GyroCube Heliogyro Solar Sail System Development

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What is Solar Sailing?

- Solar sails use momentum transfer from solar photons for *propellantless propulsion*.
- Three canonical solar sail architectures:
  - Square, kite-like, rigid solar sails (e.g., NanoSail D, Sunjammer).
  - Spinning disk solar sails (e.g., IKAROS)
  - Spinning helicopter-like *heliogyro* solar sail.
- Key solar sail design challenges:
  - Solar sails must have *extremely large* areas to obtain useful amounts of thrust from sunlight.
  - Solar Sails must be *extremely lightweight* to develop meaningful accelerations.
  - Solar sails must be *deployable*.
- Ground deployment validations are difficult or impossible, so *affordable* flight demonstrations will be needed to prove viability.
Success of JAXA IKAROS solar sail flight in 2010 renewed interest in solar sails within NASA and spinning solar sail architectures in particular.

The *heliogyro* is a helicopter-like spinning solar sail concept, first developed by MacNeal in the 1960s and studied extensively by JPL in the 1970s.

- Highly efficient and fast design due to lightweight centrifugal stiffening of sail.
- Unlike disk and square-riggers, heliogyro solar sail “blades” are compactly stowed on reels and easily deployed.
- Development has lagged that of heavier, square-rigged solar sail designs due to the impossibility of conducting full-scale ground tests.
- Heliogyros can be km across!

*In-flight photo of JAXA IKAROS 14 m spinning solar sail (2010)*

*15 km diameter heliogyro solar sail concept for the proposed JPL Comet Halley rendezvous mission (1977)*
NASA and CU are developing a SmallSat-based heliogyro technology demonstrator called HELIOS

**HELIOS**\* Heliogyro Solar Sail Technology Demonstration Mission

- Deployable videogrammetry cameras for blade deployment validation

- **Centrifugal stiffening makes the heliogyro lighter and faster than conventional rigid-structure solar sails.**

- **Spin rate:** 1/3 RPM

- **Root pitch motors** for blade attitude control and thrust vectoring

- **Low-cost heritage CubeSat-based central bus** (~5 kg)

- **Six (6) centrifugally stiffened** 2.54 μm x 0.8 m x 218 m aluminized Mylar solar sail “blades”.

  - Total solar sail vehicle mass: ~18 kg
  - Orbit: 1400 km dawn-dusk sun-synch
  - Characteristic acceleration: ~0.50 mm/s²
  - ESPA-class rideshare payload

NASA is also interested in CubeSat heliogyros

- HELIOS is based on SmallSat technology, but is larger and heavier than traditional 1U, 2U, 3U, 6U, 12U CubeSats.
- NASA would like a smaller low-cost CubeSat heliogyro demonstrator (GyroCube) suitable for launch via a standard CubeSat canisterized dispenser (e.g., CalPoly PPOD, CSD, etc.)
- Flight objectives for a GyroCube:
  - Demonstrate controlled heliogyro blade deployment.
  - Validate blade dynamics models.
  - Validate heliogyro thrust and attitude control models.
- Flight opportunities exist!
GyroCube Specific Design Project Objectives

The Project Team shall develop a CubeSat-compatible heliogyro solar sail dynamics and control proof-of-concept (“GyroCube”) in accordance with constraints of an Exploration Mission 1 (EM-1) Space Launch System (SLS) secondary payload. The project shall have four (4) measures of success:

Success level 1: Develop a blade deployment and control system incorporating flight-like structure, sensing, actuation, and control components, that can accommodate (but not develop) other spacecraft components (C&DH, EPS, COMM, spin-up).

Success level 2: Meet level 1 AND design, build, package, and successfully deploy a GyroCube flight prototype 100:1 aspect ratio solar sail “blade” assembly under 1-g.

Success level 3: Meet level 2 AND design, build, integrate and test a flight-like proof-of-concept blade damping augmentation system (active or passive) capable of providing torsional (twist) damping of the deployed solar sail blade.

Success level 4: Meet success level 4 AND provide blade damping augmentation for out-of-plane (flap) blade motions.
The GyroCube flight experiment shall be designed to deploy two identical heliogyro solar sail blades each with a minimum aspect ratio of 100:1.

GyroCube blades shall be edge-tendon-loaded, similar to NASA HELIOS reference solar sail blades.

The GyroCube flight experiment system shall fit within a standard 6U CubeSat volume; of which a minimum of 2U are assumed to be allocated for spacecraft bus systems.

The GyroCube flight experiment system shall be designed to conform to SLS EM-1 secondary payload requirements; to be provided by NASA.

No strict upper mass limit for GyroCube blade system.
- Less than or equal to 1 kg/U is typical for CubeSats.
- Blade areal density, including tip mass, shall be comparable to NASA HELIOS designs. (<6 g/m2)

Power: Assume 5W available per blade. 10W total for GyroCube experiment.

**Design of GyroCube bus and other mission systems is not required.**
- **Project shall focus on the blade systems.**
- **Guidance on notional bus systems to be provided by NASA.**
Key heliogyro and solar sail references

• HELIOS Mission Objectives:
  - Demonstrate controlled heliogyro solar sail flight at mission-enabling characteristic accelerations (ac ≥ 0.5 mm/s²).
  - Validate critical deployment technologies scalable to mission-enabling solar sail architectures.
  - Demonstrate orbit change capability (raising, lowering with de-orbit at EOL)
  - On-orbit validation of structural dynamics and sail flight models.

• HELIOS nominal orbit: 1200-1400 km sun-synchronous, dawn-dusk
  - Altitude >1000 km required to minimize aerodynamic drag.
  - Minimal eclipsing desired (thermal-elastic considerations)

• HELIOS mission duration: 4 months minimum, with de-orbit at EOL

• Mission based on DoD Space Test Program Mission S26 (STP-26)
  - Minotaur-IV launched 19 Nov 2010 from Kodiak launch Complex
  - Carried 14 separate spacecraft
  - Configured with MultibPayload Adaptor (MPA) capable of carrying 4 ESPA class APLs
  - Dual orbit capability with Hydrazine Auxiliary Propulsion System (HAPS)
  - Capable of 1200 km secondary orbit

MULTI-PAYLOAD ADAPTER HAPS FOR DUAL-ORBIT CAPABILITY

HELIOS sail-craft w/ ESPA envelope
**HELIOS deployment sequence:**

1. Separation from ESPA carrier via push-off springs. (HELIOS unpowered).
2. Sep switch powers on HELIOS.
3. Detumble via magnetic torque rods.
4. Acquire and point at sun.
5. Free deployment of blade reel hex truss.
6. Pitch blade reels to 90 degrees.
7. Spin-up with spin axis toward sun.
8. Initiate partial blade deployment.
10. Pitch blades down to engage solar radiation pressure for spin rate control.
11. Systems and flight control checkout.
12. Resume blade deployment to full radius.
Heliogyro technology lies on the mean application trend line for solar-sail-enabled missions.

IKAROS (200 m², 75 g/m²)

E2

Helios (1000 m², 18 g/m²) lies on the mean application trend line for solar sail enabled missions.

Sunjammer (1000 m², 40 g/m²)

Area of one (1) US football field

Mission taxonomy:

Class 1: High-energy mission target
Class 2: Continuous thrusting application

M: Enabled or significantly enhanced mission
M: Marginal value-added mission.

Ref: Macdonald, McInnes, 2011

HELIOS may be scaled to larger sizes. Blade aspect ratios of 1000:1 are possible with the current HELIOS ESPA heliogyro design.

7.62 µm (0.3 mil) Kapton

Ref: Macdonald, McInnes, 2011