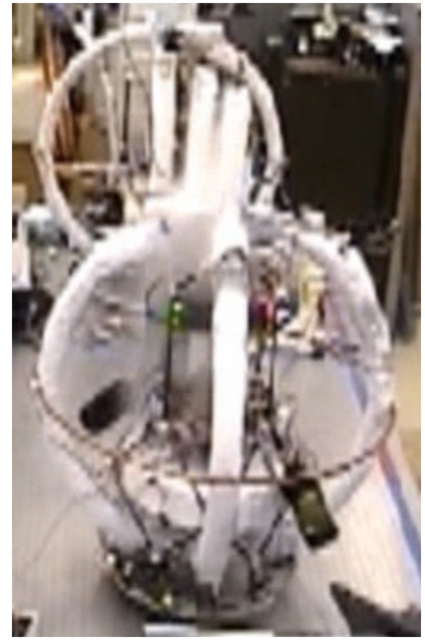
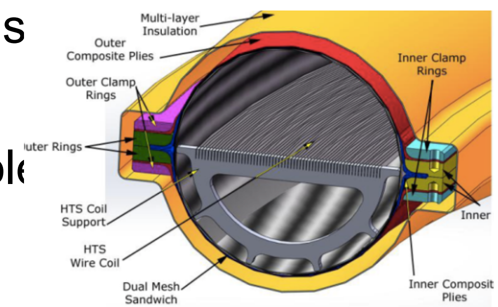
OUTLINE

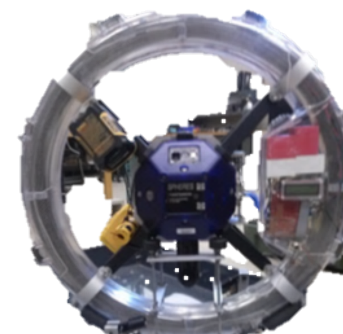
- Introduction and Motivation
- Structural and Ancillary Functions
- Use Cases and Roadmap
- Thermal System Deployment and Performance
- Thermal Maturation Plan and Roadmap

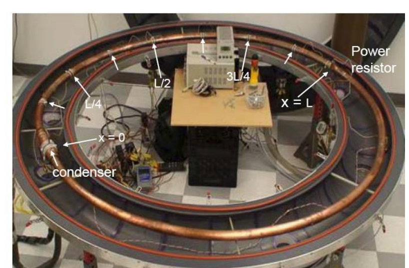
ELECTROMAGNETIC FORMATION FLIGHT (EMFF)

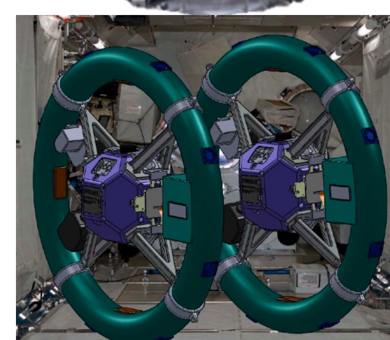
- **Subject of 2002 NIAC study**
- **Basic Concept**
  - Actuation in relative DoF for formation flight systems using EM forces/torques
- **Motivation**
  - Station-keeping for distributed systems
  - Replacement of consumables (thrusters)
  - Eliminate thruster plumes
  - Enable high DV formation flying missions
- **Implementation**
  - Create a steerable electromagnetic dipole using 3 orthogonal superconducting electromagnetic coils
  - De-couple torques using rxn wheels
  - 3DoF lab demo using cryogenic heat pipe
  - 6DoF ISS demonstration (RINGS, on right)





