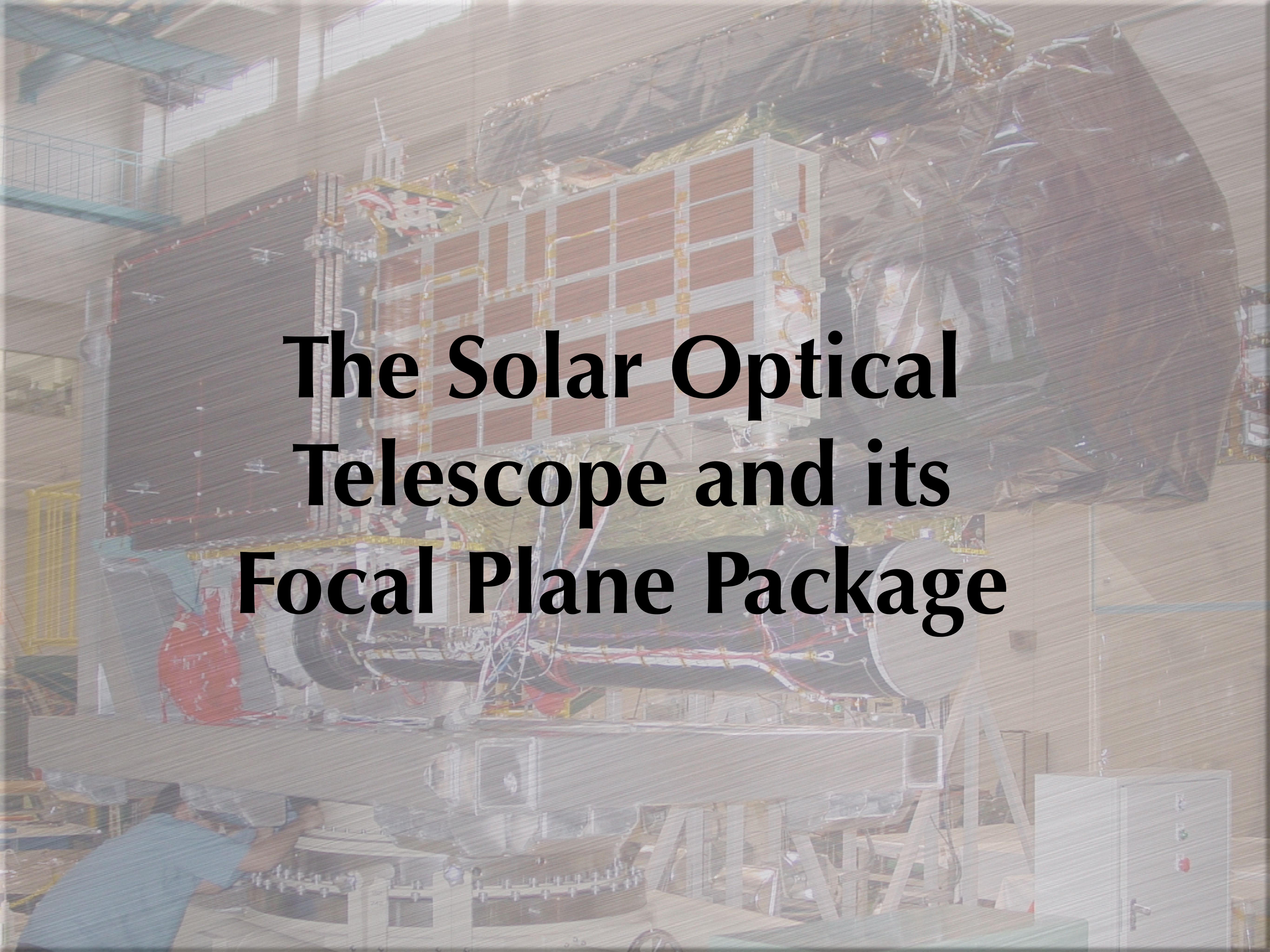
The Solar Optical Telescope and its Focal Plane Package



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.

