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The Kon-Tiki Mission – Demonstrating Large Solar Sails for Deep Space Missions

Les Johnson[a]*, Frank M. Curran[b], Richard W. Dissly[c], and Andrew F. Heaton[a]

[a] *NASA George C. Marshall Space Flight Center, Huntsville, AL, 35812, USA,* les.johnson@nasa.gov
[b] *MZNBlue Corporation, New Market, AL, USA*
[c] *Ball Aerospace, Boulder, CO, USA*
* Corresponding Author

Abstract

Two key NASA strategic documents, Our Dynamic Space Environment: Heliophysics Science and Technology Roadmap for 2014-2033 and 2013 Solar and Space Physics: Science for a Technological Society, contain over a dozen references describing the value of solar sails to enable revolutionary new observational capabilities. Based on these needs, the NASA Marshall Space Flight Center (MSFC) developed the Kon-Tiki mission concept to mature solar sail technology for use in future Heliophysics missions, as well as missions of interest across a broad user community (e.g., space weather and Earth polar observatories). Kon-Tiki would serve as a pathfinder for missions that observe the solar environment from unique vantage points such as the Solar Polar Imager (SPI), opening a fundamentally new range of observational capabilities for the Heliophysics Program and for space weather monitoring. Observations away from the Sun-Earth line (SEL) present unique opportunities for answering the outstanding science questions of Heliophysics, for improving space-weather monitoring and prediction, and for revealing new discoveries about our Sun and solar system. High solar inclinations are particularly compelling. Investment in, and demonstration of, the technology needed to enable polar missions is essential to making this unique vantage point a reality in the next decade.

Propellantless solar sails can be used to create artificial equilibria and indefinite station-keeping at locations sunward of L1 along the SEL, or at any desired offset from the SEL leading or trailing the Earth in its orbit. They can change the heliocentric inclination of a spacecraft from the ecliptic to as high as solar polar, stopping and remaining at any intermediate inclination orbit in between. Sails can be used to hover over the Earth's poles, using solar photon pressure to offset the Earth's gravitational attraction, creating functional equivalents of geostationary earth orbits.

The Kon-Tiki mission would fly a small spacecraft with a large (>1200 square meter) solar sail containing embedded reflectivity control devices (RCDs) and photovoltaic cells. The mission concept includes successful deployment of the solar sail, validation of all sail subsystems, controlled station-keeping inside of the Sun-Earth L1 point, attitude control of the sail with the RCDs (including spinning and despinning), demonstration of pointing performance for science imaging, and finally an increase in heliocentric inclination (out of the ecliptic).

Keywords: (in-space propulsion, solar sail, spacecraft propulsion)

Acronyms/Abbreviations

Marshall Space Flight Center (MSFC)
Solar Polar Imager (SPI)
Reflectivity Control Devices (RCDs)
Sun-Earth Line (SEL)
Polyimide Embedded Photovoltaics (PE-PV)
Triangular, Rollable, and Collapsible (TRAC)
High Strain Composite (HSC)
Vapor Deposited Aluminum (VDA)
Lightweight Integrated Solar Array and anTenna (LISA-T)
Interstellar Mapping and Acceleration Probe (IMAP)

1. Introduction

Solar sails have the potential to provide essentially unlimited ΔV for many types of missions. The basic concept, shown in Figure 1, is a large, mirror-like sail made of a lightweight material that reflects sunlight to propel the spacecraft. The continuous photon pressure from the sun's rays provides thrust, with no need for the heavy, expendable propellants employed by conventional on-board chemical and electric propulsion systems. Solar sail versatility enables or enhances many science mission applications:

- By accelerating along the existing velocity vector, the orbital energy of the spacecraft is increased, thereby spiralling it away from the Sun.
- By accelerating opposite to the velocity vector, the orbital energy decreases, spiralling inward toward the Sun.
- By accelerating out of the orbital plane, the sail can change inclination.
- By carefully managing attitude control, the sail can perform station-keeping in a desired location near-indefinitely.

