SOLAR-B Mission and Optical Telescope Assembly

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Solar Physics from Space in Japan

Hionotori (1981-1982)
SOLAR-B (2006)
Yohkoh (1991-2001)

With NASA and UK
With NASA and UK
With NASA and UK
Solar-B

- **Japan-US-UK** solar observation satellite following highly successful Yohkoh (1991-2001)
- Primary mission: systems approach to understand generation/transport and ultimate dissipation of solar magnetic fields with 3 well-coordinated advanced telescopes.
- Onboard instruments
  - Solar Optical Telescope (Japan, US)
  - X-ray Telescope (US, Japan)
  - EUV Imaging Spectrometer (UK, US, Japan)
  - Spacecraft and launch (Japan)
- Versatile onboard data compression (JPEG2K, and DPCM)
- Post compression rate approx. 500 kbps
- Launch on summer 2006 with ISAS M-V-7
- Orbit: Sun synchronous, Altitude: ~ 600 km, Weight: ~ 900 Kg
- **ESA provides downlink** service with Norway station, resulting in substantial increase in data rate.
X-ray & EUV Telescopes aboard SOLAR-B

- **XRT**
  - We chose *grazing-incidence* after extensive tradeoff
  - 1 arcsec resolution/1 arcsec pixel, >x3 better than Yohkoh
  - FOV: 30arcmin squares
  - Sensitive to 0.5MK-10MK(20MK)
  - Filter choice provides SXT and TRACE-like images.
  - Filter-ratio: powerful tool for T- diagnostics
  - Visible light imaging for alignment purpose

- **EIS**
  - EUV emission line spectroscopy
  - Two EUV bands: 170-210 Å and 250-290 Å, log T = 4.7, 5.4, 6.0 - 7.3 K
  - X 10 more sensitive than CDS
  - 1 arcsec/pixels, Field of View: 6 arcmin × 8.5 arcmin
  - Selectable Slit & Slot: 1”, 2”, 40” and 250” width at primary focus
  - Single line: Doppler motion, non-thermal width
    - ~ 25 km/s pixel sampling, a few km/sec sensitivity
  - Line pair ratio: Temperature, density diagnostics
  - Multiple lines: Differential emission measure
Optical layout of SOT

**Spectro-polarimeter**
- Dual 256 x 1024 CCD
- Folding Mirrors
- Slit
- Preslit
- Grating
- Filterwheel
- Birefringent Filter
- Folding Mirror
- Litrow Mirror
- Polarizing BS
- Telecentric lenses
- X3 Mag lens
- Shutter
- Image Offset Prisms
- Demag lens
- 50 x 50 CCD

**Broadband Filter Instrument**
- Beam Distributor
- Reimaging Lens
- Folding Mirror
- Correlation Tracker
- Secondary
- Primary
- CLU
- OTA

**Narrowband Filter Instrument**
- Folding Mirror
- Polarizing BS
- X2 Mag lens
- 2048 x 4096 CCD
- Field Mask
- Shutter
- Filterwheel
- Field lens
- Telecentric lenses
- Telecentric lenses
- Image Offset Prisms
- Demag lens
- 50 x 50 CCD

**Color Coding**
- OTA
- Common Optics
- CT
- NFI
- BFI
- SP
<table>
<thead>
<tr>
<th>SOT Observables</th>
<th>Broadband Filtergraph Dt : 2s</th>
<th>Narrowband filtergraphDt : 3s~30s</th>
<th>Spectro-polarimeter Dt : 3s~1hr</th>
<th>Correlation tracker, 580Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>wavelengths</td>
<td>388.3 CN molecular bandhead: chrom. network 396.8 Ca II H-line: magnetic elements in low chrom 430.5 G-band CH bandhead: magnetic elements 450.5/555.0/668.4 continuum.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FOV / pix scale</td>
<td>218 × 109 / 0.054 arcsec</td>
<td>328 × 164 / 0.08 arcsec</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polarization</td>
<td>IQUV, ~0.5% accuracy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>wavelengths</td>
<td>Fel 525.0 Photospheric magnetograms Mg I b 517.3 Low chromosphere mag./dopplergrams Fe I 557.6 Photospheric dopplergrams Na D 589.6 Chromospheric magnetic fields Fe I 630.2 Photospheric magnetograms H I 656.3 H-alpha chromospheric image and Dopp</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FOV / pix scale</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>630.2 nm (high precision vector mag. Fields)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>164 x 324 (full scan) / 0.16 arcsec</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polarization</td>
<td>IQUV full profile, 0.1% accuracy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>wavelengths</td>
<td>629-634 nm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FOV</td>
<td>11 × 11 arcsec</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
Optical Telescope Assembly

cold plate for thermal control

2\textsuperscript{nd} field stop

CLU

HDM

center section, interface to the satellite

low expansion CFRP truss

primary mirror

tip-tilt mirror
Observing wavelength: 388 ~ 668nm
Telescope wavefront error ~ 18.2nm
PSF <0.2 arcsec in blue band
>0.2 arcsec in red band
Tip-tilt image stabilization system
Stability ~ 0.002 arcsec rms
bandwidth ~14Hz