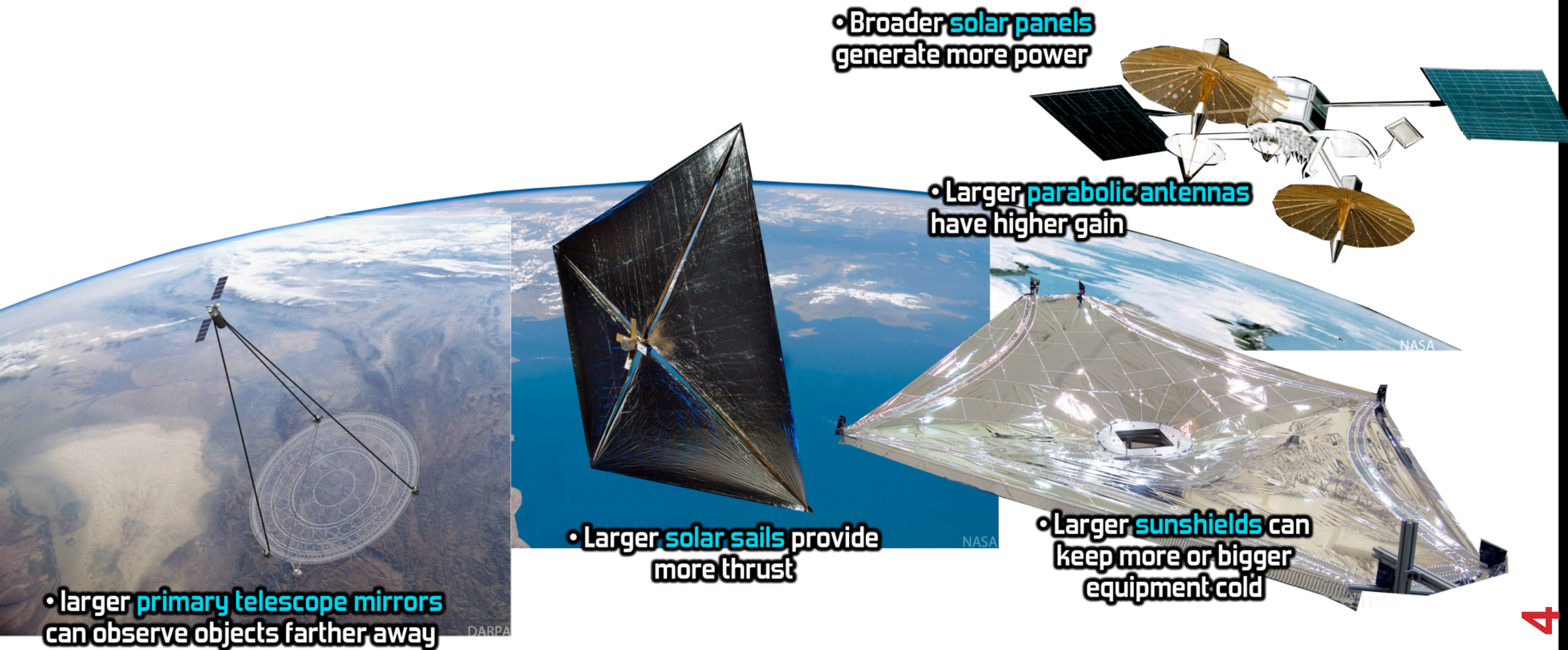






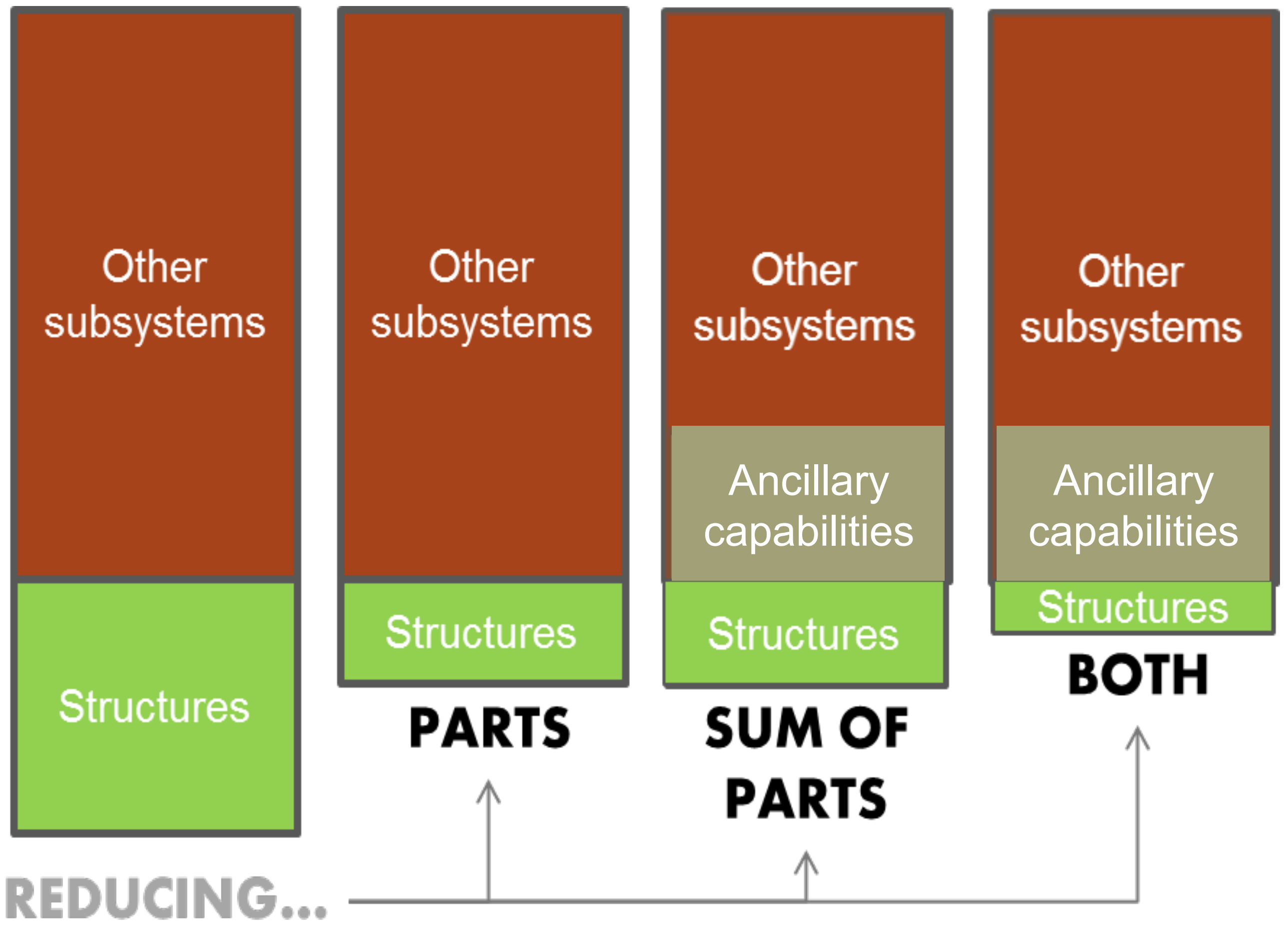
MOTIVATION

- **Larger spacecraft = better performance, but size is constrained**
- **Entire system needs to be made as light as possible**
  - <u>Structure</u>: ~20-30% of spacecraft dry mass
  - Inflatables, composites, tensegrity trying to reduce mass of structure

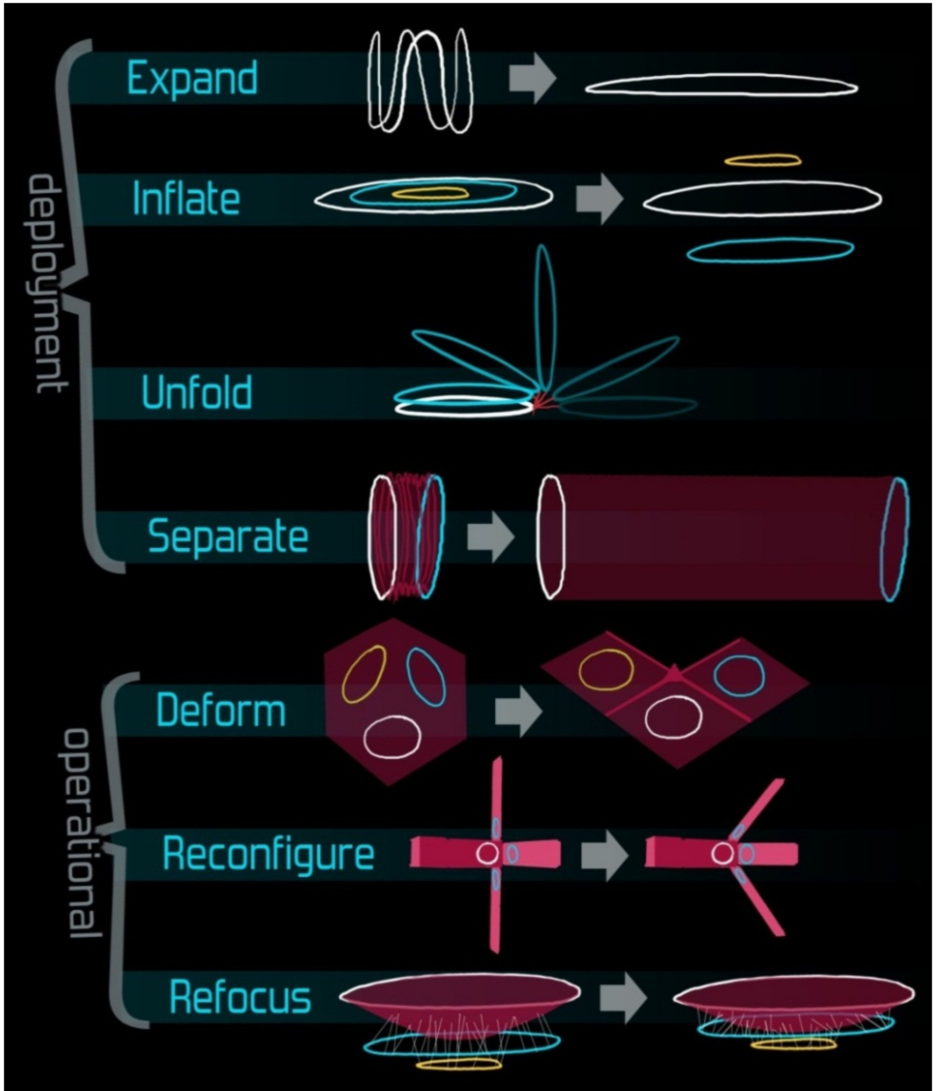


MOTIVATION

- **Electromagnets: structural functions + ancillary capabilities**
  - *Ancillary capabilities*: provided by electromagnets in addition to typical structural functions; saves SWAP in systems requiring them



STRUCTURAL FUNCTIONS



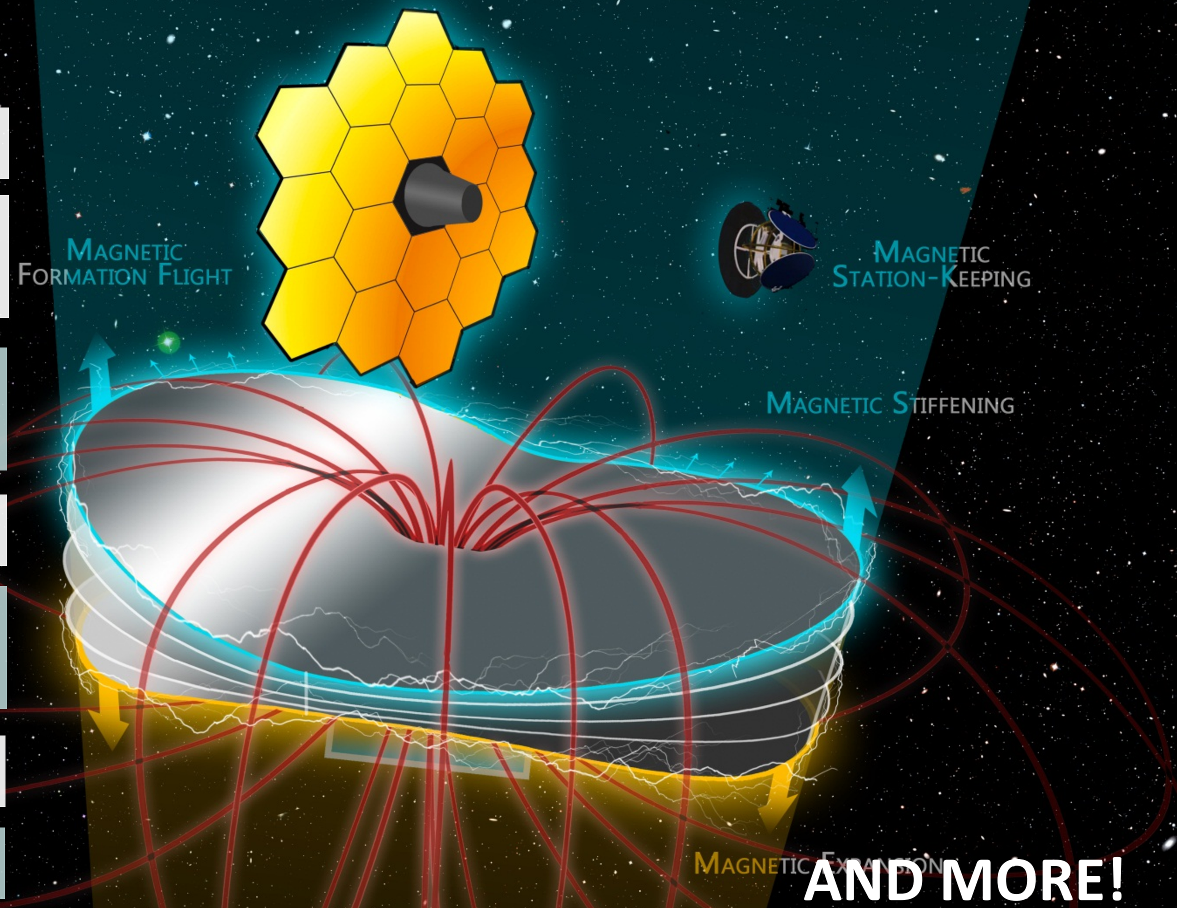
- Involve 1+ coils interacting
- Differentiated by boundary conditions
- “Deployment” configurations: during spacecraft commissioning
- “Operational” configs: during normal ops to change shape of the spacecraft