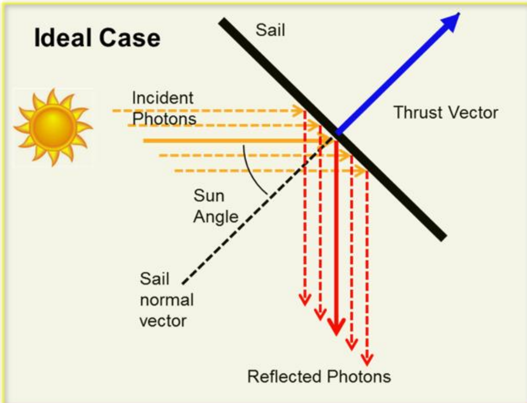

Figure 1. Solar sails derive thrust by reflecting solar photons and may change the net thrust vector by tipping or tilting the sail relative to the sun.

Most spacecraft are customized to accommodate payload, propulsion system, and instrument requirements. With solar sail propulsion, however, the spacecraft must be designed in conjunction with the sail as an integrated system. Conventional metrics for assessing propulsion system performance are not relevant for solar sails. For example, specific impulse cannot be quantified for a propellantless system. These factors, combined with the inextricable connection between the spacecraft's attitude control system and the sail, lead many in the community to use the term sailcraft to represent the integrated spacecraft-sail flight system; we adopt that term here.

For many years, fabrication and unfurling were thought to be the largest hurdles facing the development and flight of large sailcraft in space. The Kon-Tiki team understands that the more significant challenges are maintaining control of the sail and sailcraft, managing the sail's momentum, using its state information to navigate from deployment through to final destination, and then maintaining position (i.e., station-keeping). Multiple real-world phenomena create thrust efficiency losses and disturbance torques (in yaw, pitch, and roll) caused by imperfect Center of Mass / Center of Pressure (Cm/Cp) alignment that require offset mitigation. Real sails are not perfectly reflective, nor are they perfectly flat, due to sail billowing and diffuse reflection.

Solar Sail propulsion is considered enabling in the Heliophysics DS, with many explicit references calling for its development [1]. Propellantless solar sails can be used to create artificial equilibria and indefinite station-keeping at locations sunward of L1 along the Sun-Earth Line (SEL) [2] or at any desired offset from the SEL leading or trailing the Earth in its orbit. They can change the heliocentric inclination of a spacecraft from the ecliptic to as high as solar polar [3], stopping and remaining at any intermediate inclination orbit in between. Sails can be used to hover over the Earth's poles, using solar photon pressure to offset the Earth's gravitational attraction, creating functional equivalents of geostationary earth orbits [4]. NASA is already pioneering their use to propel CubeSats for low-cost asteroid reconnaissance with the NEA Scout mission [5] and future sails will enable missions as ambitious as the Interstellar Probe [6]. Solar sail propulsion therefore has immediate applications beyond those in Heliophysics.

While solar sailing has been demonstrated in small applications such as NanoSail-D2 [7], and will be further matured with the upcoming flight of NEA Scout, larger sails come with complexities. Building and deploying a large-scale, flexible membrane for use as a solar sail is non-trivial. For NEA Scout (sail area of 86m^2), a relatively straightforward metallic boom assembly was used. The larger Kon-Tiki sail area is much more complex.

2. The Solar Sail System

The solar sail for the Kon-Tiki mission is >1200 m^2 and provides a characteristic acceleration (Ac) of >0.12 mm/s^2. The solar sail architecture uses a quadrant sail design with four composite booms that are deployed from a central rotating deployment mechanism and sail hub. The sail membrane is the space- and sail-proven aluminized CP1 polyimide substrate successfully flown on NanoSail-D2 and to be flown on NEA Scout. To further advance the solar sail architecture, Kon-Tiki also demonstrates polyimide embedded photovoltaics (PE-PV) to generate power, and attitude control using reflectivity control devices (RCDs) on the sail surface.

The Kon-Tiki solar sail is pictured in both the stowed and deployed configurations in Figure 2. The solar sail membrane is deployed and tensioned using four triangular, rollable, and collapsible (TRAC) high strain composite (HSC) booms, the same geometry of the boom flight-validated by NanoSail-D2 and used on the upcoming NEA Scout mission.

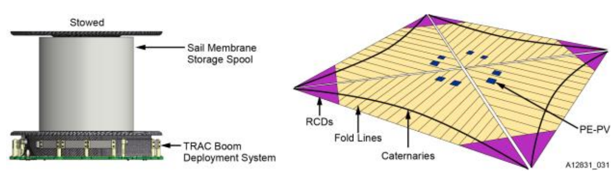

Figure 2. Stowed and deployed solar sail. RCDs are in the respective corners and the PE-PV arrays near the center. Representative fold lines are also shown.