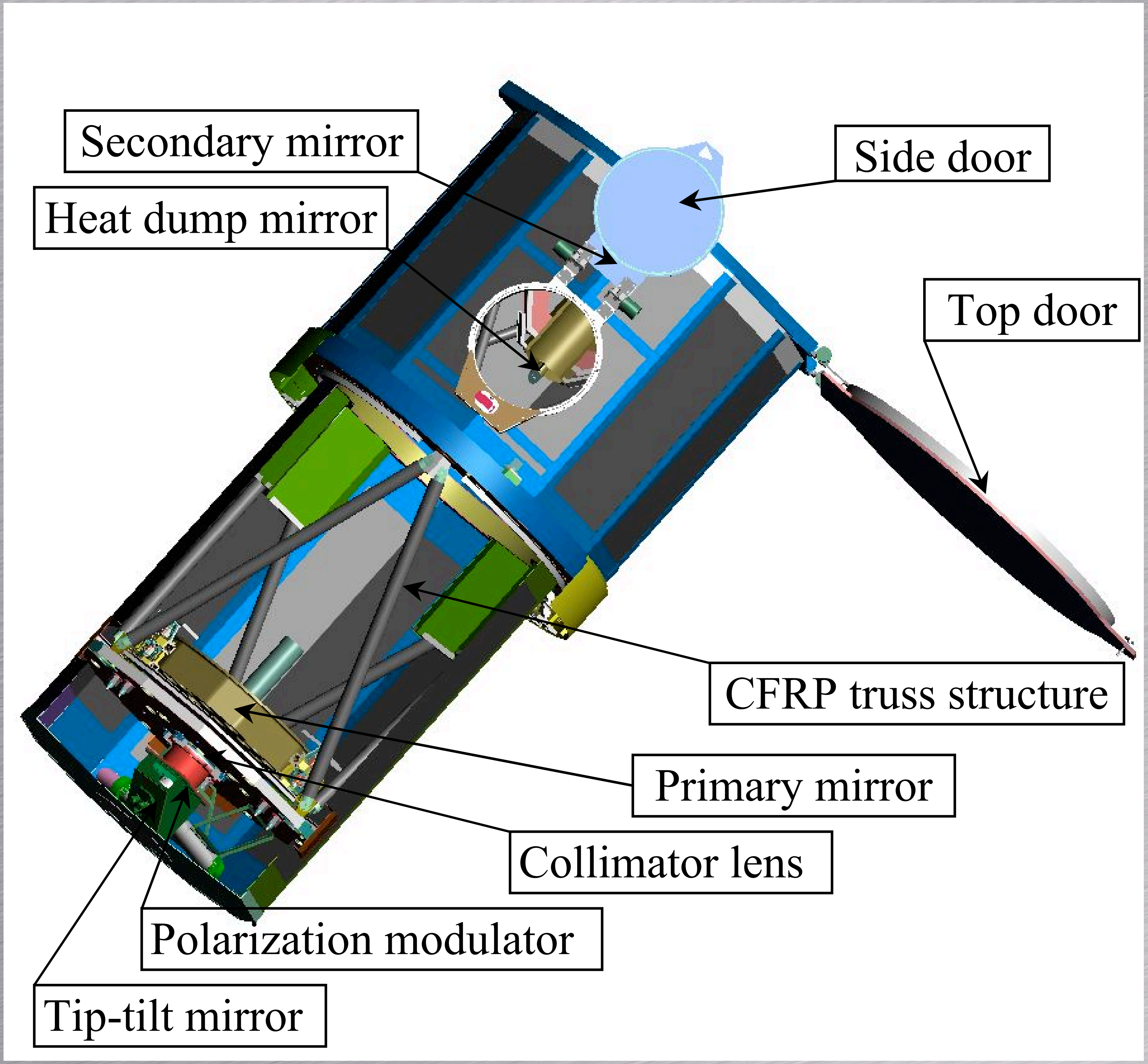
Primary Science Tasks

- Detailed studies of vector magnetic field structure, evolution and discontinuous changes on all spatial scales ranging from micro-flares to the very largest explosive events to determine whether these events are different manifestations of the same or similar process.
- A determination of whether the quasi-steady state magnetic field plays an active or passive role in coronal heating.
- A determination of whether the solar cycle spectral irradiance variation has a magnetic origin and the nature of the controlling mechanism identified.
- From the knowledge of the three-dimensional structure of the coronal field, studies of how the field is restructured in transient events will be performed to provide unambiguous evidence for magnetic reconnection.
- The dependence of network and intra-network magnetic structure and activity on latitude and proximity of sunspot groups will be determined.

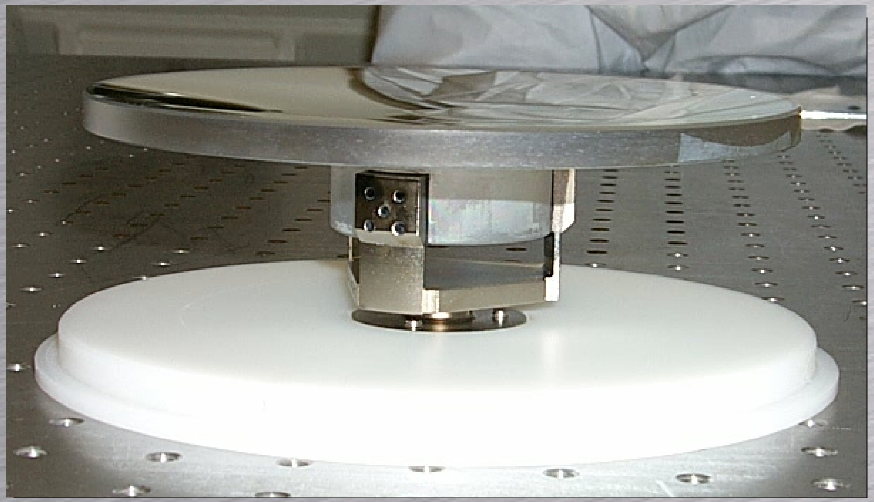
Features of the Solar Optical Telescope System

- Diffraction-limited images (0.2-0.3 arcsec), achieved by a 50 cm-diameter aperture Gregorian Telescope
- 388-668 nm spectral range that contains spectral lines and continuum bands useful for studying photosphere and chromosphere
- Telescope optimized for minimum polarization to allow accurate measurement of vector magnetic fields
- Observation from space, free from the atmospheric seeing
- Active tip-tilt mirror to remove spacecraft jitter
- Continuous observation for during ~8 months per year, due to the sun-synchronous polar orbit

