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🛰 – SoSo-Steering: Can Solar Radiation Pressure Be Demonstrated on Earth?

> **“I used to believe it myself: Solar radiation pressure can't be measured on Earth – air pressure is thousands of times stronger.
> But is that really true?”**

PanelSat challenges this assumption.
Even the minimal force generated by a simple suspension thread was enough to visibly rotate the relatively large PanelSat model during Earth-based tests.

So what happens if we suspend PanelSat inside a vacuum chamber – taking airpressure out and illuminate it with directional light sources?

My prediction:

> **The model will rotate – solely driven by light pressure, around the virtual axis defined by the thread.**

The exact rotation speed would be determined by the experiment –
but the effect should be measurable and repeatable.

TU Delft, which will receive the first research-licensed PanelSat model after the symposium, already operates high-end vacuum chambers suitable for SRP testing.
This creates an ideal setting for early validation of SoSo-Steering behavior on Earth – without requiring launch resources.

- The ESA's large vacuum chamber includes internal mirrors primarily to simulate uniform sunlight from various directions. This helps in testing spacecraft thermal loads and solar interaction under space-like illumination conditions. In contrast, the proposed black chamber for PanelSat® experiments avoids such reflections to isolate directional light effects more accurately during dynamic orientation tests.
- TU Delft, which will receive the first research-licensed PanelSat model after the symposium, already operates high-end vacuum chambers suitable for SRP testing.
  This creates an ideal setting for early validation of SoSo-Steering behavior on Earth – without requiring launch resources.

- **Note on Chamber Design for PanelSat® Testing:**
- While mirrored wall elements may serve thermal balance testing in some spacecraft setups, on the other hand PanelSat® relies on precise directional light input (as it is the case in space) to control panel orientation via voltage differentials in exposed measurement solar cells. For accurate validation of its autonomous steering logic (SoSo-Steering), reflected or scattered light would introduce ambiguities into the sensor data.
- To preserve the integrity of the experiment, a matte-black chamber interior without reflective elements is therefore preferred — ensuring that all sensor input corresponds strictly to the intended direction of solar radiation.
- A cooled external corridor or enclosure around the vacuum chamber could further enhance the realism of test results, as it would reduce infrared radiation emitted by the chamber walls, minimizing thermal interference with the light-sensitive sensors and solar cells on PanelSat®

The setup allows manual control via a standard remote, enabling a clear visualization of how the gravitational alignment concept works. One distinct advantage is the visible movement of the stroke section, making the shift in mass clearly observable. A scale could be added — either marked on the stroke segment itself or on the mounting bracket along the actuator’s path — to quantify displacement.

Another benefit of this mounting bracket is its versatility: multiple mounting holes enable variable installation of the actuators — higher, lower, or flipped — making it easy to rebalance the system as the mass distribution between the two rings changes (e.g., when components are added).

This yields a simple two-stage alignment concept:

- **Coarse alignment** by shifting actuator positions mechanically on the bracket
- **Fine-tuning** and movement of the model by extending or retracting the stroke segment

Advantages of PanelSat as Solar Sail Controller

1. Integrated Pre-Alignment

- Uses gravitational self-alignment and MSUs to establish stable initial attitude.
- Ensures the sail is deployed in an optimized configuration.

2. Unified Motor and Logic Architecture

- Two motor types for three control principles:
  - 28BYJ-48 for panels and AMT-MSUs
  - NEMA 8 for horizontal MSUs
- Shared control logic and hardware for all axes

3. Structural and Functional Modularity

- Plug-and-play interface at the bottom of the main case
- Allows mounting of:
  - Large solar sail (e.g., like Solar Cruiser)
  - Drag sail
  - Laser communication unit (e.g., Mynaric)

4. Ground-Testability of Attitude Control

- Key components of the PanelSat attitude control system can be **tested on Earth in a vacuum chamber**
- Includes:
  - MSU-based gravity alignment
  - SoSo-Steering (panel-based light pressure control) around the virtual thread
- Enables **pre-launch verification of control behavior under near-space conditions**

🌌– Simulating Space: A Realistic Vacuum Test for PanelSat

To study the behavior of PanelSat under space-like conditions, we propose a ground experiment inside a vacuum chamber:

Vacuum Chamber Requirements:

- Large enough to suspend a full PanelSat model by a thread
- Attached to a lightweight frame or the ceiling for free rotation
- Directed light source from one side to simulate solar radiation
- Black interior walls and black structural frame to minimize reflections

This setup eliminates both **air pressure** and **light reflections**, creating conditions **similar to space**.
Only the **tension of the thread** remains – a factor that can be calculated or compensated by physicists and material scientists.

