Small Solar Power Sail Demonstrator “IKAROS” and Its Achievements

Ryu Funase

JAXA Space Exploration Center (JSPEC),
Japan Aerospace Exploration Agency (JAXA)
Deep Space Solar Power Sail Demonstrator

IKAROS

Sail Size: 14m x 14m
S/C Weight: 307kg
Orbit: Venus Transfer

Launch: May 21, 2010
Sail Deployment: June 9, 2010
Solar Sail is a space yacht that gathers sunlight for propulsion by means of a deployed large membrane (i.e. “sail”) in space.

Solar Power Sail is an original concept that combines solar sail propulsion and electricity generation from thin film solar cells attached on the sail.

The Japan Aerospace Exploration Agency (JAXA) developed and operates the world’s first solar power sail craft to demonstrate both photon propulsion and thin film solar power generation during its interplanetary cruise.

IKAROS = Interplanetary Kite-craft Accelerated by Radiation Of the Sun
Sail Development in JAXA

2002
Vacuum Chamber Test (D=2m)

2003
Balloon Drop Test (D=4m)

2003-2004
Spin Table Test (D=2.5m)

2004
Ballistic Flight Test (D=10m) (Sounding Rocket)

2006
Balloon Test (D=20m)

2010
Interplanetary Demonstration! (D=20m)
The project was authorized in the 4th quarter of FY2007. Development phase=2.5yr.

Existing components and reproduction of existing design are extensively utilized in order to adjust to the given development period.
Spacecraft Outline

Sail Membrane

Diagonal 20m => 200m²
Side 14m

Kept extended by centrifugal force. No spar needed.

Thin film solar cell

Tip mass

Diameter 1.6m
Height 0.8m

Main body: 293kg
RCS fuel: 20kg
Solar Sail: 16kg (14kg Membrane + 2kg tip masses x 4)
Total Wet Mass: 307kg

Solar Sail (Stowed)
# Spacecraft Specifications

<table>
<thead>
<tr>
<th>Structure</th>
<th>S/C body: φ 1.6 × h0.8m Cylindrical Solar Sail: 14 × 14m Rectangular</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>Wet: 307kg              Dry: 287kg</td>
</tr>
<tr>
<td></td>
<td>Solar Sail: 16kg</td>
</tr>
<tr>
<td>Attitude</td>
<td>Spin Stabilized</td>
</tr>
<tr>
<td></td>
<td>• Sun sensor</td>
</tr>
<tr>
<td></td>
<td>• Earth angle measurement (by spin modulation on Downlink RF)</td>
</tr>
<tr>
<td></td>
<td>• 3 axis Gyro</td>
</tr>
<tr>
<td></td>
<td>• Nutation Dumper</td>
</tr>
<tr>
<td></td>
<td>• Gas-Liquid Phase-Equilibrium Thruster (Fuel: HFC-134A) 0.4N × 8 heads</td>
</tr>
<tr>
<td>Power</td>
<td>Body Mount SAP 300W</td>
</tr>
<tr>
<td>Comm.</td>
<td>X-band TT&amp;C</td>
</tr>
<tr>
<td>Orbit</td>
<td>R&amp;RR</td>
</tr>
<tr>
<td>Determination</td>
<td>VLBI (experimental)</td>
</tr>
<tr>
<td>Solar Sail Support System</td>
<td>Deployment Mechanism</td>
</tr>
<tr>
<td></td>
<td>• Flexible Solar Array (FSA)</td>
</tr>
<tr>
<td></td>
<td>• Reflectivity Control Device (RCD)</td>
</tr>
<tr>
<td></td>
<td>• Dust Particle Detector (ALDN)</td>
</tr>
<tr>
<td></td>
<td>• Surface Charge Sensor</td>
</tr>
<tr>
<td></td>
<td>• Temperature Sensor</td>
</tr>
<tr>
<td></td>
<td>• Tip Acceleration Sensor</td>
</tr>
<tr>
<td>Other Payloads</td>
<td>Solar Sail Mission</td>
</tr>
<tr>
<td></td>
<td>• Onboard Camera × 4</td>
</tr>
<tr>
<td></td>
<td>• Deployable Camera (DCAM) × 2</td>
</tr>
<tr>
<td>OptionalMission</td>
<td>X-band VLBI Transmitter</td>
</tr>
<tr>
<td></td>
<td>• GAmmma-ray burst Polarimeter (GAP)</td>
</tr>
</tbody>
</table>
The definition of the IKAROS mission is summarized as follows:

### (1) Deployment of Large Membrane Sail
- **Minimum Success Criteria**
  - Deployment and Expansion of a Large Membrane in space using similar mechanical device and procedures to those in the Jupiter mission
  - Obtaining a number of data indicating the expansion status of the membrane

- **Done!**

### (2) Power Generation by Thin Film Solar Cells
- Demonstrating Solar Power from Thin Film Solar Cells
  - Evaluating performance of thin film solar cells on the membrane in space

- **Done!**

### (3) Demonstration of Photon Propulsion
- Verification of Reflectance as well as Comparison with Diffuse & Specular Property
- Measurement of overall Reflectance with the rigorous relation examination of the temperature and surface status

