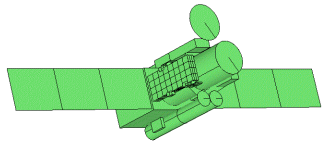


The Focal Plane Package of the Solar Optical Telescope

Overview and Operations

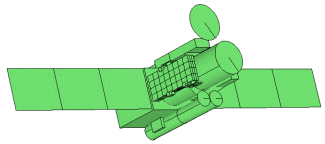
Ted Tarbell
Lockheed Martin Solar & Astrophysics Lab
(650) 424-4033
tarbell@lmsal.com

The Solar-B Mission Goals

The primary goal of the Solar-B mission is to advance our understanding of the origin of the outer solar atmosphere, the corona, and of the coupling between the ***fine magnetic structure at the photosphere*** and the dynamic processes occurring in the corona.

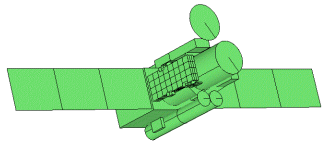
Solar-B is a Japanese national science project with international cooperation from the US and UK.

Solar-B Overview



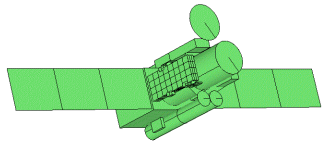
- **Solar-B will be launched from Japan in summer, 2005**
  - **Prof. Takeo Kosugi of ISAS is the Solar-B Project Manager and PI**
- **Solar Optical Telescope (SOT) -- 50 cm Gregorian Telescope provided by ISAS**
  - **Built by Mitsubishi Electronics Company for ISAS & NAOJ**
  - **Japanese PI Prof. Saku Tsuneta**
- **Focal Plane Package (FPP) -- Spectropolarimeter and Filtergraph Instrument provided by NASA**
  - **Built at LMSAL in collaboration with HAO**
  - **US PI Alan Title**
- **Other Solar-B Instruments**
  - **X-Ray Telescope (XRT), by ISAS and NASA (SAO, Leon Golub is US PI)**
  - **EUV Imaging Spectrometer (EIS), by UK, ISAS, and NASA (NRL, George Doschek)**

FPP Science Goals



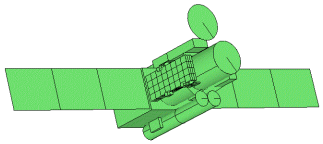
- **Magnetic Flux Transport**
  - **– Observe how magnetic flux emerges, disperses & disappears from the solar surface, including weak intranetwork fields (B <400 G).**
  - **– Determine whether magnetic field is generated in or near the surface: *fast dynamo action*.**
- **Scales of Convection**
  - **– Investigate the relationship of the granulation, mesogranulation, and supergranulation.**
- **Sunspots and Active Regions**
  - **– Measure the vector magnetic field of sunspots and plage areas.**
  - **– Observe the formation, dynamics & decay of entire active regions**
- **Upper Atmospheric Connections**
  - **– Determine the role of the surface magnetic field on the structure and dynamics of the outer atmosphere**
- **Solar Cycle Evolution**
  - **– Measure the effect of active regions on the solar cycle irradiance modulation.**

Level 1 Requirements



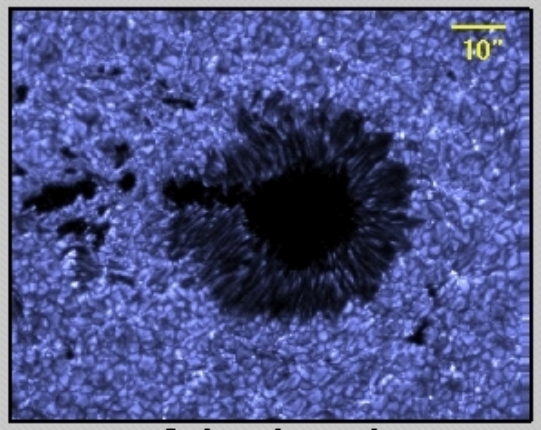
- **Spatial Resolution < 0.25 arcseconds**
  - **Preserve imaging quality of SOT from 3880 — 6600 Å.**
- **Field of view > 200 x 100 arcseconds**
  - **Capture entire active region and significant portions of surrounding quiet network.**
- **Image stabilization system < 0.02 arcseconds**
  - **Stabilize S/C jitter to < 0.02 arcsec over range of 2 — 20 Hz.**
- **Science Instruments**
  - **Narrowband Tunable Filter: better than 1% precision magnetograms**
  - **Broadband Filter Instrument: 0.2 arcseconds 3880Å**
  - **Spectro-Polarimeter: better than 0.1% precision Stokes vector measurements.**