> **Conclusion:**
> Under these conditions, PanelSat’s response to light pressure can be observed and quantified **on Earth** – no launch required.

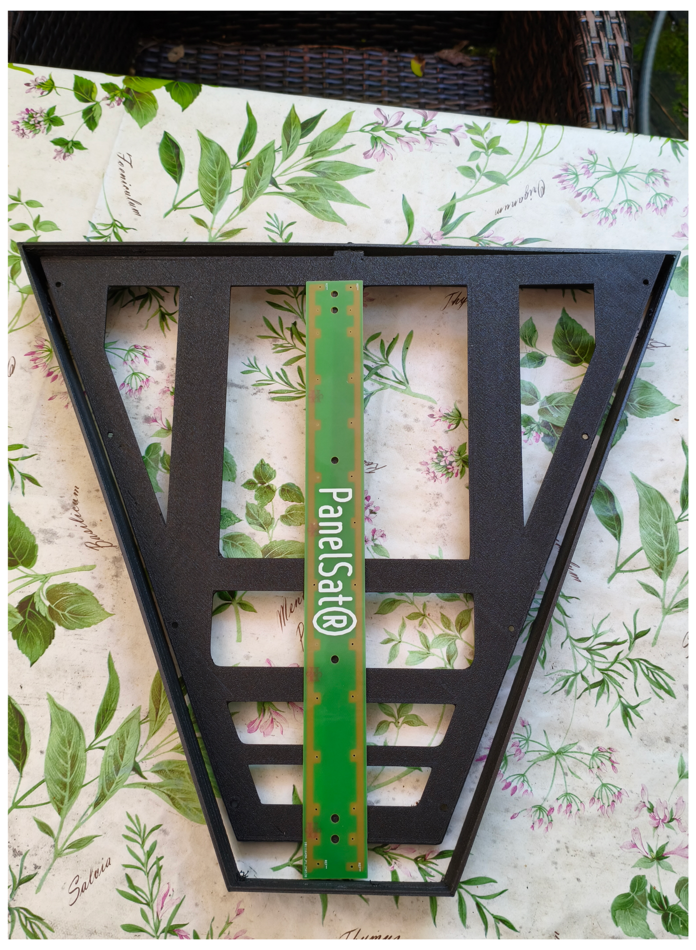
🧪 **Preliminary Test (without Panels):**
To verify the SRP effect before activating panel rotation:

1. Cover a section of the outer ring (where two panels would later rotate edge-on to the light) with **black, absorbent paper**
   → Expose to directional light → **Model begins to rotate slowly**
2. Replace the same section with **highly reflective mirror film**
   → Expose to light again → **Noticeably faster rotation**

This simple test confirms that **reflected light produces more torque** than absorbed light – even without moving parts.

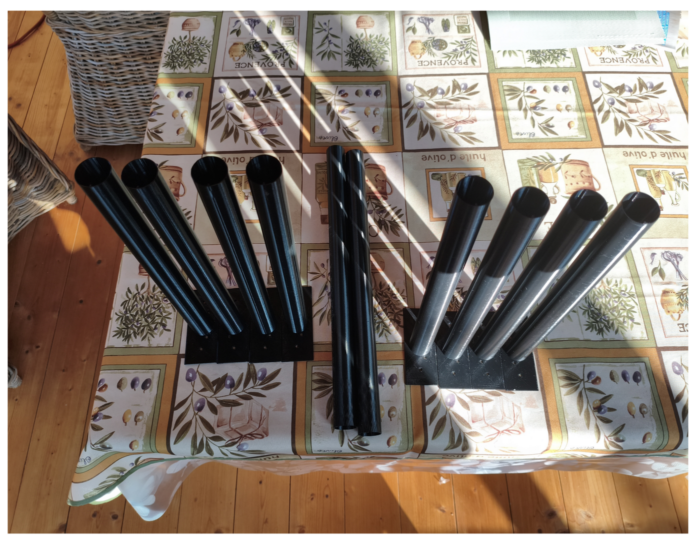
Panel Hardware: Power Routing & Sensor Integration

(Photo: Base panel with power-routing PCB – solar cells not yet installed)



Industrial-Grade MSU Components Provided by Stratasys

📸 (Photo: Multiple MSU and AMT-MSU parts printed by Stratasys GmbH, Rheinmünster)



During early tests with desktop 3D printers, the MSU housing tubes presented major challenges:

- The print head slowed down when approaching internal guide ridges
- This caused uneven extrusion and **surface distortions**, both **inside and outside** the tube
- As a result, the **inner mass element** could not move smoothly – rendering the MSU non-functional

🔍 This level of ground-testability is **not possible** for conventional flat-panel solar sailcraft,
where radiation pressure effects and full-scale deployment behavior are **not reproducible on Earth**.