Stability analysis is an ongoing task; we want to define stability conditions for *n*-magnet shapes post-deployment

Vision: Next Next Generation Telescope

Many potential functions and advantages of electromagnets on spacecraft, including:

- Wireless power and data transfer
- Electromagnetic formation flight and positioning
- No obscuration from 2nd mirror assembly
- Unfolding from stowed position
- Staged deployment and element upgrades/replacement
- Magnetic stiffening and tensioning
- Reduced # of deployments
- Attitude control & momentum trading
- Dynamic and thermal isolation
- Membrane mirror shaping



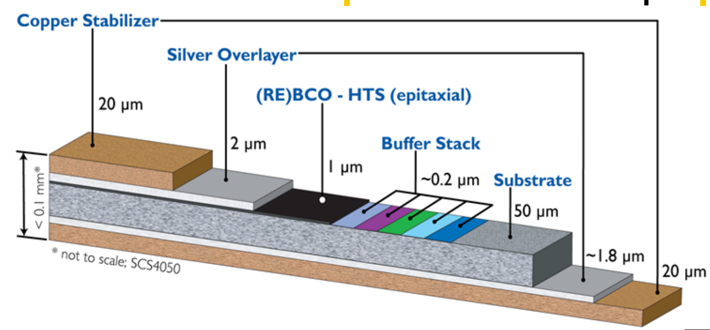
AND MORE!

- Strong controllable magnetic field
- Circular deployed/tensioned area
- Performs ≥ in cold environs
- Lossless energy storage

INTERLUDE: FORCE B/W COILS

- **Force acting on each of two identical 77K coils made of SuperPower 2G HTS wire in far-field (>10R apart):**

4mm wide tape



$$F_{SP} \sim 128.3 (MR)^2 / d^4$$

- **If copper stabilizer removed, can get:**

$$F_{SP,\ no\ Cu} \sim 383.31 (MR)^2 / d^4$$

- **Note: increasing R always *decreases* needed mass M for given F at separation d**

$$F(SP, 100m, 1m\ R, 30kg) = 1.16\ mN$$

$$F(SP\ no\ Cu, 100m,\ 1m\ R,\ 30kg) = 3.45\ mN$$

11.6 N

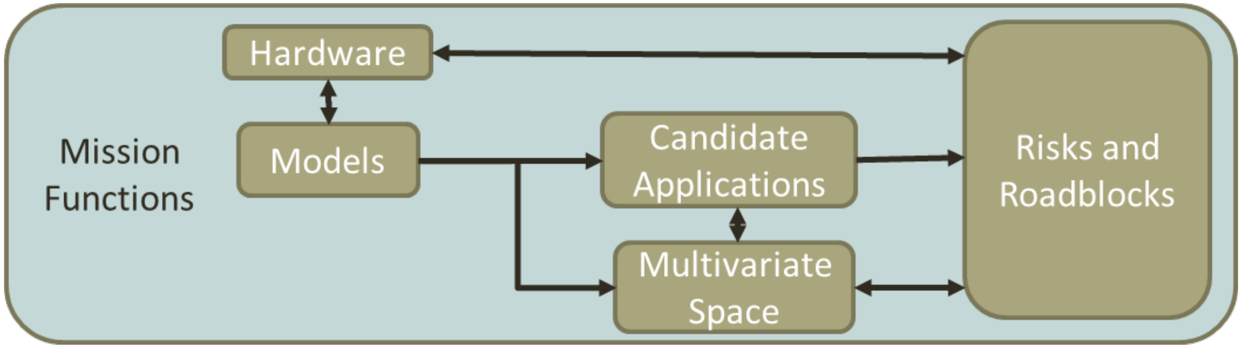
For d=10m, multiply force by 10000

$$M(SP, 100m,\ 1m\ R, 1N) = 882.85\ kg\ per\ coil$$

$$M(SP\ no\ Cu, 100m,\ 1m\ R, 1N) = 510.77\ kg\ per\ coil$$

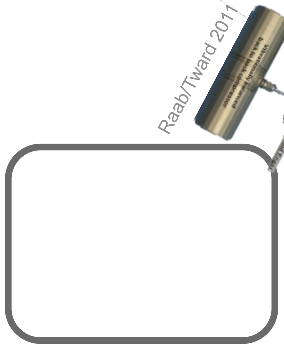
APPROACH

1. Describe & analyze **mission functions** which can be performed by an electromagnetic subsystem
2. Create and refine **models** of single- and multi-coil systems and their thermal management systems
3. Reduce risk and validate modeling via **hardware proof-of-concepts**
4. Map **multivariate space** based on models, functions, & other technologies
5. Assess utility for **candidate applications**
6. Identify and evaluate **risks and roadblocks** to technology integration

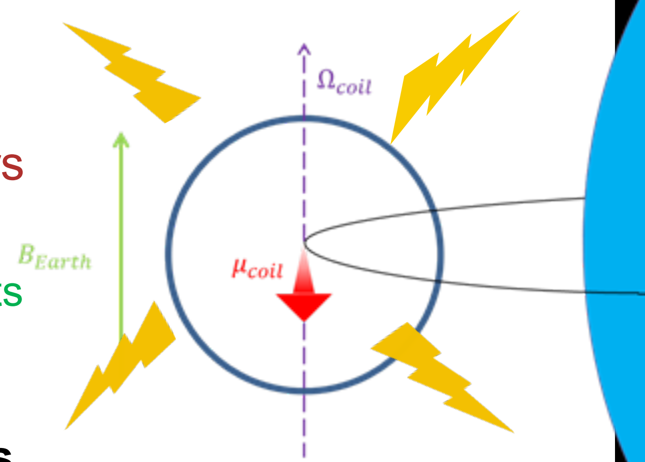


USE CASES

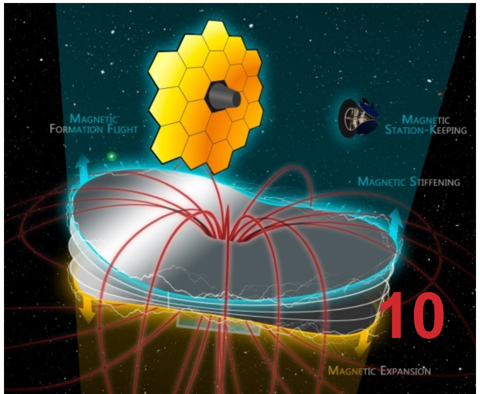
1. **"Near-Term": GEO Magnetorquers**
   - ≤ 5 years, *achieve TRL 5* and propose demo mission
   - Focused on flight heritage & maturation
   - Progress:
     - Determined sizing required for GEO desat and comparative design of HTS vs. Cu torque coils



2. **"Mid-Term": EMIC Wave Antenna**
   - 5 - 15 years, *enable* or *enhance* new missions
   - Focused on addressing technical feasibility barriers
   - Progress:
     - Defined thermal, science, and antenna requirements
     - Studied dynamics & required inertial ratio of continuously spinning antenna in geomagnetic field