- **Done!**

### (4) Demonstration of GNC for Interplanetary Solar Sailing
- Navigation / Orbit Determination under continuous and small acceleration
  - Acceleration Direction Control via Steering via appropriate attitude control means

- **Now Undergoing…**
Mission Sequence

1) H-IIA Launch
   Sun-pointing
   Spin separation (5rpm)
   (21/May/2010)

2) Radio telemetry ON
   Tip mass separation (2rpm)
   Spinning-up (25rpm)
   (~02/June/2010)

3) Sail deployment (2.5rpm)
   Power generation by thin film solar cells
   confirmed and evaluated
   (~10/June/2010)

4) Acceleration and navigation experiment by solar sail
   (~Now)
Sail Configuration

Steering device: variable reflectance element
Thin film Solar cell: Amorphous silicon cell of 25mm in thickness
Dust counter: piezoelectric elements (optional payload)
Tether: Mechanical and electric connection between main body and membrane
Bridge: connecting trapezoid petals
Tip mass: A 0.5kg weight supports the deployment of the membrane

7.5μm thickness Polyimide base film
Sail Material

Front side (facing to the sun)

Trapezoid petal

Back side (Not facing to the sun)

- Sail Thickness is 7.5µm.
- Aluminum-coated on front side to efficiently reflect the sunlight

Two kinds of polyimide films with different chemical compositions are adopted for IKAROS sail.
Sail Deployment Sequence

First Stage Deployment

Tip mass release

1st stage deployment complete

May 26

June 2-8

2nd stage deployment

Second Stage Deployment

June 9

guide roller
System development concept

• Preconditions
  – Short development period: 2.5yr (mid 2007 – end of 2009)
  – Extremely low budget: 1/10 of conventional science satellite
  – Project team: ~10 young professionals (around 30~40yrs old)
  – Very challenging mission!

• Development policy
  – Reliability of “Bus” system is prioritized (within the budget)
  – Use any available technology and components from other satellites
    \(\rightarrow\) Cost reduction
  – No redundancy
    \(\rightarrow\) Simple system
  – Man power is focused on mission components development
  – Many COTS parts for mission components
    \(\rightarrow\) Cost reduction
Operation results
Deployment Confirmed by Onboard Cameras!

Captured by onboard camera

FOV of onboard camera
First SRP Measurement -- Set Sail for Solar Sailing!

Photon acceleration is confirmed right after the sail deployment on June 9.

Real-time Two-way Doppler measurement

The thrust by solar light pressure is 1.12mN
SRP Thrust Evaluation by Precision Orbit Determination

Thrust curve based on orbit determination

Solar Photon Thrust = 1.3 mN

Design value of the flat sail

Expected range on orbit

Sail Effective Cross Section Area Ratio

Sail Specular Coefficient
DCAM captures solar-sailing IKAROS!

On June 14, 2010
On June 14, 2010
Attitude control by Reflectivity Control Device (RCD)

Power = ON (specular)

Power = OFF (diffuse)

Stable and fuel-free attitude control can be achieved
SRP even for attitude control! : Reflectivity Control Device

On June 19, 2010

72 liquid crystal devices are attached to the edge of the sail. Optical reflectivity can be controlled electrically. By synchronizing spin phase with the reflectivity changing, the attitude control purely by SRP is realized.
'10/07/13 Attitude control experiment using RCD

Sun angle [deg]

7/12 12:00  7/13 0:00  7/13 12:00  7/14 0:00  7/14 12:00

Time (UTC)

Control OFF  Control ON  Control OFF (extrapolated)

Attitude maneuver by RCD
IKAROS flying toward Venus with the assist of SRP

Ikaros is here
In solar sail, attitude dynamics and orbital dynamics are tightly coupled. To achieve the solar sail GNC, SRP torque and force modeling is continuously performed. It is then fed back to the attitude and trajectory maneuver plan.
IKAROS Guidance strategy on Venus B-plane
IKAROS has extra payloads for both science and engineering missions utilizing this interplanetary flight opportunity.

- **Science mission**
  - GAP (GAmma-ray burst Polarimeter)
    - observe polarization of gamma-ray burst (GRB)
    - determine the direction of GRB
  - ALADDIN (Arrayed Large-Area Dust Detectors for INterplanetary cruising)
    - evaluate dust distribution in the region of inner planets by PVDF (Poly Vinlydene Di-Fluoride) Piezoelectric Film

- **Engineering mission**
  - VLBI mission (key technology for deep space navigation)
    - DDOR (Delta Differential One-way Range) orbit determination technology demonstration
Conclusions

• IKAROS achieved the world’s first solar power sail craft, demonstrating both photon propulsion and power generation on the sail.

• IKAROS confirmed SRP acceleration as designed, and is now flying toward Venus with the assist of solar sail propulsion.

• Venus closest encounter will be on December 8th, when the nominal mission is to be completed.

• IKAROS mission contains many key aspects of solar sail technologies: Sail production, Sail Deployment and support system, Device-on-Sail, GNC with Solar Sail, etc.
Thank you!

http://twitter.com/ikaroskun