5. Enhanced SRP, Mass-Based Steering, and Propulsion

- Combines mass shifting with solar radiation pressure via panel orientation
- Additional DTU thrusters allow extended maneuver capability when needed
- Capable of full passive and active control with minimal energy use

6. Extended Lever Arm Through Externalized Control Units

- Mass-shifting units (especially AMT-type MSUs) are positioned beyond the structural perimeter
- This placement maximizes torque efficiency and enables control of ultra-large sails with minimal internal complexity

Conclusion: PanelSat can serve as the core control and energy unit for missions like Solar Cruiser, offering pre-alignment, integrated control logic, structural efficiency — and additional thruster-based propulsion.

🧪 **Main Experiment (SoSo-Steering Test):**

- Two panels on one side are tilted **edge-on** to the light source
- Opposing panels remain **fully exposed**
- The imbalance in radiation pressure creates torque
- **PanelSat begins to rotate** around the thread axis

We can study real space dynamics – without ever leaving Earth.Liberation Sans

Extended Experimental Concept – Demonstrating Light-Based Steering in a Vacuum Chamber

Stage 1: Rotation Test

- Suspend PanelSat by a thread in a darkened vacuum chamber.
- Eliminate atmospheric scattering and air drag.
- Rotate two panels on one side to face light source edge-on.
- Observe counter-rotation from SRP on opposite side panels.
- Demonstrate torque response to SoSo-Steering under vacuum.

Stage 2: Heliocentric Simulation (Inspired by early philosophical models: The Sun "orbits" the Earth.)

- Build rotating light installation that simulates a light source which moves around a stationary PanelSat.
- The chamber becomes a miniature theater of motion.
- Use track or rotating boom arm to move lights.

Each PanelSat panel features:

- A **power-routing PCB** centrally embedded in the panel base
- This board contains only **+ and – copper lines** with multiple soldering pads
  → Solar cell films will be connected here to generate power

⚠️ **The PCB does not contain any logic or sensors.**
Its sole purpose is to distribute power and provide contact points for solar harvesting.

🛠 **Planned: Sensor & Control PCB (per panel)**
A **separate PCB** has to be developed for each panel’s **rear side**, containing:

- An **Arduino Nano BLE Sense**
- Sensor connectors
- Motor control interface

This board will measure panel orientation using front-mounted sensor cells
and send the data via Bluetooth to the central MotorCase controller.

🔧 **Development challenge:**
Due to limited funding, I initially commissioned low-cost external PCB developers.
Unfortunately, the results were unusable, resulting in **wasted time and money**.

💡 **ESA-BIC funding is crucial** to now commission a reliable PCB design and assembly from an experienced partner.

Despite repeated tuning, I was unable to resolve this issue within my time and resource limits.

✅ **Solution: High-Precision Parts from Stratasys**
Thanks to the generous support of **Stratasys GmbH (Rheinmünster)**, I now have:

- A full set of **functional MSU and AMT-MSU components**,
- Printed in **industrial-grade ABS** with excellent surface quality

These parts will be used for the **next round of mechanical tests and functional demos**.

> 🙏 Special thanks to Stratasys GmbH for their commitment and for providing these parts **free of charge**.

Comparison – Solar Cruiser vs. PanelSat as Control Core for Solar Sail

Mission Purpose

- **Solar Cruiser**: Demonstration of solar sailing using a 1,650 m² reflective sail for heliophysics.
- **PanelSat (as control unit)**: Modular, self-orienting satellite capable of stabilizing and controlling large external payloads like solar sails.

Architecture

- **Solar Cruiser**: Central bus with deployed sail; separate control modules (AMT, RCDs, reaction wheels).
- **PanelSat**: Octagonal double-ring structure with integrated power generation (fixed solar panels), mass-shifting units (MSUs), dual MSU types (NEMA8 and AMT-like), and preinstalled mounting interface for additional payloads.

7. Distributed Sensor Network on All Panels

- Each panel includes an **Arduino Nano BLE Sense** with IMU sensor
- Enables:
  - Local detection of gravitational and acceleration vectors
  - Cross-checking and **redundant orientation feedback**
  - Enhanced control accuracy and **autonomous adaptation to sail dynamics**

📡 The decentralized sensor setup forms an integrated inertial sensing mesh — without relying solely on central IMUs.

Conclusion:
PanelSat is more than a structure – it is a **core control, sensing and energy platform** for next-gen solar sail missions.
It unifies attitude control, sensor feedback, deployment alignment, and even propulsion – reducing system complexity while improving redundancy and autonomy.