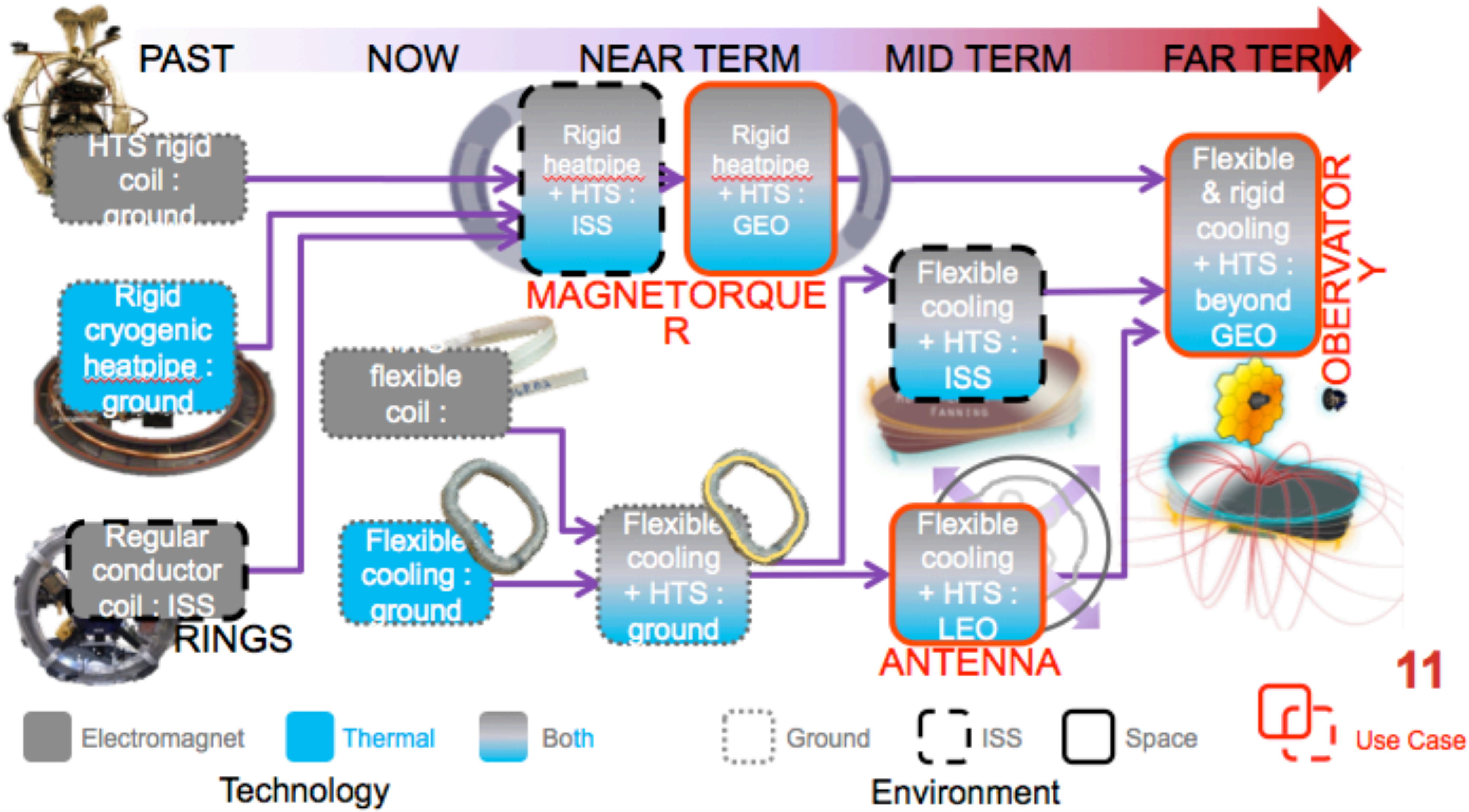


3. **"Far-Term": Commissioning of Large Observatories**
   - Beyond 15 years: applications to *revolutionary mission concepts*
   - Focused on addressing integration viability barriers
   - Progress:
     - Conducted modularity and servicing trades for large observatories (16.89 class)
     - Enumerating EM functions useful in in-space assembly



TECHNOLOGY ROADMAP

- Use cases are used as key steps along roadmap forward
- Maturing technologies first individually then together



UTILIZATION OF 2ND GENERATION HTS WIRE

- **Characteristics**
  - Minimum bend radius of 1.1 cm
  - HTS material is a solid epitaxial monolayer
  - Option to remove copper and silver layers
  - 4 mm wide ribbon wire rated to 100 Amps

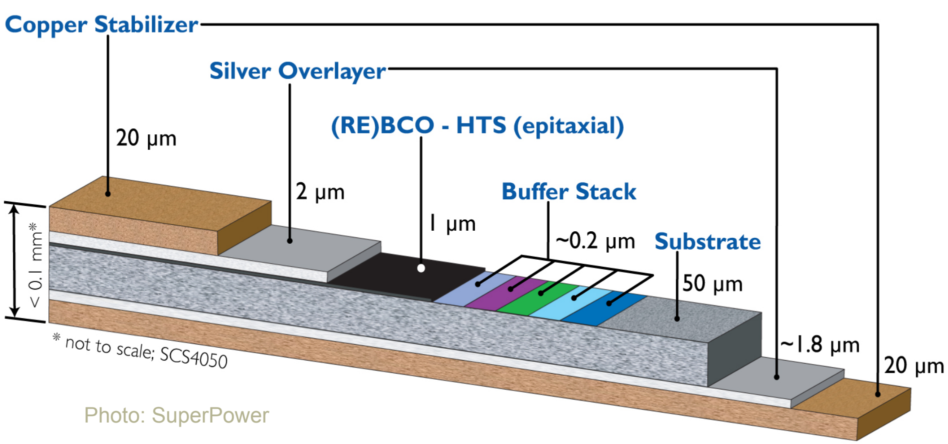


Photo: SuperPower

- **Operation**
  - Initial concept bellows
  - Desire highly flexible cryogenic enclosure
  - Critical temperature can be achieved using nitrogen close to boiling point
  - Vapor-cooling advantageous over liquid due to lower loss tangent

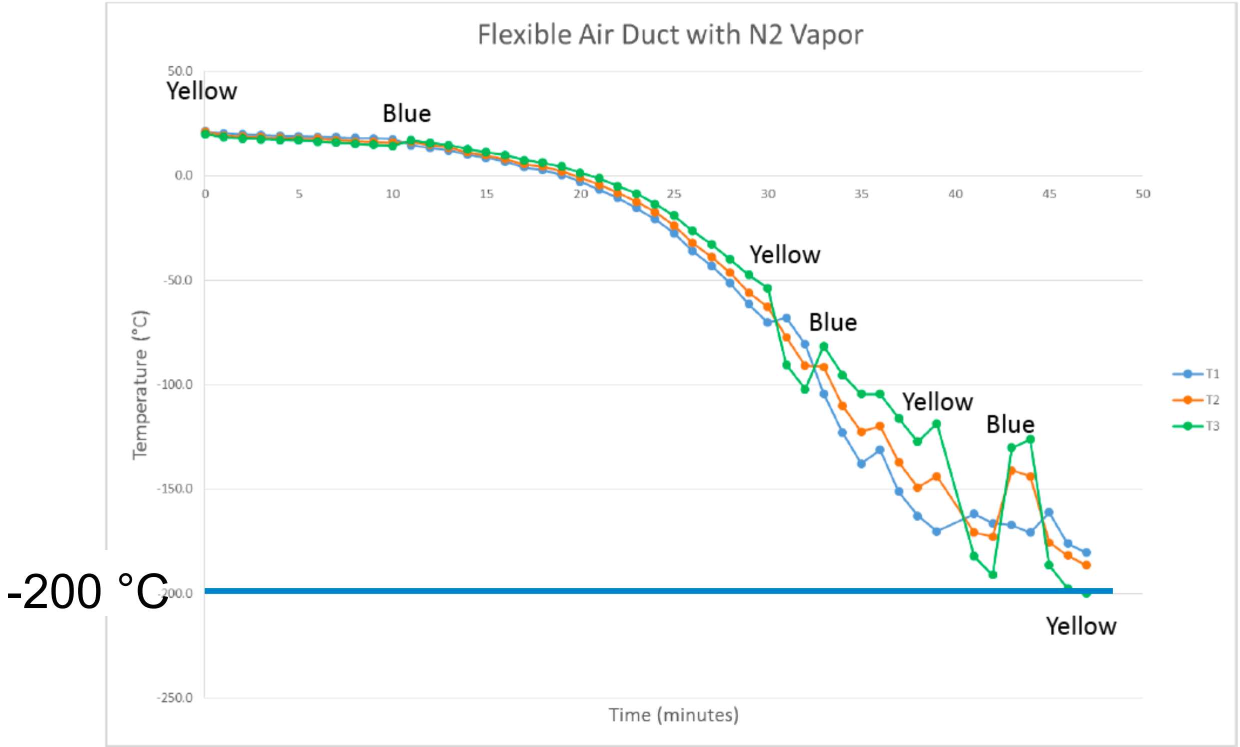
THIN-WALLED COOLING SYSTEM

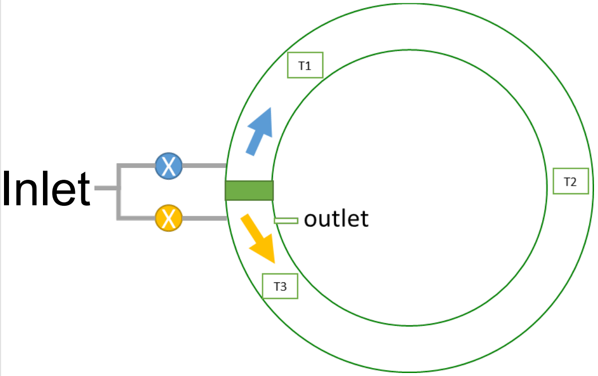
- **More flexible than heat pipe**
  - Does not require internal mesh structure for fluid wicking
  - Small bend radius and higher compression ratio than metal bellow
  - Pump nitrogen vapor using cryo-cooler

- **Prototype constructed from COTS dryer vent hose**
  - Aluminum-coated plastic similar to aluminized Mylar
  - Similar in size to spring deployment prototype
  - Sections connected by internal PVC collars
    - Reduce twisting due to helical ribbing
    - Fabricating custom multilayer insulation sleeve for radiation shielding