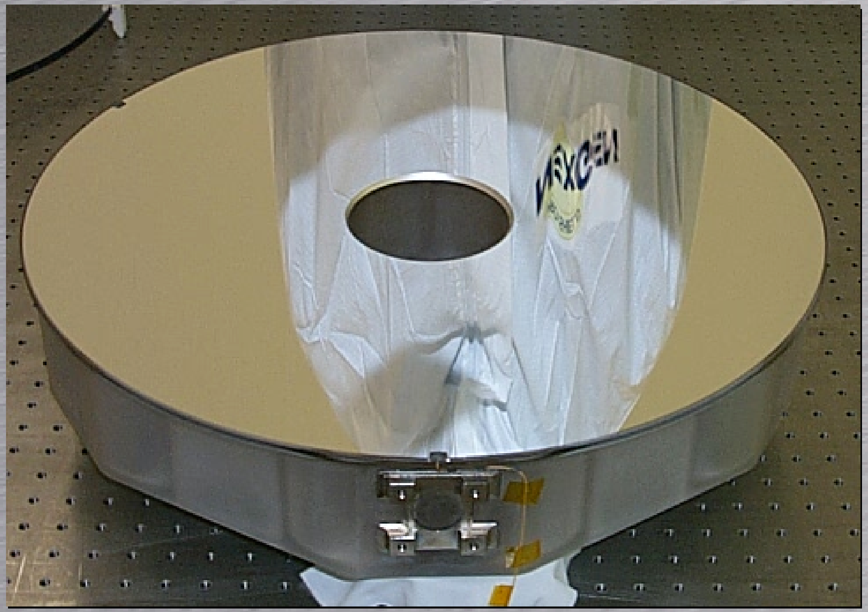
Optical Telescope Assembly (OTA)