Sample FPP Data

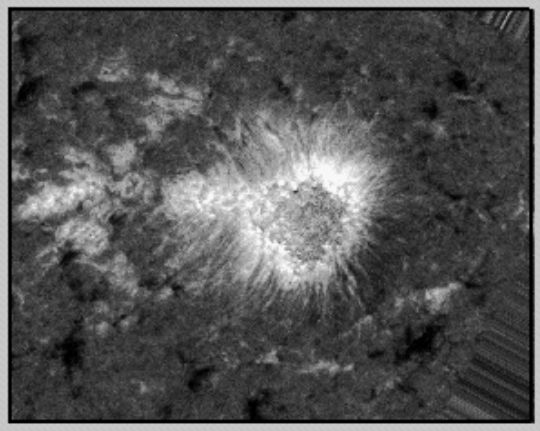


Solar–B Focal Plane Package Imaging

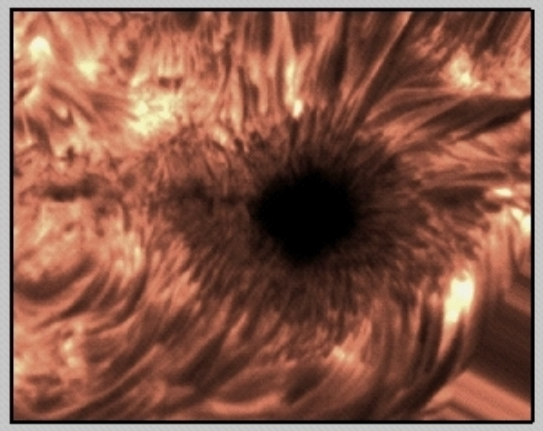
SVST La Palma, 13–May–1998



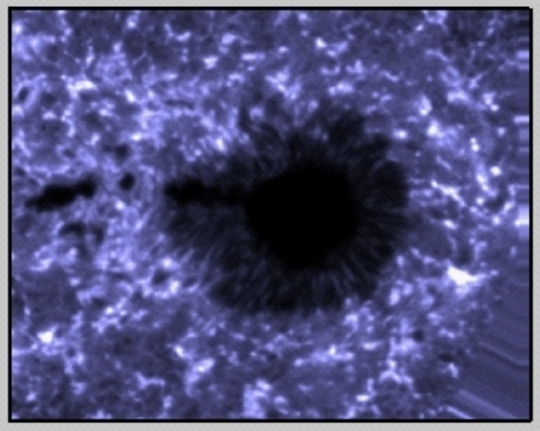
G–band 4305A



Fe I 6302A Magnetogram

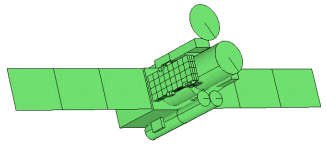


H–alpha 6563A



Ca II K–line 3933A

SOT Major Components



- **SOT: Solar Optical Telescope**

  ➔ OTA: Optical Telescope Assembly

  1/2-meter class for 0.2 arcsecond spatial resolution at 5000 Å.
  Axisymmetric design for minimal instrumental polarization.

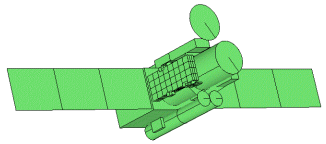
  ➔ PMU: Polarization Modulator Unit

  Rotating waveplate for polarization modulation before any oblique reflections.

  ➔TTM: Tip/Tilt Mirror

  PZT- actuated folding mirror for image stabilization.

FPP Major Components



- **FPP: Focal Plane Package**

➔ NFI: Narrowband Filter Imager

Tunable Birefringent filter: ~ 0.1 Å bandwidth, vector magnetograph. Data similar to the SOUP filter images from La Palma, with higher sensitivity and spatial resolution.

➔BFI: Broadband Filter Imager

Interference filters for short exposures and highest image quality. Data similar to G- band movies from La Palma, with perfect seeing.

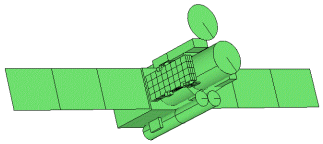
➔SP: Spectro-Polarimeter

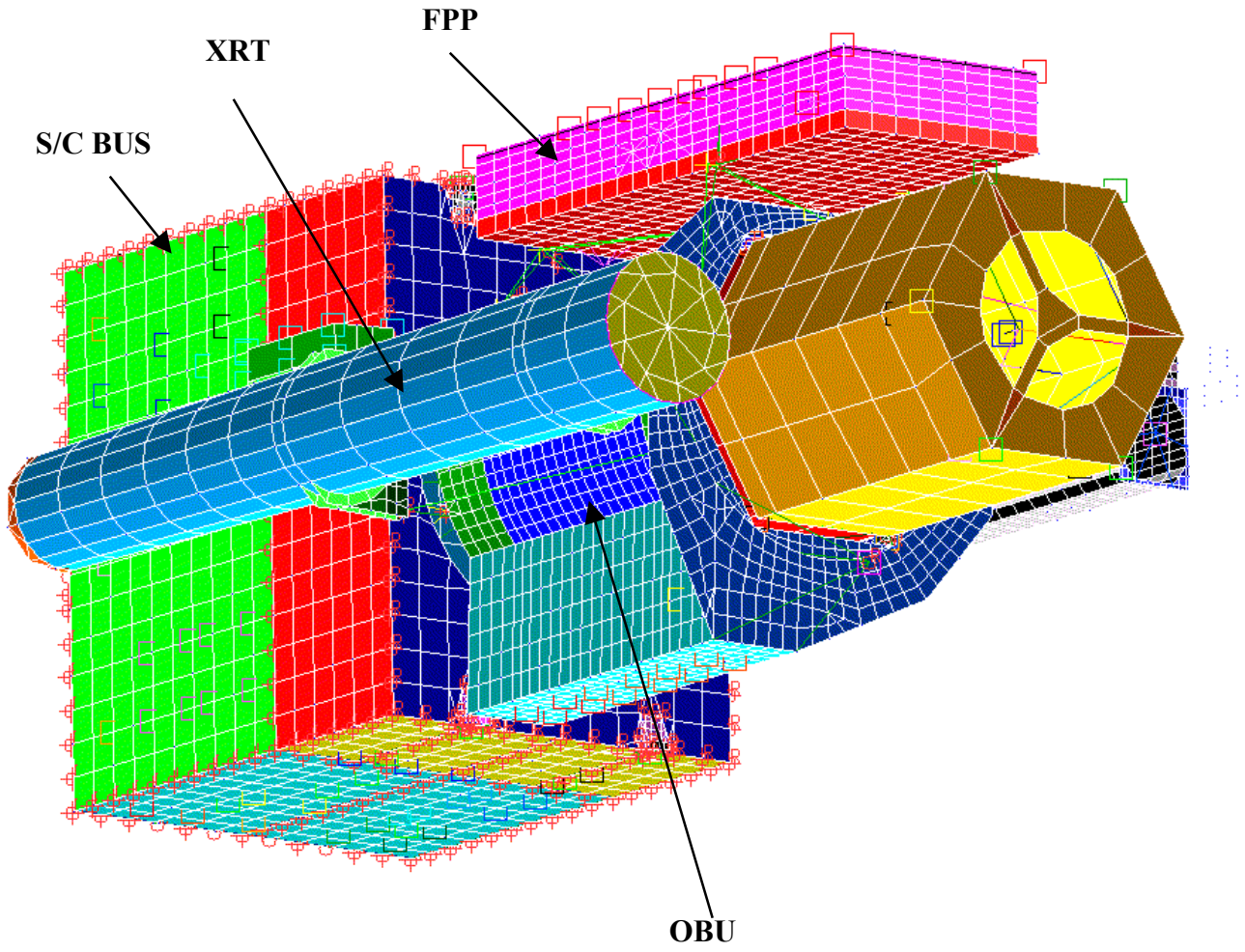
Fe I 6301/2Å lines: dual-line dual-polarization spectra for high precision Stokes polarimetry.
Data similar to HAO Advanced Stokes Polarimeter, with much higher spatial resolution.