SOT (Solar Optical Telescope)
Optical Telescope Assembly (OTA) NAO, Japan
Focal Plane Package (FPP) Lockheed Martin/HAO/NASA with NAO

Fixed ULE 2dary mirror
Metal heat dump mirror
Collimated beam
afocal optical I/F
Field stop
Collimator lens unit
ULE primary mirror
Polarization modulator
Tip-tilt mirror
Ultra-low CTE composite structure
Focus mechanism
Evaluation Method of Image Quality

**Specification of Image Quality by Strehl ratio**

Strehl ratio = \( \frac{I}{I_0} \)

Diffraction-limited performance
\(~0.2" (\lambda = 388 – 670 \text{ nm})\)

SOT target: Strehl ratio \((I/I_0) = 0.7\) at \(\lambda = 500\text{nm}\)

**Relation between Strehl ratio and rms Wavefront error**

\[ \text{Strehl ratio} = e^\left( \frac{2\pi\sigma}{\lambda} \right)^2 \geq 0.7 \]

\(\sigma\): rms Wavefront error
\(\lambda\): Wavelength = 500 nm

Total rms Wavefront error for OTA-FPP: \(\sigma < 47.5 \text{ nm}\)

\{ OTA: 37.8 \text{ nm} \\
FPP: 25.8 \text{ nm} \\
Guidance: 12.8 \text{nm} \}
OTA development with budgets

- There are multiple internal and external elements that contribute to error and performance degradation. These have been controlled with strict budget during development.
  - WFE budget
  - Focus budget
  - Pointing budget
  - Contamination budget
  - Weight budget
  - Power budget
OTA Key Components

Secondary Mirror

Primary Mirror

Zero-CTE composite structure

Collimator lens unit

Polarization modulator (Lockheed Martin/HAO)

Tip-tilt mirror
OTA primary secondary mirrors

- ULE with protected Ag coat
- M1 ~ 11Kg
- WFE for M1-M2 combination
  18nm (rms)
Collimator lens unit requirements

- 388-690nm
- F/9
- Achromatic focus shift < 35micron
- WFE < 17nm (rms)
- No retardance/no di-attenuation
- Orbital temperature range: 20±10 degree C
Optical IT&T

Dedicated Optical Test Tower for IT&T at NAOJ

Interferometric test

M2 alignment

OTA assembly in the Class-10 clean tent

M1 alignment

Dedicated Optical Test Tower for IT&T at NAOJ

Interferometric test

60cm dia. Auto-collimation mirror

Interferometer

OTA

4.4m

3.0m

2.4m
END-TO-END WFE measurement with 60cm dia. auto-collimation mirror
Measured wavefront error 18.2nm

- Telescope configuration for WFE measurement: vertical (nominal and upside-down)

- Telescope is deformed under 1-G condition. 0-G WFE is obtained by averaging data taken with nominal and upside-down configurations.

- WFE (rms) is 0.0288 lambda at 632.8nm, and is 18.2nm (0.0182micron).

- WFE (RMS) at short-end of the observing band (388nm) is 0.0469 lambda. Telescope is diffraction-limited (<0.071 lambda) for all observing bands.
Gravity cancellation by overturning OTA for WFE measurement
Telescope IT&T

Assembly

Preparation for Opto-thermal-vacuum test

OTA&FPP Integrated to S/C Optical bench
System level optical test (1)
Opto-thermal test for WFE & alignment measurement in orbit environment
NAO Clean room for space optics

190m², 10m High
Class 100
Class 0-10 in the booth
Space-chamber, large optical flat, fast interferometer, large Newport table

Heliosat to introduce natural star and sun light: Beam size 55 cm dia.
Telescope in clean room illuminated with 50cm sun beam

System level optical test (2)
Natural sun-light test
at NAO clean room
Natural sun-light test Engineering first light with full flight model 2004 August