TRAC booms have a triangular cross-section that flattens and rolls around a spool for stowage. This proven design has higher strength/weight for a given flattened height than other rollable boom designs (Figure 3), is easy to fabricate and taper, and has flight heritage. The double omega boom was rejected due to the manufacturing difficulties for long booms, expensive tooling, and the fact that the sail application does not require the additional torsional stiffness. For the Kon-

Tiki sail design, the four booms are stowed on a common spool, and deployment is actuated via a single motor controlled by the bus.

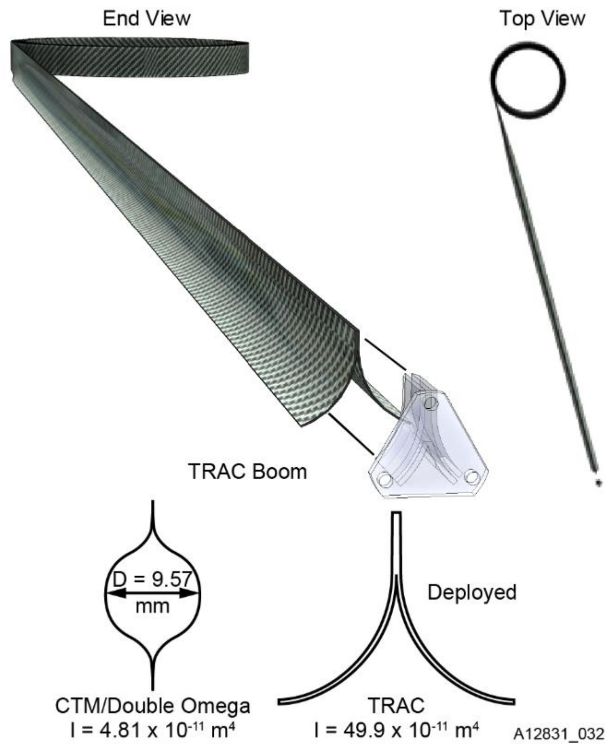

Figure 3. TRAC boom deployment geometry and comparison to the double omega geometry. The TRAC boom has more than 10 times the cross-sectional inertia for the same packaged height and stowed strain.

The sail membrane is attached to the booms via springs to accommodate thermal expansion differences between the booms and sail membranes, and to account for small differences in sail and boom deployment speed.

The Kon-Tiki sail membrane consists of four tight triangular quadrants made from 2.5-micron CP1 film with 1000AÅ Vapor Deposited Aluminum (VDA) coating. This film has been used for prior solar sail missions including NanoSail-D2 and NEA Scout. CP1 is a fluorinated polyimide, which is space durable and has a very high glass transition temperature of 263ºC. The high temperature benefit is important for future missions involving operations at <0.5 AU. CP1 coupons were extensively tested in the MSFC Space Environmental Effects test facility and shown to be durable and not subject to charging [8].

As on NEA Scout, the sail membrane material fills the region between the catenary reinforcement and outside straight edge to increase the sail's propulsive area . Other key features of the sail membrane include seams, rip-stops, corner reinforcements, and edge reinforcements.

Thin-film photo-voltaic devices are directly integrated onto the solar sail by embedding them into the surface of the CP1 membrane. These PE-PV help power the Kon-Tiki sailcraft but are not required to be power positive. PE-PV is currently TRL 6, being developed as a part of NASA's Lightweight Integrated Solar Array and anTenna (LISA-T) small spacecraft program [9]. PE-PV is a very thin, low mass, flexible stack of a polyimide substrate + thin-film PV + protective polyimide coating. The entire stack is <100µm and assembled without the use of adhesive. Attachment to the sail membrane uses liquid CP1, providing a bond of the same strength as the base material that was qualified for the LISA-T mission. Kon-Tiki has a 150W (at 1AU) PE-PV array.

Kon-Tiki uses RCDs based on polymer dispersed liquid crystals, which allow control of the radiation pressure on different parts of the solar sail, enabling torque compensation and attitude control. The devices consist of micro-sized liquid crystal droplets dispersed in a matrix of a UV-curable adhesive.