➔CT: Correlation Tracker

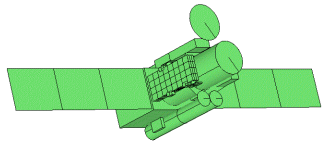
Jitter sensor for image stabilization with tip/tilt mirror.

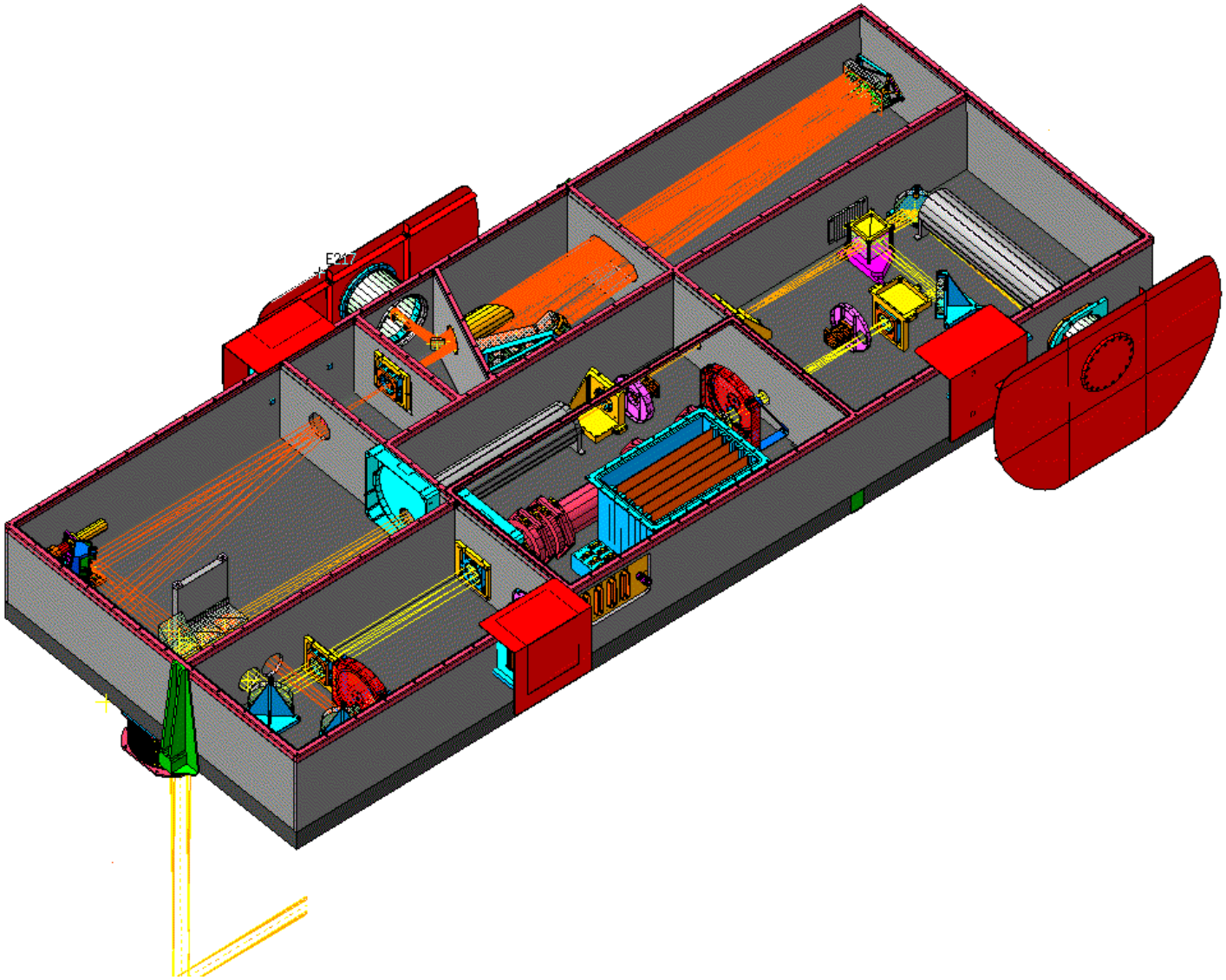
SOLAR-B SYSTEM FINITE ELEMENT MODEL



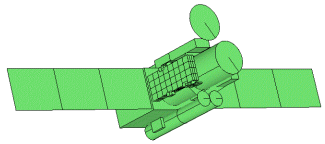


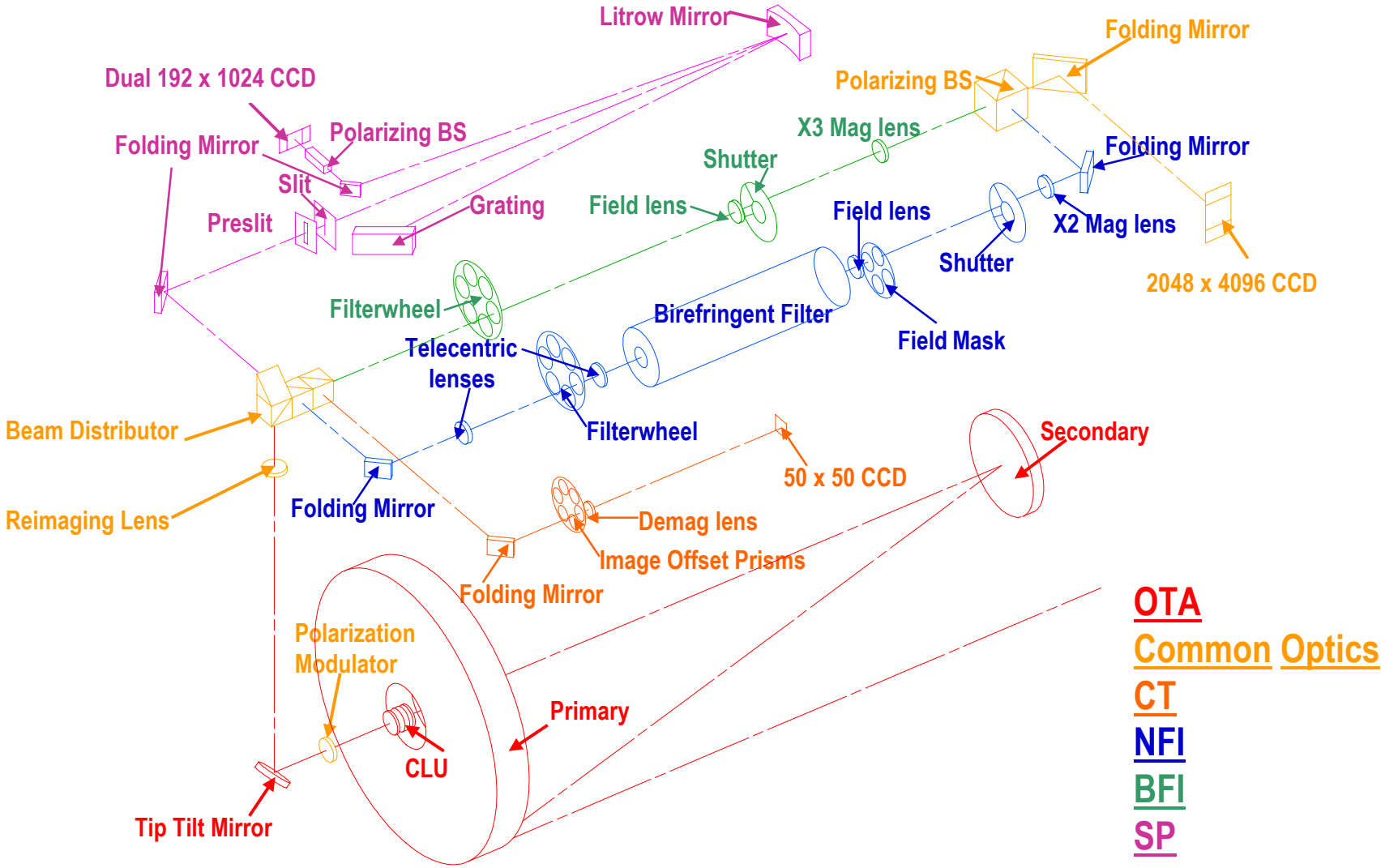
FPP Instrument - Y Side



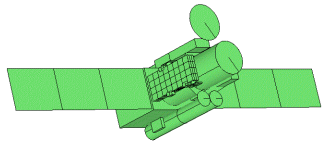


Optical Schematic of SOT/FPP



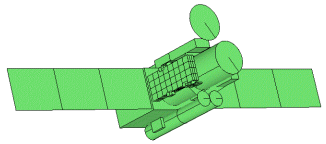


PMU System Overview



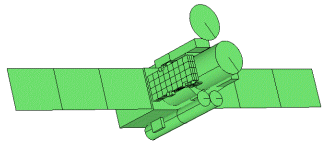
- **Polarization Modulator: Rotating Waveplate**
  - Immediately follows telescope for minimal instrumental polarization.
  - Quartz substrate retarder.
  - Optimized retardation for linear and circular polarization at 6302 Å and 5173 Å .
  - 1.6 second rotation period.
  - DC hollow core motor - continual operation throughout mission lifetime.
  - Multiple wedged optics to minimize beam wobble and reduce fringing.
- **Tip/Tilt Mirror System**
  - ISAS/NAOJ/MELCO design and manufacture.
  - Provides 2-axis image stabilization of <0.02 arcseconds up to 20 Hz bandwidth.