PRELIMINARY THERMAL TESTING

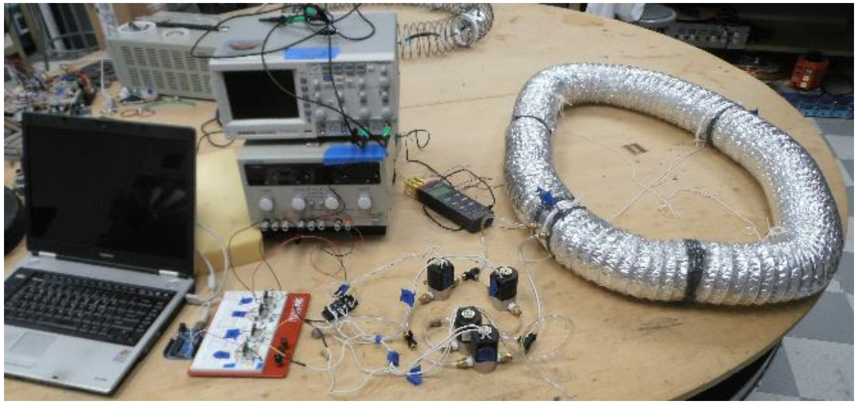
- **Alternate direction of flow using manual valves**
  - Achieve sub-critical temperature for inlet and outlet
  - Dryer vent insulated only using ¼ foam (pink) and felt cloth (white)

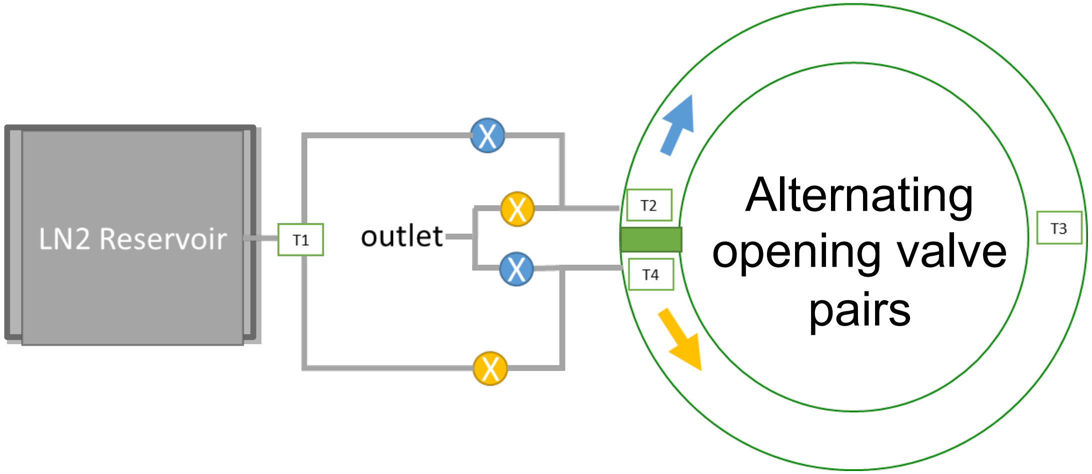




THIN-WALLED COOLING SYSTEM (REV. 2)

- **Cryo-rated solenoid valves to control flow direction**
  - Four normally closed, two-way solenoid valves
  - Measure temperature at inlet, outlet, and middle of enclosure
  - Flow rate measured at outlet

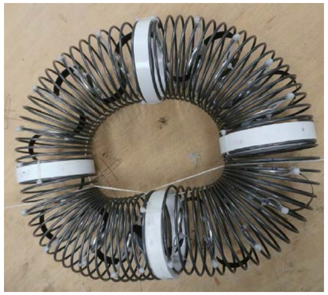




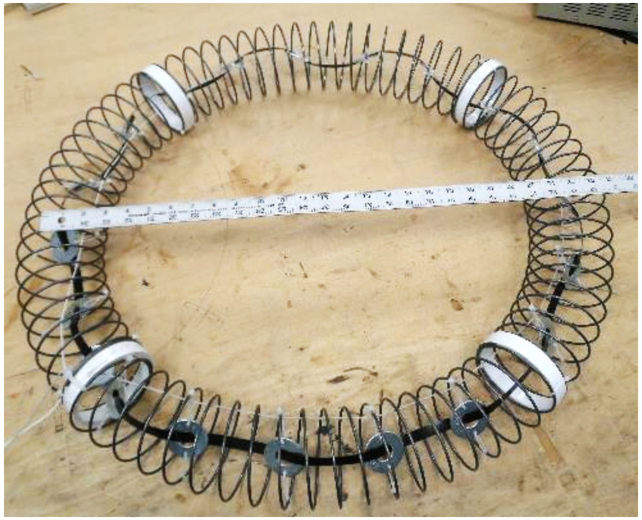
- **Arduino used for flow control**
  - Fixed interval for flow direction
  - Shorter transition time compared to manual valves (which got stiff and hard to manipulate)

DEPLOYMENT USING SPRING FORCES

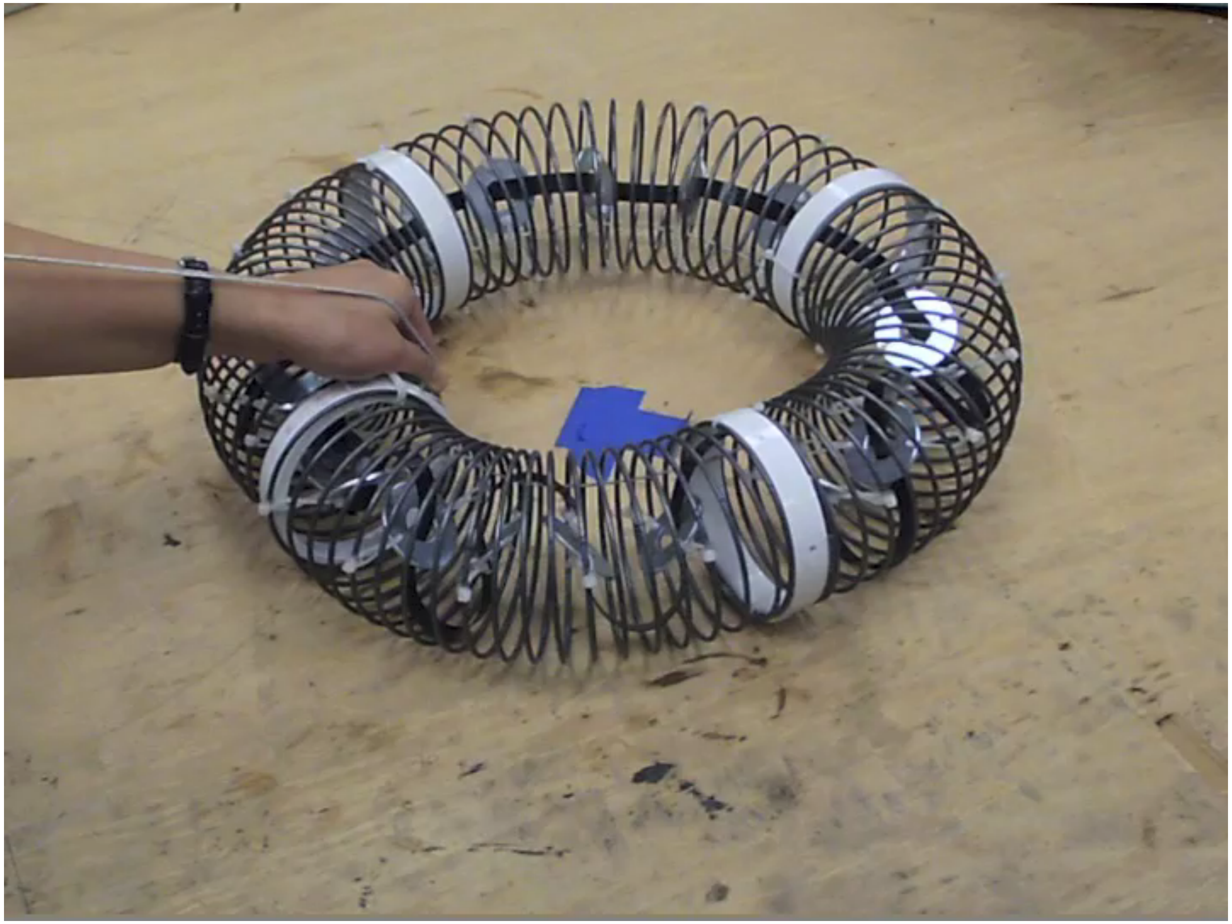
- **Large springs use potential energy to deploy coil**
  - Doubles as structural support for thermal enclosure
  - Takes advantage of small minimum bend radius of Gen-II wire
- **Concept prototype**
  - Built using four springs connected by PVC rings
  - Major diameter of 25 inches, cross-sectional diameter of 4 inches
  - Plastic ribbon as HTS coil stand-in