- Goal: PanelSat tracks the moving light and turns toward this source, using only SoSo-Steering.

Stage 3: Vertical Light Movement (3D Test)

- Add vertical motion to the light source.
- PanelSat should follow both azimuth and elevation using:
  - SoSo-Steering for horizontal alignment
  - MSU-based gravitational pitch control for vertical response
- Demonstrates full spatial solar tracking by light-induced control only

Significance

- Proof of autonomous light-following behavior without active sensors (i.e., no photodiodes or camera-based systems)
- Enables demonstrations in a laboratory setup.
- Foundation for proving viability of PanelSat as a solar sail controller.

Note on Ideal Vacuum Chamber

- Round shape for even suspension and motion
- Matte black walls and installations to avoid light reflections
- Wall markings for angular position reference
- Laser pointer mounted on PanelSat® for optical tracking of rotation and inclination
- High-resolution photographic documentation of movement

Clarification:

🔌 Panel Power Transmission

The panel’s generated power will be:

- Routed through the central PCB
- Transferred via **two flexible cables** in a small loop from the panel’s rotation axis to the MotorCase and on the other side to the Outer actor units (MSU, DTU).

Manual Demonstration of Gravity-Based Control Using Miniature Linear Actuators

To demonstrate gravity-driven attitude control, this prototype uses **compact linear actuators** as a fallback system.

Each actuator can extend and retract along its stroke segment, causing a **controlled shift in mass** – simulating the function of a Mass Switching Unit (MSU).

These actuators are mounted on the same positions and axes that will later be used for real MSU components.

🛠 **Why this fallback?**
The intended **centralized electronic control** is not yet available due to the **lack of fully functional PCBs**.

Initial development efforts with low-cost external designers failed, causing delays and budget loss.

> This fallback solution ensures that the **gravity-based control concept** can still be presented and evaluated, even before final PCB integration is complete.

Attitude Control

- **Solar Cruiser**:
  - AMT unit for CM/CP alignment
  - Reflective Control Devices (RCDs)
  - Reaction wheels for roll
  - Optional thrusters
- **PanelSat**:
  - Horizontal (with respect to the gravitational direction) MSUs (NEMA8) for gravity-based CM shifting
  - AMT-like MSUs (28BYJ-48) along the underside for CP balancing and sail control
  - Panel rotation for SoSo-Steering (SRP vector control)
  - Optional DTU thruster units for additional propulsion
  - No flywheels, minimal or no propellant

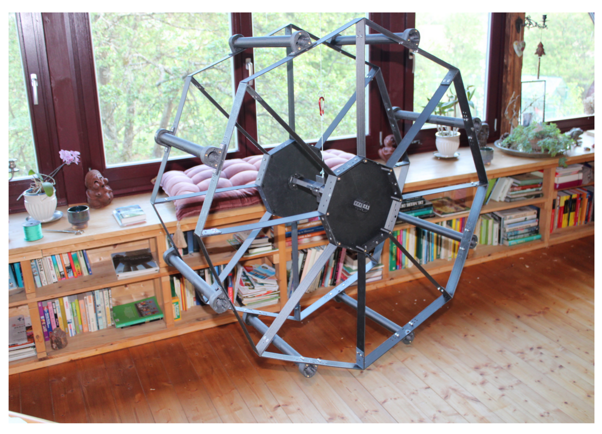
Control Strategy

- **Solar Cruiser**: Control begins *after* deployment.
- **PanelSat**: Self-aligns *before* deployment, deploys sail only in optimal orientation.

6. Extended Lever Arm Through Externalized Control Units

- PanelSat’s AMT-type MSUs are mounted on long arms extending beyond the central body case
- This design increases the **distance to the center of mass**, enhancing **torque efficiency**
- The extended layout allows PanelSat to **control much larger solar sails** than comparable central-mass systems

🧠 The mechanical complexity of PanelSat’s AMT units is comparable to other approaches, but their placement allows for more efficient mass shifting.



Let’s rethink how we stabilize spacecraft.

Mass shifting isn’t weak – it just needs the right axis.

If internal masses are displaced along an axis that points toward the nearest dominant gravitational center, even small mass movements can generate significant torque – without reaction wheels, and potentially without jitter.

The idea of a virtual “thread axis” is more than a metaphor: it can serve as a universal reference for attitude control. Whether the center of gravity lies within Earth, the Moon, the Sun, or even at the galactic core – this imagined axis always exists.

By aligning internal mass displacement (e.g., through MSUs) along this virtual line, spacecraft can achieve efficient, reactionless rotation – even for large structures.

On the photo above the satellite model is suspended on a real thread. In Space we have to imagine this threadline.

This may mark the beginning of a new control philosophy in spaceflight.