SP System Overview



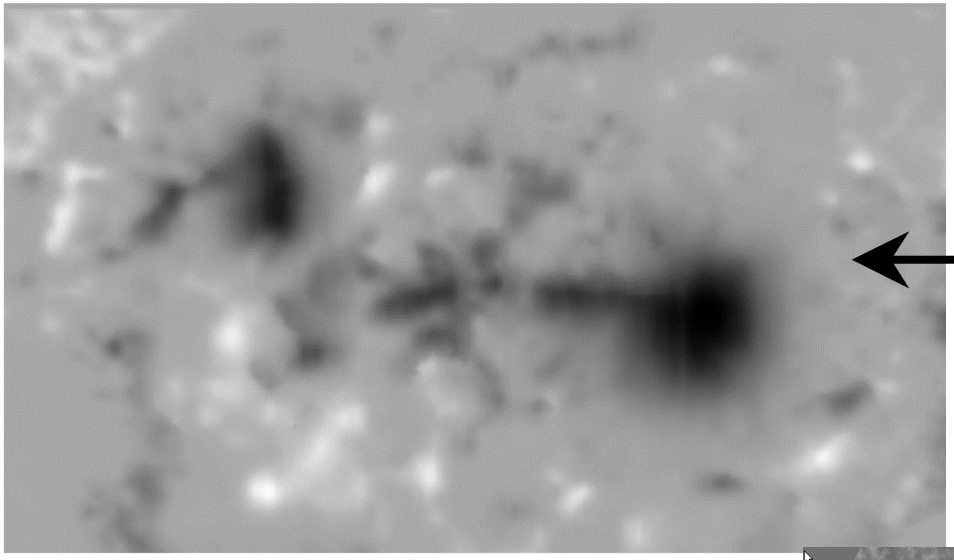
- **Littrow design**
  - Off-axis parabolic mirror.
- **Slit: 160” x 0.16”**
  - Maximum map FOV = 320” x 160”
  - Dual-beam polarization analysis
    - Calcite prism gives provides both modulated polarizations simultaneously for minimum crosstalk.
- **Fe I 6301.5 Å (g=1.67) and 6302.5 Å (g=2.5) lines**
- **Spectral resolution ~ 25 mÅ**
- **Spectral range ~ 2 Å**
- **Polarization precision better than 0.1 %**
- **Polarization S/N for map > 10^3**

SP Observing Modes



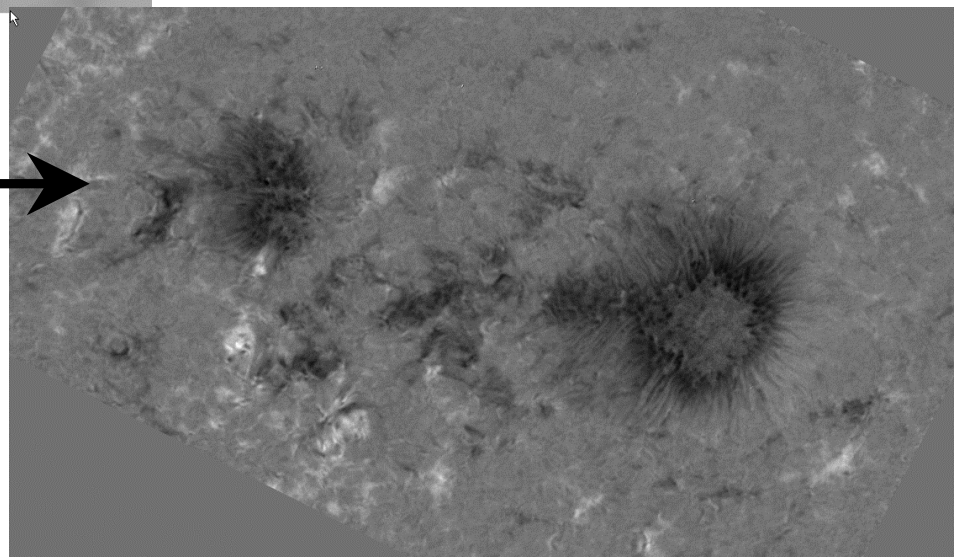
- **Normal Mapping Mode**
  - Expose/read/demodulate for 3 modulator rotations (4.8 seconds).
  - Move the slit one step of 0.16 arcsec (0.2 sec).
  - Raw data rate ~200 kPixels/sec.
  - Send to MDP for compression and downlink.
  - 160” raster takes ~80 minutes, 320” raster takes ~160 minutes
- **Fast Map Mode**
  - 0.32” spatial resolution, 3.4 seconds per slit position
  - 5.1” raster takes 55 seconds, 160” raster takes ~ 30 minutes
- **Other modes have higher cadence or higher sensitivity**

Comparison of ASP and Filtergraph Magnetograms



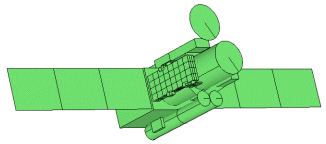
Stokes Longitudinal Magnetogram obtained with the Advanced Stokes Polarimeter at the Dunn Solar Telescope (NSO/Sacramento Peak) on 13 May 1998, created from a sequence of Stokes spectra. Vector magnetic field and Doppler shift maps with high accuracy are also produced from this data.

Longitudinal Magnetogram obtained with the SOUP Filter at the Swedish Vacuum Solar Telescope (La Palma) on 13 May 1998, constructed from a pair of filtergrams.



FPP will make vector field maps with accuracy and sensitivity similar to the ASP's and with spatial resolution similar to these filtergrams'.