Achieves large expansion ratio

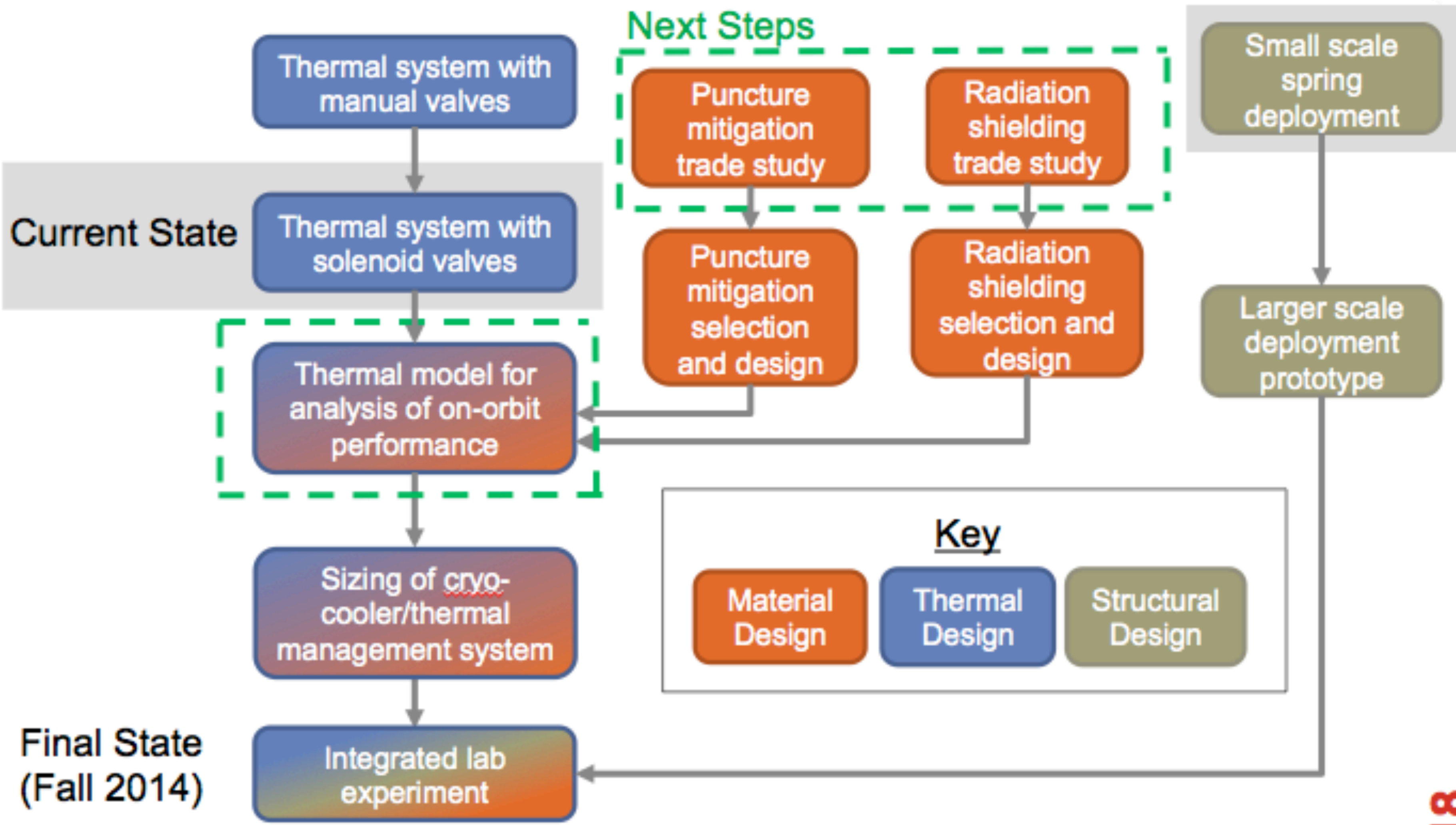


DEMO OF PROTOTYPE DEPLOYMENT



Note: Control of deployment not finalized

THERMAL ENCLOSURE PLAN FORWARD



TECHNOLOGY ROADMAP

Steps to Full On-orbit Demonstration

NIAC	NASA GCD	NASA FOP	NASA TDM
Flow control system	Integration of Cryo-cooling	Full-scale ground testing	On-orbit testing
Flexible Thermal Shielding	Flexible thermal shielding	Parabolic flight testing (small scale)	
High Expansion ratio deployment system	Self-healing materials	Sub-orbital Testing?	

Key

- Material design
- Thermal design
- Structural design
- Integrated system

QUESTIONS?

Additional contributors to MAGESTIC include:

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- Dr. Maria de Soria-Santacruz Pich
- Aaron Perez
- Guillermo Bautista
- Zachary Schwartz
- Scott Kindl

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- Prof. Karen Willcox
- Prof. Kerri Cahoy

BACKUP SLIDES

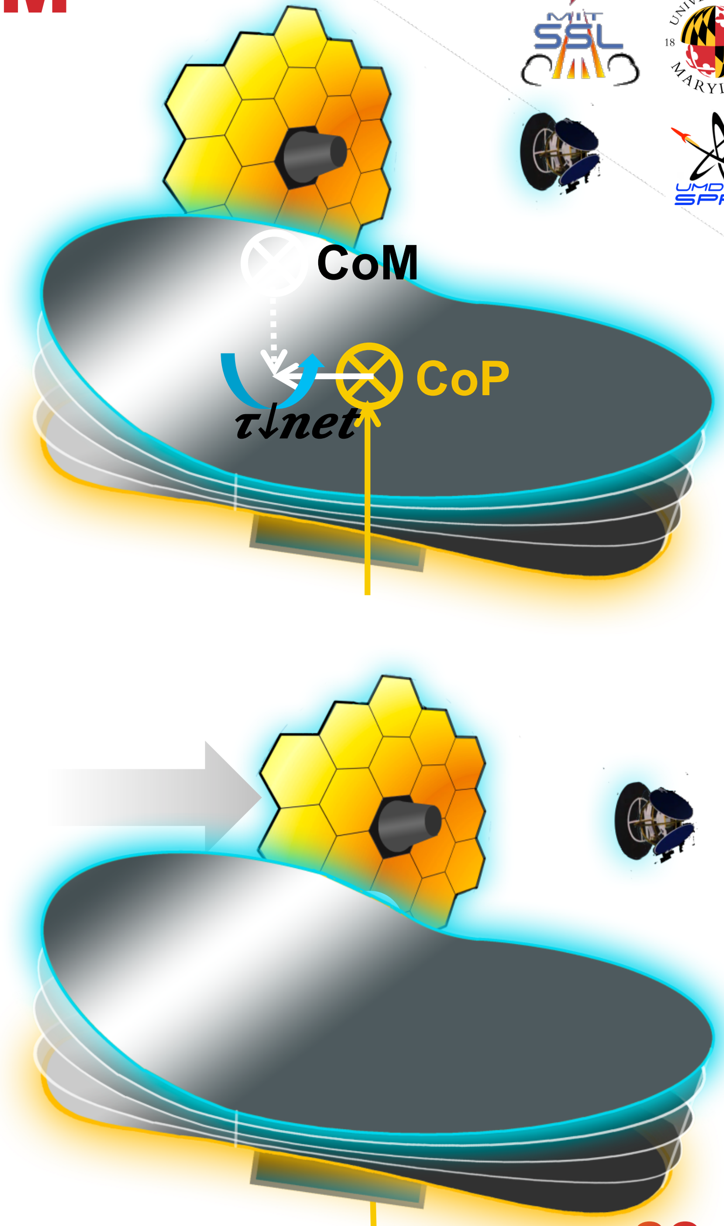
ALIGNMENT & MOMENTUM MANAGEMENT

JWST's lifetime limited by propellant, used for two purposes after reaching L2:

- **Stationkeeping in halo orbit around L2**
- **Desat reaction wheels**
    - Saturated by net solar radiation pressure torque due to center of pressure/center of mass offset

Disconnecting OTA and sunshield and formation flying → translational momentum exchange

- **OTA drives CoM, sunshield drives CoP**
- **"Trimming" sunshield w.r.t. OTA over course of orbit → reduce offset and net solar pressure torque and desat propellant**

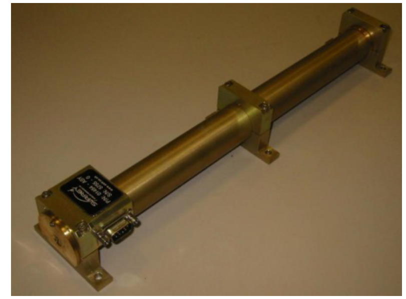


CU VS HTS – 3500 Am^2

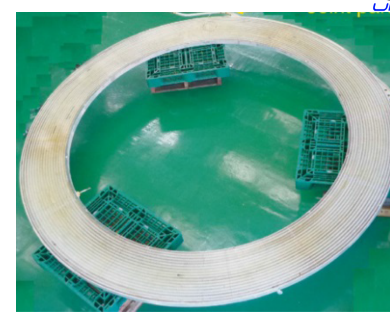
- **Compare to HTS for magnetic moment required in GEO**