Note
• Bad seeing in Tokyo
• Under 1-G

H-alpha

G-band

Stokes polarimeter
## 1. Test items of Sunlight test

<table>
<thead>
<tr>
<th>item</th>
<th>purpose (possible source of error)</th>
<th>Methodology</th>
<th>goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Vignetting</td>
<td>OTA-FPP alignment</td>
<td>DC exposure by NFI</td>
<td>No 2FS edge,</td>
</tr>
<tr>
<td>2. Ghost</td>
<td>Possible sources: CLU filter, PMU, as correction lens</td>
<td>Limb exposures</td>
<td>$I &lt; 10^{-3}$</td>
</tr>
<tr>
<td>3. Scatter light</td>
<td>Edge of sunshade, HDM, 2FS, FPP returned light into OTA</td>
<td>Pupil image</td>
<td>&lt; 0.02</td>
</tr>
<tr>
<td>4. Focus</td>
<td>Confirmation of overall setting Initial setup for Sun test</td>
<td>Reimaging lens scan</td>
<td>Prediction ± 5mm</td>
</tr>
<tr>
<td>5. Throughput</td>
<td>Filter design, etc.</td>
<td>Guide sensor signal → absolute intensity</td>
<td>Prediction ±30%</td>
</tr>
<tr>
<td>6. Polarization (SP&amp;FG)</td>
<td>Determine the sign of V Evaluate V→Q,U crosstalk map</td>
<td>Sheet polarizer on heliostat window</td>
<td></td>
</tr>
<tr>
<td>7. End-to-end performance as a magnetograph</td>
<td>Start scientific data analysis Practice of polarization calibration using solar data</td>
<td>‘Observing mode’ is described in this document</td>
<td></td>
</tr>
<tr>
<td>8. Tunable filter property</td>
<td>Check the uniformity of filter property.</td>
<td>Scan tunable filter WL at DC.</td>
<td></td>
</tr>
<tr>
<td>9. Other engineering</td>
<td>HDM/shield tube alignment</td>
<td>Limb pointing, visual inspection</td>
<td>Clearance &gt; 3mm</td>
</tr>
<tr>
<td>1) HDM &amp; OTA side window clearance</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Image stabilizer US-J interface test

Correlation tracker
Electronics BOX

Light source with nanopositioner
Tip-Tilt Mirror

Correlation tracker
CCD
SOLAR-B 可視光望遠鏡完成
国立天文台高度環境試験棟クリーンルーム 2005年4月27日

The Team
Spacecraft-level testing

Assembly → Vibration test → Acoustic test (telescope) → Micro-vibration

Launch → Integration to rocket → Final inspection → Thermal-vacuum

(ASTRO-E II)
Preparation for S/C thermal vacuum test with OTA thermal model
OTA WFE & alignment check as well as FPP optical tests can be done on the spacecraft level after each environment test

OTA optical performance check (measure WFE)
OTA-FPP alignment check
Micro-vibration problem
resonance vibration of sensitive optical elements due to
moving parts such as gyro-scope and filter wheels
SOT Image stabilizer performance

サーボオン時には、20Hの制御帯域内では、1σ = 0.0002”の安定度を達成している（太陽角換算）
実線：サーボオン、破線：制御オフ
Advantage of SOT

- High resolution (0.2arcsec)
- Very stable PSF
  - Only need seasonal focus adjust
- Continuous 24 hours observations
  - Made possible by ESA Norway station
- Both filtergraph and spectro-polarimeter
- Versatile observing modes
- Simultaneous X-ray/EUV observations
Science Topics

- Continuous high resolution observations of elemental flux tube
- Flux emergence and formation of sunspot simultaneous with helio-seismic observations
- Demography of magnetic fields with different origins
- Detection of MHD waves
- Photospheric-chromospheric reconnection
- Pico-flares and Lagrangian tracking of elemental magnetic fields (The Parker concept)
- Magnetic properties of hot and cool loops
OTA current status

- OTA development completed, and integrated to the spacecraft.
- Diffraction limited performance verified.
- Image stabilization system performance with FPP superb.
- On-spacecraft WFE/alignment measurements repeatedly done after testing milestones: no change in performance
  - Final test to be done in July
Mission Lifetime

• Desires to observe the sun as close to the next maximum as possible
• Sun-synchronous orbit maintained over > 7 years
• No fuel limit
• Limited-lifetime Gyroscopes fully redundant
• Lifetime for SOT diffraction-limited imaging
  – Contamination of organic materials to M1 increases the heat absorption, resulting in higher M1 temperature.
  – Current best estimate will be presented in this meeting.
  – Prioritization of the science observations important.
Schedule

• 2006 End July: Spacecraft shipped to the launch site
• 2006 September 23: Launch date
• 2006 October: Spacecraft verification and checkout phase
• 2006 November: Instrument Checkout phase (first light phase) for three telescopes
• 2006 December: Performance and Verification (PV) Phase
  – In-orbit calibration and
• 2007 January Initial Observing Phase