BFI System Overview



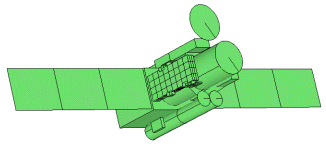
- **Filtergrams with highest spatial and temporal resolution**

- **Field of View: 216” x 108” maximum**
  - Partial readout and subarea selection in computer also possible

- **Spectral range 3880 - 6700 Å**
- **Temporal resolution < 5 sec for 108 x 108 arcsecond FOV**
- **Photometric accuracy better than 2% for continuum irradiance measurement.**

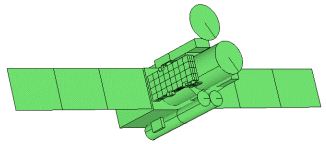
- **Common Focal Plane with NFI**
  - 2048 x 4096 back illuminated frame transfer CCD, 0.053 arcsecond pixels.

BFI Interference Filters



Center	FWHM	Purpose
3883.5 A	10	CN molecular band head: chromospheric network
3968.5 A	3	Ca II H-line: magnetic elements in low chromosphere
4305.0 A	10	CH G-band molecular band head: magnetic elements in photosphere; convection flow mapping.
4505.5 A	5	Blue continuum window for continuum irradiance
5550.5 A	5	Green continuum window
6684.0 A	5	Red continuum window

NFI System Overview

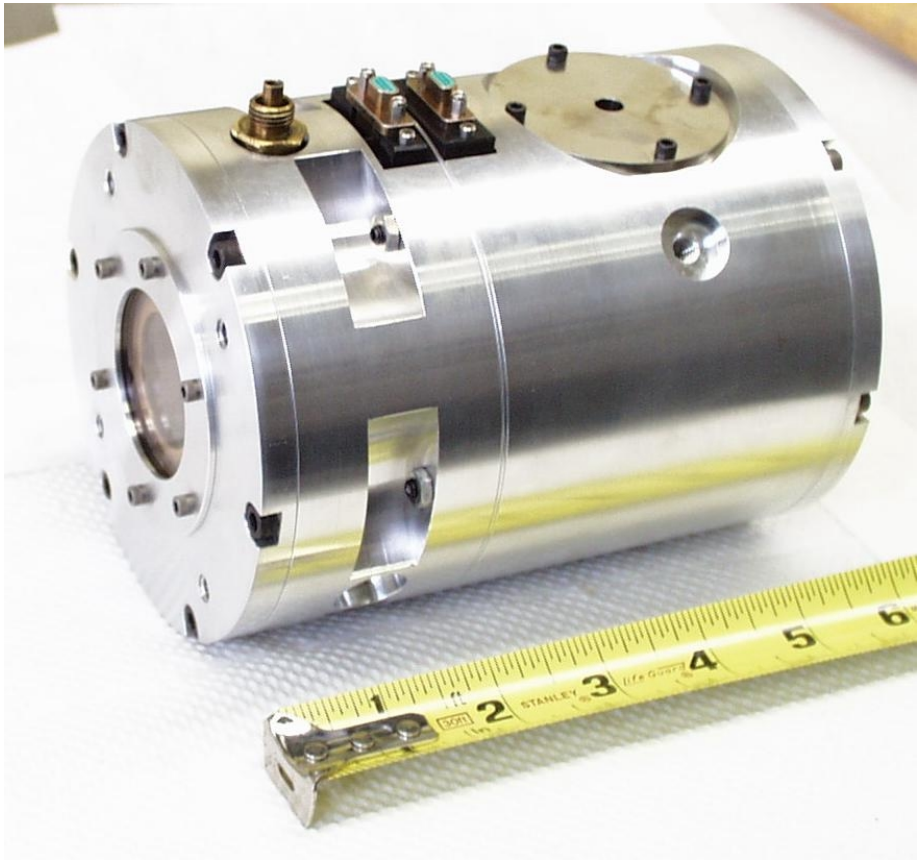


- **Tunable Lyot Filter System**
  - 8-calcite wide-field elements.
  - Temperature calibrated.
  - 0.25 arcsecond spatial resolution over range from 5170 — 6570 A.
  - 0.1 - 1 second exposure times for filtergrams
  - Spectral resolution 60 - 100 mA.
  - Polarization precision better than 1 %.

- **FOV selectable via focal plane mask**
  - 320” x 160” wide FOV (some vignetting in corners) for filtergrams.
  - 160” x 160” FOV for Dopplergrams & magnetograms made onboard
  - 8, 16, 32” x 160” narrow FOV for most sensitive Stokes vector maps

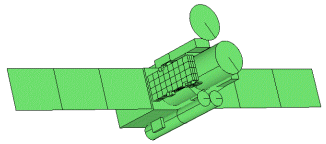
- **Common Focal plane with BFI**
  - 2048 x 4096 back illuminated frame transfer CCD, 0.08 arcsecond pixels.

Tunable Filter Test Cell



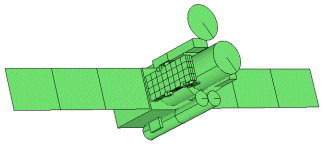
- **Prototype for space imaging missions such as Solar-B**
- **Two wide-field birefringent calcite elements**
- **Two integral, hollow core, tuning motors**
- **Oil filled to minimize internal reflection losses and ghost images**