To achieve 3500 Am^2 with these torquer styles:

https://directory.eoportal.org/web/eoportal/satellite-missions/s/studsat-1



Surrey Satellite Technology MTR - 30



Japan Atomic Energy Agency

Area m^2	5	0.424 (max CSA)	5
# of turns	761	117 x single rod	5
Current A	0.92	0.2	150
Mag. moment Am^2	3500	3500	3500
Mass kg	19.94	210	**1.54** (w/ cooler & MLI)
Mag moment per unit mass Am^2/kg	175.53	16.66	**2272.72**
Thermal output W	305	117	**.25W (w/ 10W in cryocooler)**
	TORQUE COIL	TORQUE ROD	HTS TORQUE COIL

DYNAMICS CONSIDERATIONS

- Rotation at EMIC frequencies (~ 0.5 Hz)
- Coil axis should remain close to perpendicular to Earth's magnetic field → maximum R_{rad}
- **Gyroscopic torque** → tends to align Ω_{orbit} || ω. Stable when spinning around major axis of inertia

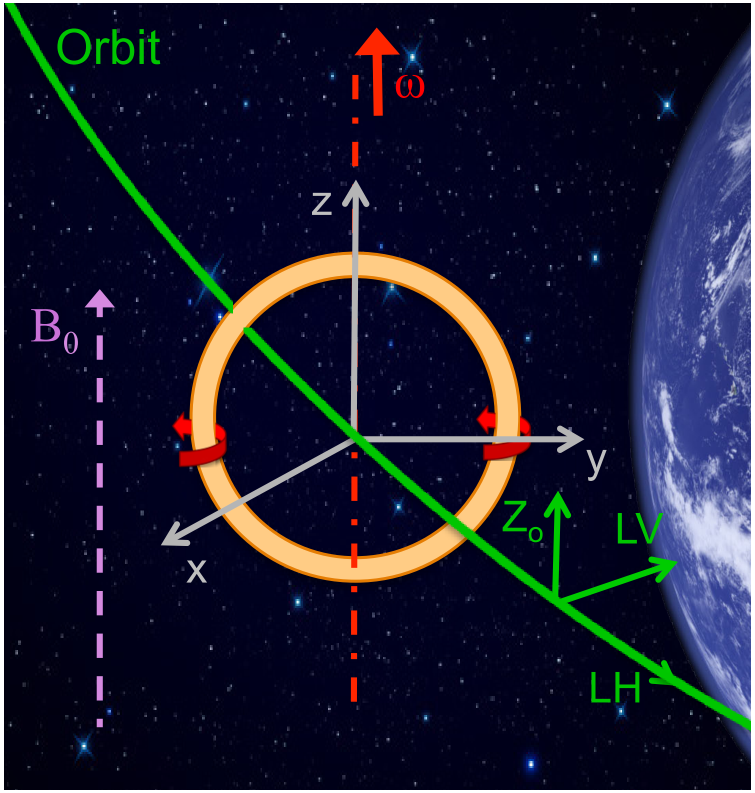
$$\tau_{gyro}\Big|_{\max} \approx \Omega_{orbit}\omega I_r \approx 165\ N{\cdot}m$$

- **Magnetic torque** → tends to align magnetic moment of antenna with external magnetic field

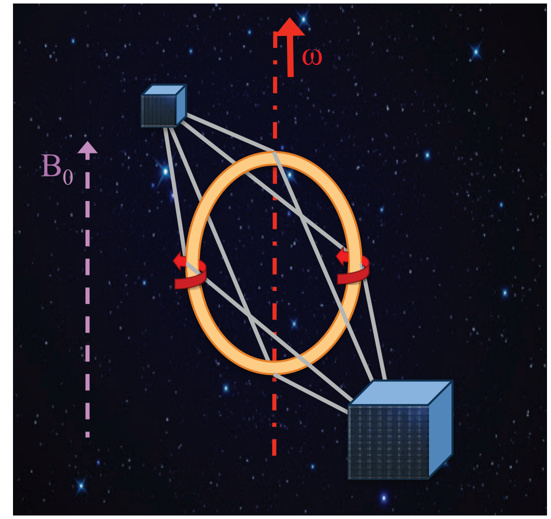
$$\tau_{mag}\Big|_{\max} \approx N_{turn} I \pi R_a^2 B_0 \approx 180\ N{\cdot}m$$

- **Gravity gradient** → tends to align coil's axis of smaller inertia with vertical direction towards Earth's center

$$\tau_{gg}\Big|_{\max} \approx 3\Omega_{orbit}^2 I_r \approx 0.1\ N{\cdot}m$$



DYNAMICS CONSIDERATIONS



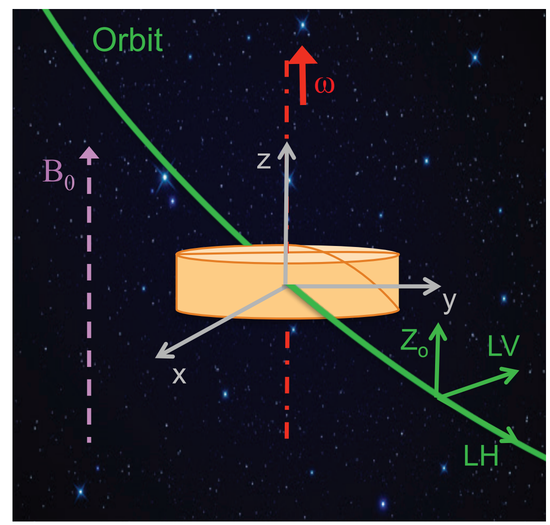
- **SOLUTION:** distribute S/C subsystems such that body becomes major-axis spinner → gyroscopic stability much larger than perturbations from magnetic torque
- For body acted by constant magnetic torque, τ_{magY}, perpendicular to the angular momentum (H) as an initial condition, the magnitude of H is conserved, and its vector precesses describing a small cone if

$$\omega > \frac{2}{I_z}\sqrt{\tau_{magY} I_y} \approx 0.02\ Hz \qquad \left(@ I_z / I_y = 1.9\right)$$

- For unbalanced initial cor
a small forced precession
of the antenna. Dissipatio
time. The maximum ser
precession of H is