OTA Components



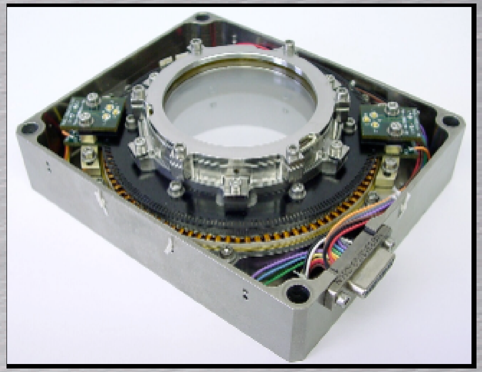
Secondary Mirror



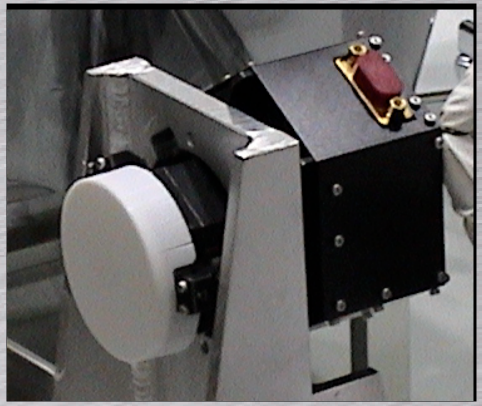
Primary Mirror

CFRP Truss Structure

Collimator Lens

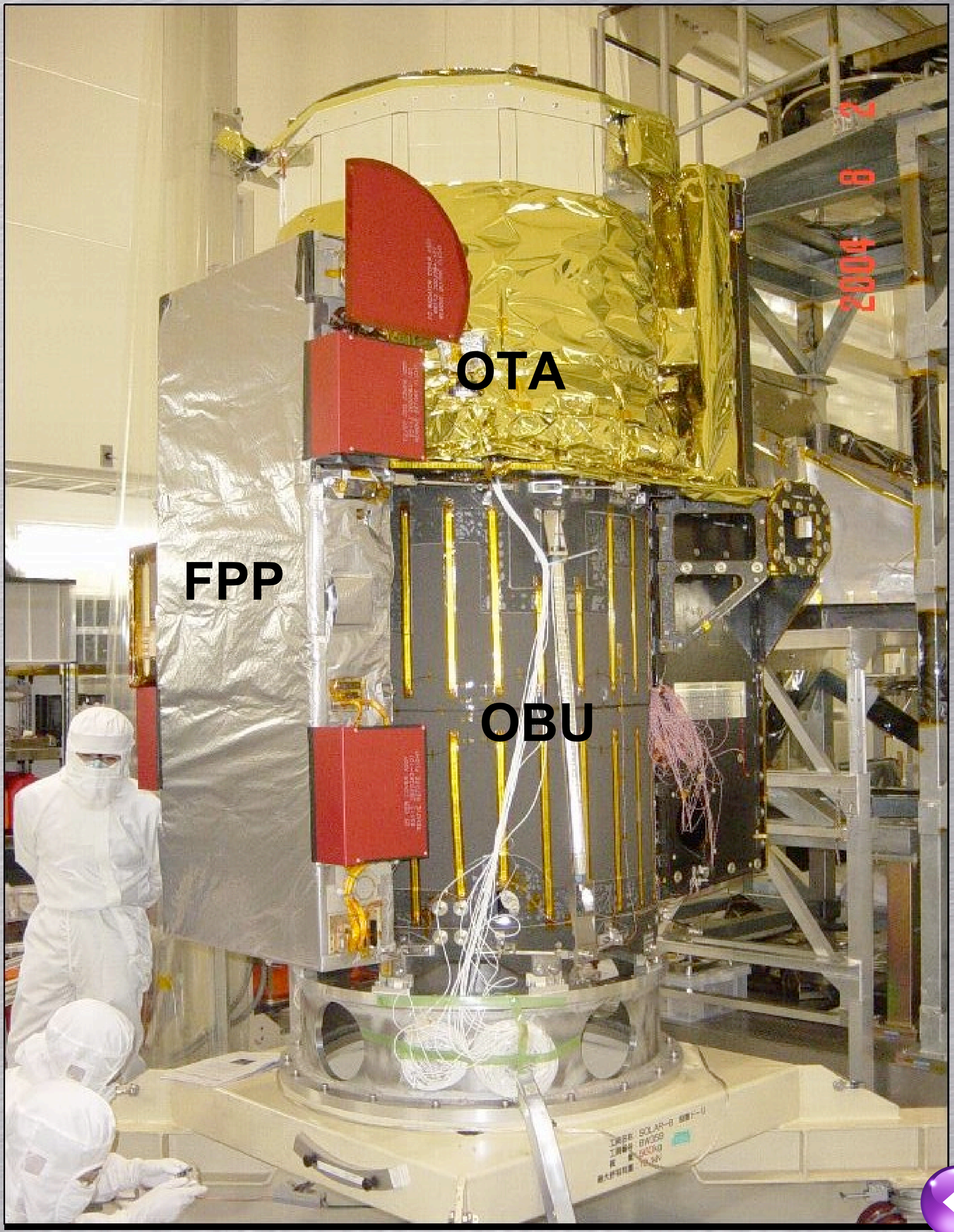


PMU

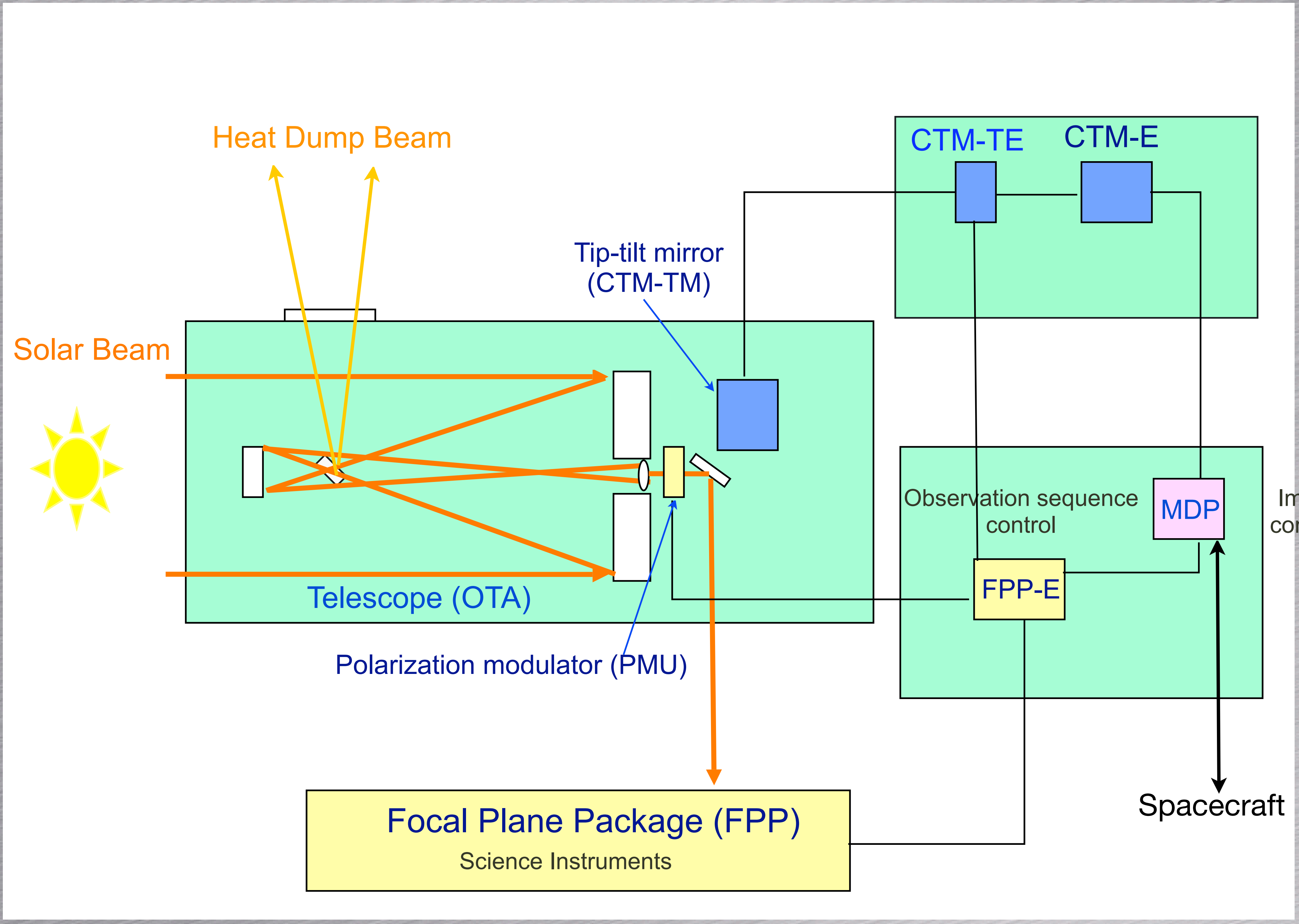


Tip-Tilt Mirror

Solar B Assembly in Test



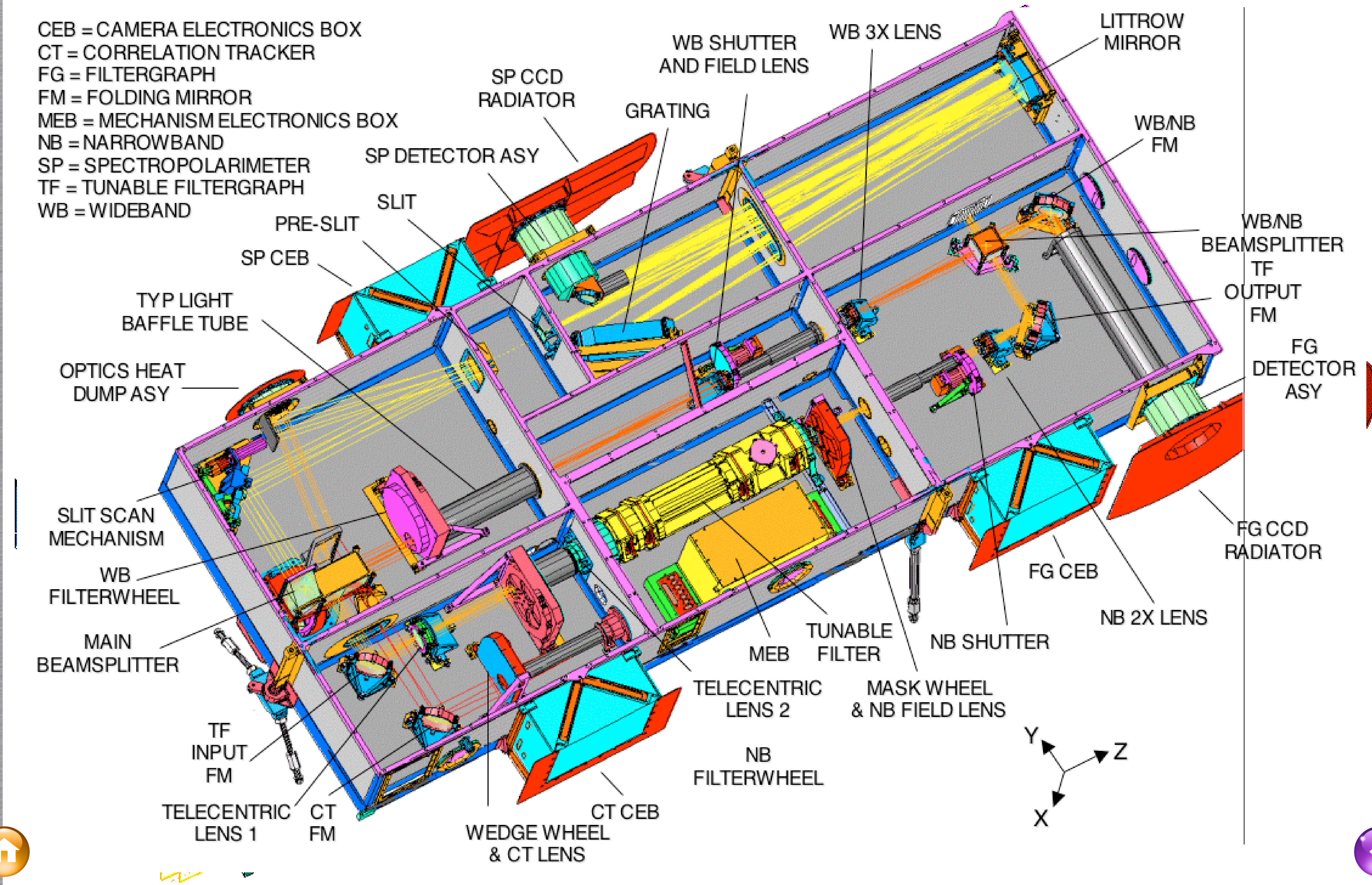
SOT System Block Diagram



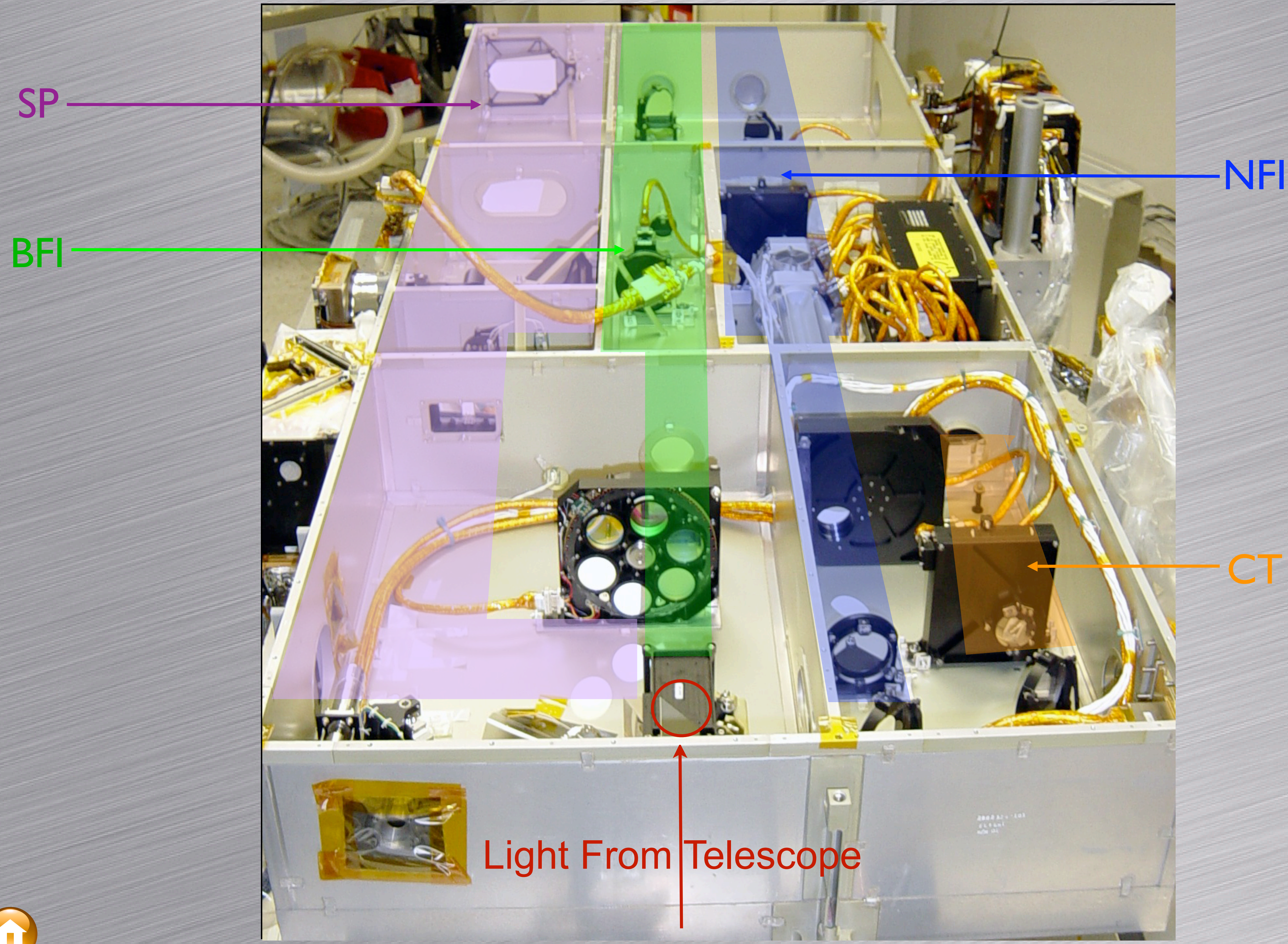
FPP Science Systems

- The SOT broadband filter imager (**BFI**) records diffraction-limited images, over the wavelength range 396.8 nm to 668.4 nm to observe both photospheric and chromospheric structure in quiet and active Sun. Irradiance data is obtained from observations in the blue (450.45 nm), green (596.25 nm) and red (668.40 nm) continuum.
- The SOT narrowband filter imager (**NFI**) records high spatial resolution (250 km) rapid for large (160 x 160 arcsecond) field of views, moderate polarimetric accuracy (10^{-2} or better) magnetograms over the full range of magnetic conditions from quiet Sun to moderate scale active regions.
- The SOT Spectro-Polarimeter (**SP**) records the photospheric vector magnetic fields of both quiet and active Sun with the highest possible precision (polarimetric accuracy 10^{-3} or better), observing the vector magnetic field over spatial scales of 500 km.