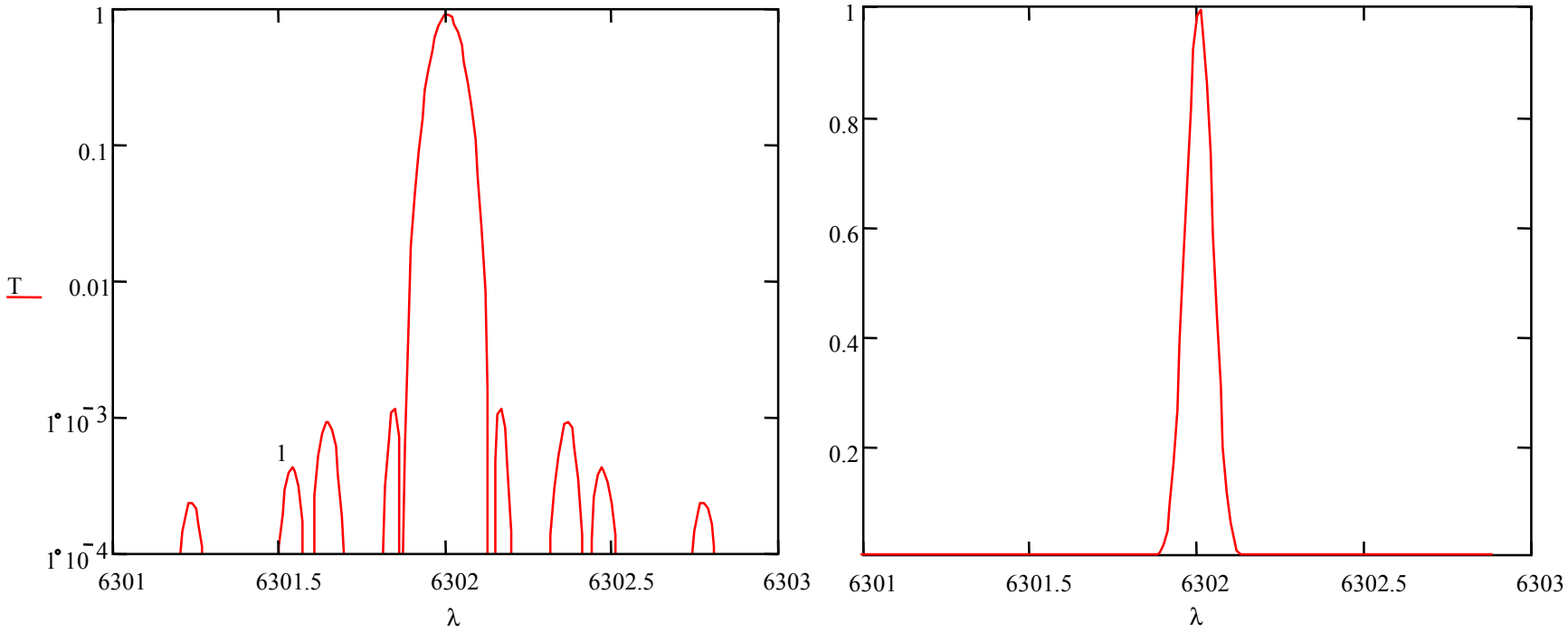
NFI Spectral Lines



Ion	Wavelength	g,eff	Purpose
Mg Ib	5172.7Å	1.75	Low chromosphere magnetograms, dopplergrams, Stokes vectors
Fe I	5247.1	2.00	Secondary photospheric magnetic line.
Fe I	5250.2	3.00	Used with 5247 line for ratio analyses.
Fe I	5250.6	1.50	"
Fe I	5576.1	0.00	Photospheric dopplergrams
Fe I	6301.5	1.67	Secondary photospheric magnetic line
Fe I	6302.5	2.50	Primary photospheric magnetic line.
Ti I	6303.8	0.92	Sunspot umbral magnetogram line
HeNe	6328.1		Laser alignment and testing line
H I	6563		H-alpha chromospheric filtergram and dopplergram line.

Tunable Filter Passband Detail

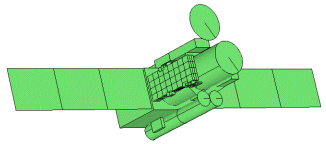




FWHM: 100 mÅ at 6302 Å

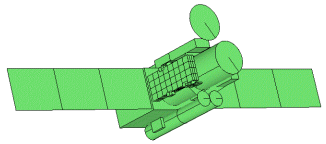
Sidelobe level: < 1%

Filtergraph Observables



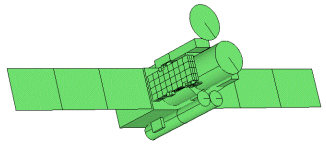
- **Filtergrams**
  - **Broadband Filtergraph: all bands, only observable made by BFI**
  - **Narrowband Filtergraph: all lines & nearby continuum**
- **Dopplergrams**
  - **Made onboard from 4 or more tunable filtergrams**
  - **Primary line is Fe I 5576 (g=0)**
- **Longitudinal Magnetograms**
  - **Made onboard from tunable filtergrams converted to Stokes I & V**
  - **Give the location, polarity and crude estimate of flux of magnetic field components along the line-of-sight**
  - **Primary lines are Fe I 6302.5 (photosphere) and Mg I 5172.7 (low chromosphere)**

Stokes Parameters



- I, Q, U, V made onboard from tunable filtergrams at 4 to 8 phases of the polarization modulator for each wavelength setting
- Stokes Parameters from filtergrams (using the shutter)
  - **0.4 sec exposures possible for V, 0.2 sec for Q & U**
  - **Noise sources due to time between frames & cross-talk between polarizations**
- Shutterless modes for higher time resolution & sensitivity, with tall narrow FOV: like the EIS “slot”
- Onboard processing very similar to that for Spectro-polarimeter
- Analysis of IQUV at multiple wavelengths yields vector magnetic field information

FPP NFI Performance Examples

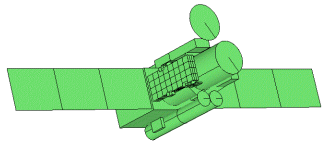


Shuttered Polarimetry

Observable	Line	Pixel (arcsec)	FOV (arcsec)	Time (s)	Sensitivity I / Sigma(V)
I, V	6302	.08”	164 x 164”	10	220
I, V	6302	.16”	328 x 164”	10	440
I,Q,U,V	6302	.08”	82 x 164”	13	140
I,Q,U,V	6302	.16”	164 x 164”	13	300
I,Q,U,V	5250	.16”	164 x 164”	13	180
I, V	5173	.32”	328 x 164”	10	380
I,Q,U,V	5173	.32”	328 x 164”	13	210