$$\nu_{\max} = \frac{\tau}{\omega \quad -} \approx$$

i.e. very small precession

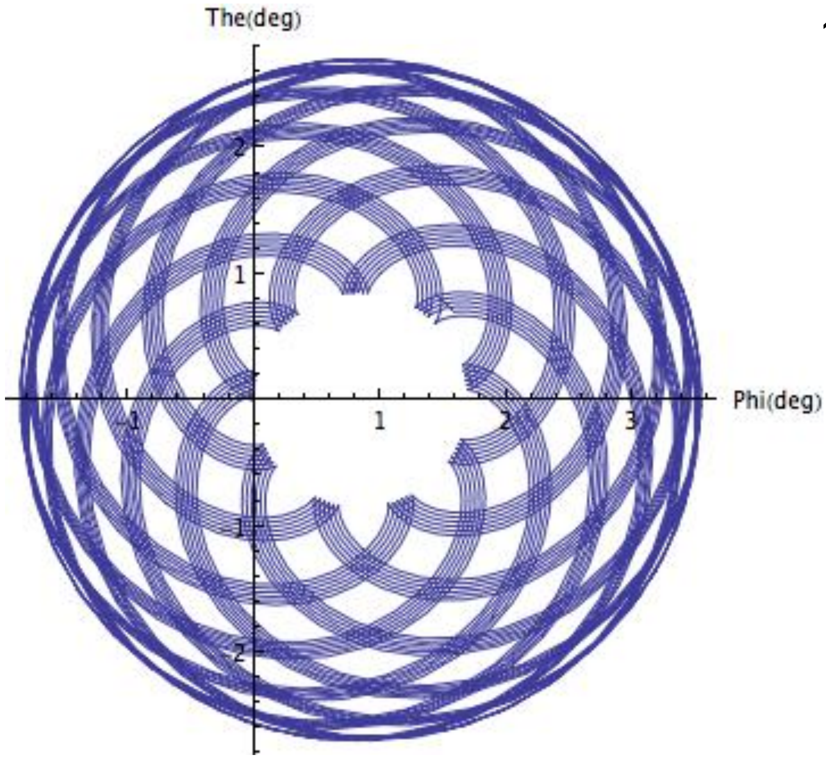


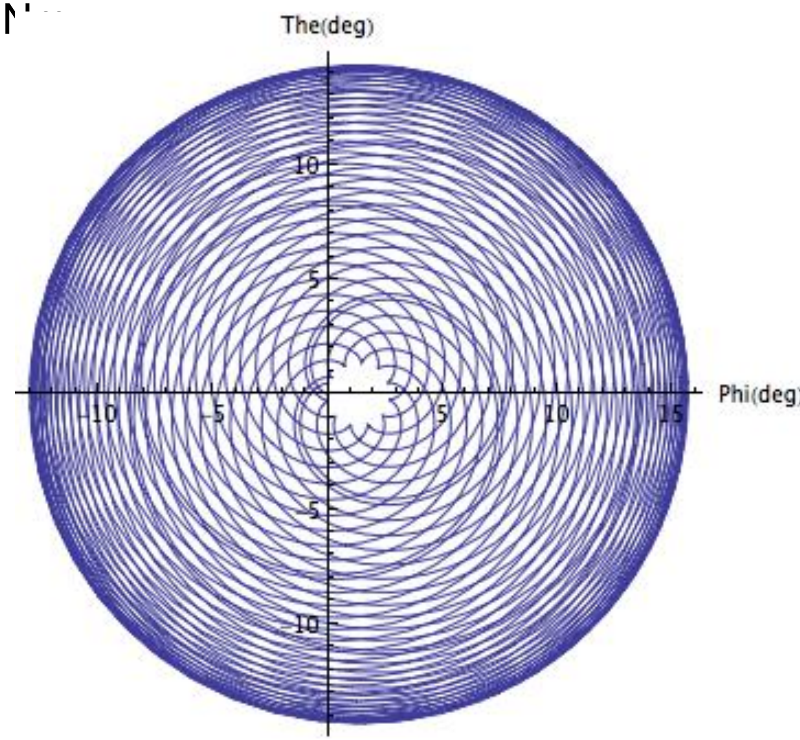
DYNAMICS CONSIDERATIONS

- If ω high enough and starting from null initial conditions except for $\omega_z = \omega$, body axis-z will describe a closed figure as shown in terms of tilt angle ϕ [deg] about LV and roll θ [deg] about LH.

ω = 0.628 rad/s

110 N





(1) $I_z/I_y = 1.9$, $I_y = 10^4$ kg-m^2,

(2) $I_z/I_y = 1.2$, $I_y = 10^4$ kg-m^2

MATURATION PLAN

- Use cases provide incremental maturation of technology in increasingly relevant environments and increasing size

Technology Areas

Use Cases:	Torque Coil	Antenna	Observatory
Electromagnets & Deployment	★ Rigid electromagnets, ★ No deployment	★ Much bigger electromagnet, ★ Flexible, requires deployment and spinning	★ Multiple electromagnets, operating simultaneously /out of phase, ★ Rigid *and* flexible
Thermal Control	★ Rigid cryogenic heatpipe operating in vacuum	★ Flexible cooling system in vacuum	★ Flexible, rigid, and possibly passive behind a shield
Power Mgmt & Control	★ DC current, ★ Familiar controller, ★ Power provided by ISS	★ Constant high DC current	★ Phased operations, ★ Wireless power transfer, ★ Time-variant operations
Example Mission:	**Torque Coils on ISS (step towards GEO)**	**EMIC Wave Antenna**	**Next-Next-Gen Space Telescope**
Environment:	Human-accessible	Free-Flying in LEO+	Free-Flying beyond LEO
Example Est. Cost:	~$5m	~$10m	AMP, parallel investment

ISS AS MATURATION PLATFORM

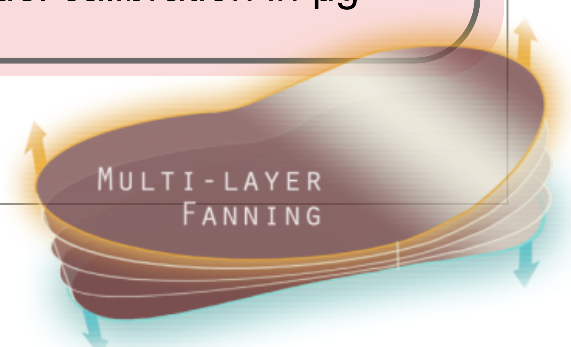
- **Ideal platform for space technology demonstration and maturation**

Inside ISS:

- Human-in-the-loop testing, convective environment
- Allows for complicated experiments & multiple trials with variable parameters

Ex: Deployment and tensioning of 2+ membranous layers

- ISS interior allows testing of multiple stowed configurations and numbers of layers
- Demo of flexible cooling and flexible HTS tensioning
- Provides model calibration in μg environment

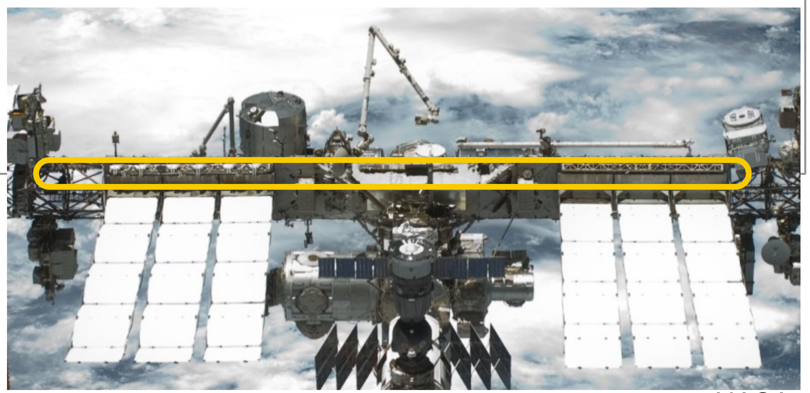


Outside ISS:

- LEO environment, ISS power and mass Observable & recoverable (if necessary)

Ex: Torque coil for ISS desat

- ISS requires large torque to desat CMGs; good LEO testbed for large magnetic moment MTQ
- Demo of rigid HTS and rigid cooling, as well as system lifetime
- Data on hysteretic losses in HTSs with changing current in coil
- Possible quenching experiments at end of experimental life



NASA

KEY ENABLING TECHNOLOGIES

- Table below maps identified KETs to the first major roadmap milestone that uses them
- Spaced out over time

MAGNETORQUER	ANTENNA	OBSERVATORY
• Striated superconductors for lower AC losses • More power-efficient cryocoolers • Controller for desaturation in GEO magnetic field	• Twisting tape stacks to reduce perpendicular magnetic field • Flexible cooler for flexible HTS • Non-helical MLI sheath	• Self-reversible electromagnetic latches • Phasing for 2+ matched sets of magnets w/out cross-interaction • Controller for tethered or otherwise constrained magnets

LEGEND

Electromagnets & Deployment

Thermal Control

Power Mgmt & Control

USE CASES GOING FORWARD

- Use cases can be refined and detailed through further analysis in remainder of Phase II

MAGNETORQUER (ISS and GEO)

- **Determine propellant offset for ISS and example GEO satellite with use of HTS MTQ**
- **Improve upon thermal analysis and mass estimates**

ANTENNA

- **Flexible coil deployment model that realistically incorporates stress and strain**
- **Describe a spacecraft design that would make antenna spin axis a major axis of inertia**

OBSERVATORY

- **Determine how to orthogonalize sets of magnets performing different functions**
- **Model sunshield**

OTHER USE CASES

- **Use cases selected based on driving the technology forward and are by no means the only applications of MAGESTIC**

Corollary Mission Functions	Other Example Use Cases
Strong controllable magnetic field	Radiation deflection
Naturally circular deployed area and/or tensioned perimeter	Solar sails
Consumable-free controllable actuation w.r.t non-contacting elements	Reconfigurable spacecraft, formation flight, assembly of any large structure
Performs as well or better in cold environs	Outer belt interplanetary missions
Lossless energy storage	Missions with large amounts of energy needed at once
Low exported vibration and heat transfer	Missions with sensitive optics or long flexible structures
Wireless power and/or data transfer	Formation flying clusters of satellites

MAJOR ROADMAP STEPS

Technology(s)	Environment	Application	Purpose of Step	Stage
Flexible HTS coil	Ground	Proof-of-concept	Evaluating feasibility	Now
Flexible cooling	Ground	Proof-of-concept	Evaluating feasibility	Now
Rigid heatpipe + HTS	ISS (external)	Torque coil to offset some ISS desat	Flight heritage and operational use of hardware in space as a non-essential component	Near-term
Rigid heatpipe + HTS GEO MAGNETORQUER	GEO	Torque coil for GEO desat	Actual integration into spacecraft design and operations; flight heritage of HTS and cooling system	Near-term
Flexible cooling + HTS	Ground	Proof-of-concept and ground deployment testbed	Evaluate feasibility; testbed for deployment & tensioning configs	Near-term
Flexible cooling + HTS	ISS (internal)	Tensioning & separation of 2+ membranous layers	Repeatable and resettable testing of HTS structural support capacity in μG	Mid-term
Flexible cooling + HTS ANTENNA	LEO	Deployment & tensioning of a flexible coil antenna	Scientific mission to determine if man-made EMIC waves can precipitate protons from van Allen belts	Mid-term
Flexible & rigid cooling + HTS OBSERVATORY	Beyond GEO	Assembly, deployment, and support of large space observatory	Integration of multiple electromagnetic functions into one spacecraft	Far-term