FPP Optics Package



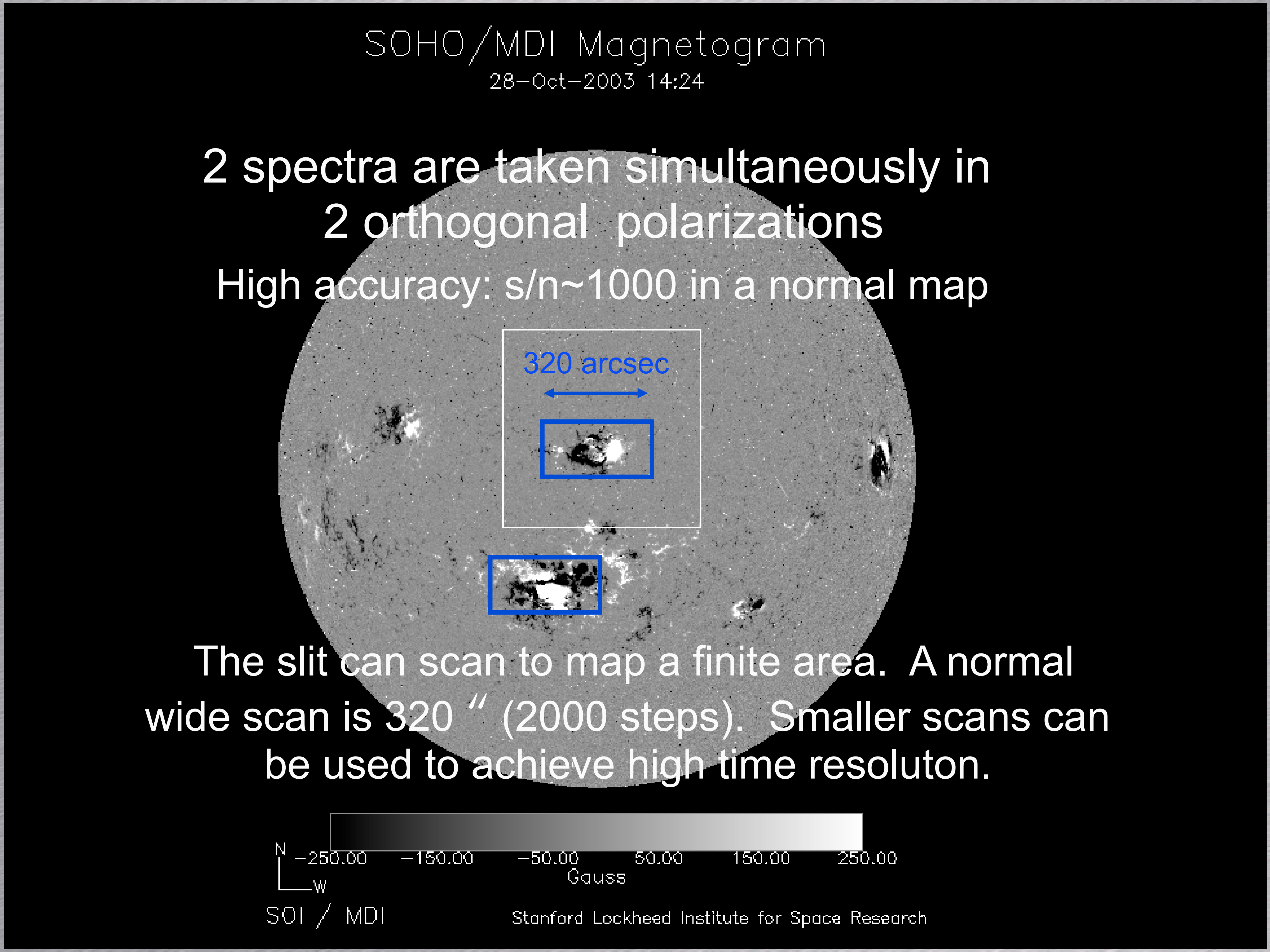
View Toward to Grating



Spectro-Polarimeter (SP)