The AMT is a compact, two-axis rail guide that is a scaled version of the design built and tested for NEA Scout. The AMT is the mechanical interface between the bus and the sail deployer hub, and moves the bus relative to the sail, shifting the center of mass (Cm) relative to the center of pressure (Cp) to manage torques and momentum about the in-plane body axes of the sail (which align with the booms). The AMT schematic is shown in Figure 4. The design has an internal area to accommodate harness feedthroughs between the bus and sail.

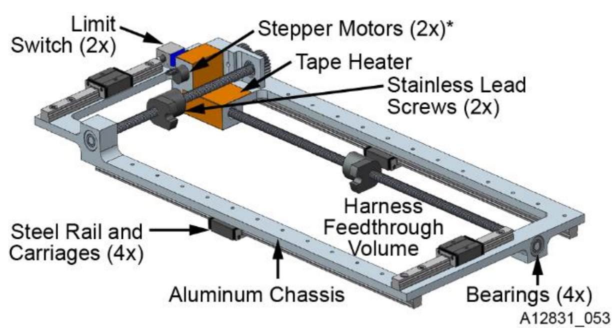

Figure 4. The Kon-Tiki AMT is used to shift the CM/CP offset by moving the sail relative to the bus in the X and Y axes to achieve desired pitch and yaw.

3. Mission Profile

Kon-Tiki will be co-manifested with the NASA Interstellar Mapping and Acceleration Probe (IMAP) mission in 2024. Carried to space on a secondary payload adapter, Kon-Tiki will separate after the IMAP deployment on an Earth escape trajectory. Following separation, the spacecraft will self-stabilize using onboard reaction wheels, deploy its solar arrays, and undergo basis system checkout.

Kon-Tiki's onboard science instrument, a compact spectropolarimeter, will then begin its checkout and operational phases before the sail is deployed.

Approximately two months into the flight, the solar sail will be deployed. A complete checkout of the system, including AMT, RCDs, and LISA operation. Once the sail is commissioned, onboard trajectory software will begin navigating the sailcraft to begin non-Keplerian station-keeping sub-L1 as shown in Figure 6. After arriving at the station-keeping location, the onboard coronagraph will resume observations, validating the stability of the sailcraft for science operations.

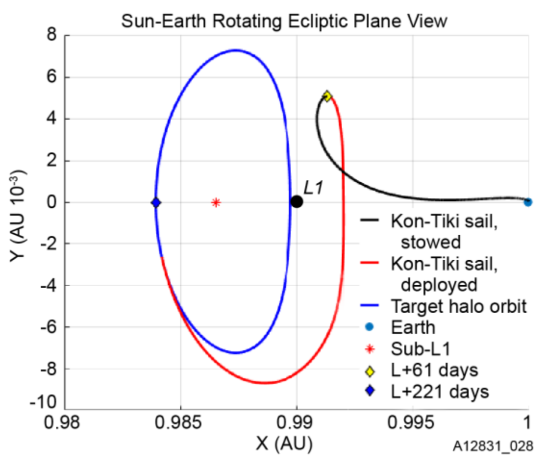

Figure 6. The Kon-Tiki trajectory gets into a sub-L1 orbit with only solar sail propulsion.

After approximately one year, the sailcraft will reorient the sail to raise its heliocentric orbital inclination out of the ecliptic plane. If the extended mission is approved, the Kon-Tiki sailcraft will then maneuver to a 5-degree Earth trailing orbit and station-keep there for up to eight months.

4. Discussion

Solar sail propulsion has long been considered an enabling capability for multiple high-interest science observations of the sun and other objects within the solar system. The Kon-Tiki mission will validate the technologies required to build, fly, and successfully operate a large solar sailcraft as a platform for science. Following the flight of the Kon-Tiki, missions such as the long-anticipated Solar Polar Imager will be feasible. In addition, the ability of the Kon-Tiki to station-keep sub-L1 will provide the solar storm monitoring and warning communities with a new capability that could be fielded in operational space weather systems as early as 2030.

5. Conclusions

The Kon-Tiki solar sail mission builds upon over 30 years of technology development within NASA. The successful flights of the NASA NanoSail-D2, the Planetary Society's LightSails, and the soon-flight of NASA's NEA Scout were all critical steppingstones on the path to Kon-Tiki.

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