Time is for measurement at one wavelength

FPP NFI Performance Examples

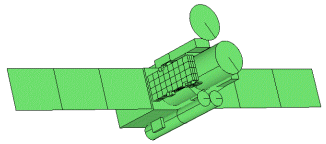


Shutterless Polarimetry

Observable	Line	Pixel (arcsec)	FOV (arcsec)	Time (s)	Sensitivity I / Sigma(V)
I, V	6302	.08”	32 x 164”	10	530
I, V	6302	.16”	64 x 164”	10	1080
I,Q,U,V	6302	.08”	8 x 164”	10	490
I,Q,U,V	6302	.16”	16 x 164”	10	1060
I,Q,U,V	5250	.16”	16 x 164 “	10	630
I, V	5173	.32”	128 x 164”	10	760
I,Q,U,V	5173	.32”	32 x 164”	10	730

Time is for measurement at one wavelength

Data Compression



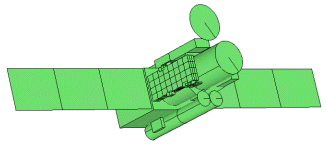
- All data compression is performed in the MDP, by ISAS-provided software and firmware

- Compression options are:
  - **No compression**
  - **Lossless DPCM compression**
  - **16 to 12 bit compression by lookup table, followed by 12-bit JPEG**

- Studies of compression quality & efficiency are ongoing
  - **Lites/Shine study of compression of Stokes spectra showed no loss of scientifically important information with JPEG compression to 1- 2 bits/pixel**
  - **Similar results found for examples of high resolution La Palma images**
  - **Sample FPP data products with known SNR have been made for compression software testing**

- Based on our TRACE experience with 12-bit JPEG and our studies to date, we have confidence in compression of most data to ~ 2 bits/pixel

Sample Observing Sequence (1)



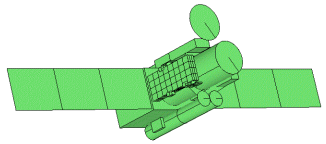
- Photosphere/Chromosphere Connectivity & Flows

- Goals
  - Observe fast transients (micro-flares, transient X-ray brightenings) in an active region coordinated with XRT and EIS
  - Determine if changes in magnetic connectivity accompany these transients
  - Record the geometry of the field changes and flows for comparison with numerical models of reconnection.

- FOV: an active region and connections with its surroundings, say 164 x 164 arcsec in H-alpha and mgrams, smaller in G-band

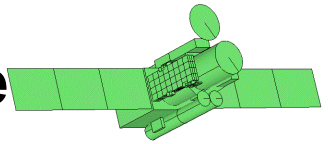
- SP Observations: Fast Map mode, takes about 30 minutes per map

Sample Observing Sequence (2)



- Filtergraph Observations: overall cadence 256 seconds
- For four 12.8-second intervals every 64 seconds, take an H-alpha set consisting of
  - **-1500 mA, .16 arcsec px, for signs of energy deposition in the low chromosphere**
  - **-350 mA, line center, +350 mA: .16 arcsec px, for connectivity and flows**
- In the fifth 12.8-second interval, take:
  - **G band (4308) image, .053 arcsec px, for photospheric flows and flux tube evolution**
  - **For 3 cycles, Mg b (5173) Stokes parameters, .32 arcsec px, for field changes in low chromosphere, first in blue wing, then line center, then red wing; shutterless mode with smaller FOV (123 x 164 arcsec for IV, 61 x 164 for IQU)**
  - **For the next cycle, 6302 longitudinal magnetogram, .16 arcsec px, 164 x 164 arcsec**

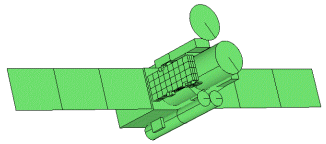
Data Rates of Sample Observing Sequence



	To MDP	To Telemetry
	Kpixels/sec	Kbits/sec
SP Data	146	219
H-alpha	262	393
G-band	65.5	98
5173 Stokes	9.2	13.8
6302 Mgram	4.1	6.1
Totals	487.	730.

- Assumes all data is compressed in the MDP to 1.5 bits/pixel
- Peak rate to MDP is much higher: limited to 1 Mpixel/sec
- 3.6 Gbit mass memory is filled in 82 minutes, less than 1 orbit;
  - **Therefore sequence must pause for telemetry passes**
  - **For some but not all science goals, 80 minute runs with gaps are acceptable**

Mission Operations Overview



- ISAS will play the leading role in defining Mission Operations concepts and procedures
  - **Initial concepts presented at December 1999 Science Meeting**
  - **Experience from Yohkoh and TRACE is very relevant**
  - **Scientists in US will participate in science priorities & plans by email & telecon**
  - **LMSAL will provide SW and engineering support from Palo Alto as needed**

- Science planners at ISAS for each instrument will:
  - **Reach consensus on scientific plans and on coordinated vs. separate observing**
  - **Agree daily on Solar-B targeting schedule**
  - **Choose detailed observing programs and schedule them on ~ daily basis**
  - **Construct loads of observing programs and "timeline"**
  - **Monitor Solar-B status and quick look solar data during telemetry passes**

- Key aspect will be managing mass memory & telemetry schedule
  - **Planners must try to make observing programs consistent based on predicted data rates**