2 spectra are taken simultaneously in 2 orthogonal polarizations

High accuracy: s/n~1000 in a normal map

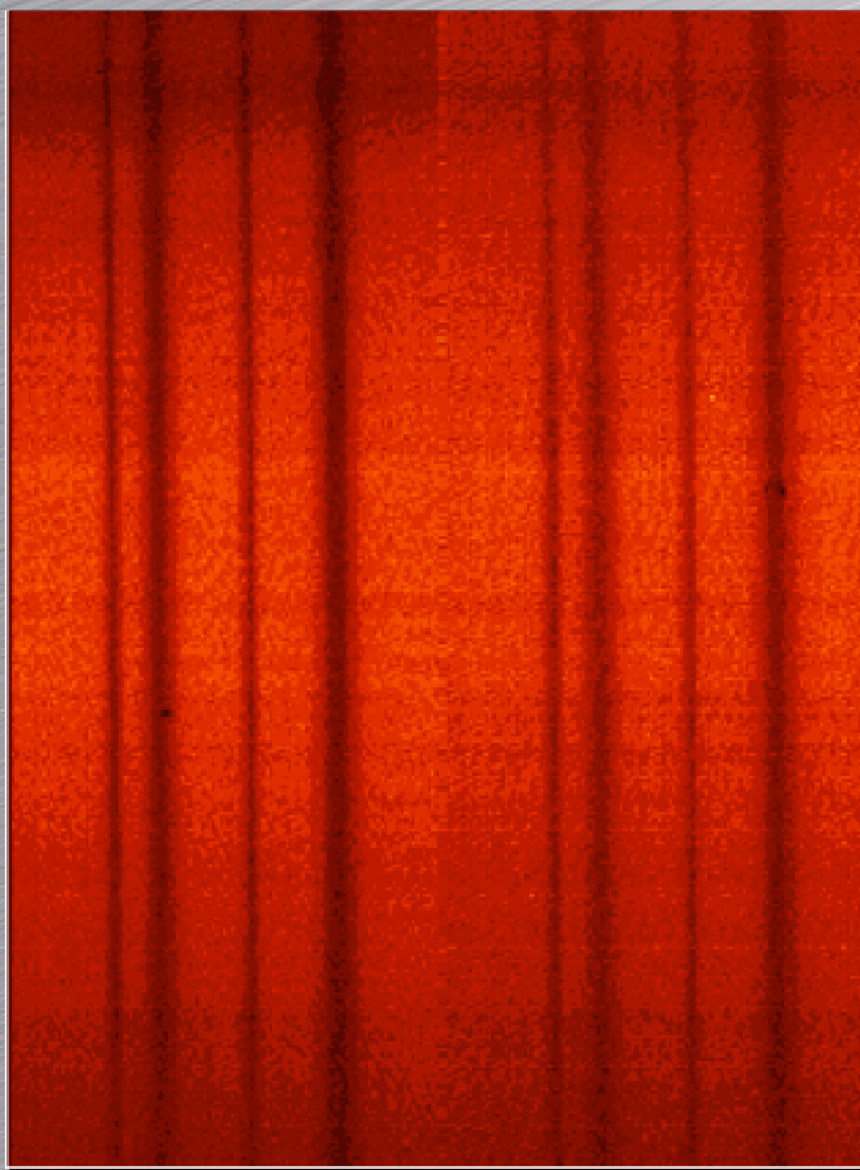


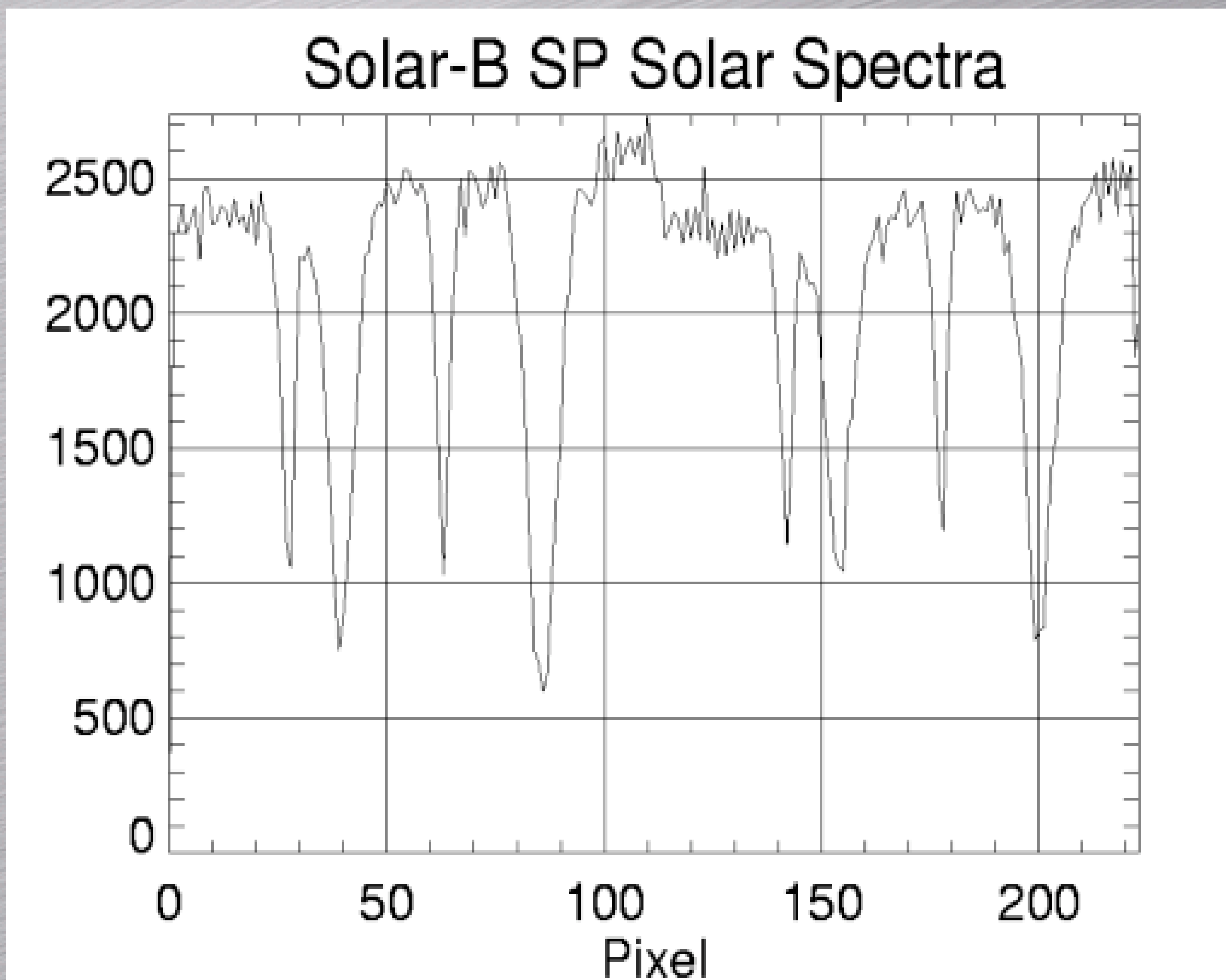
The slit can scan to map a finite area. A normal wide scan is 320 " (2000 steps). Smaller scans can be used to achieve high time resoluton.

Spectro-Polarimeter Observables

- Spectra of two Fe lines at 630.15 and 630.25 nm and nearby continuum are exposed, with a 0.16 x 164 arcsecond slit
  - 2 spectra taken simultaneously in orthogonal linear polarizations
  - Spectra are exposed and read out continuously, 16 times per rotation of the Polarization Modulator
- Raw spectra are added & subtracted into 4 memories to "demodulate," forming Stokes Parameters I, Q, U, V
  - Single observation is 2 sets of IQUV spectra (from the 2 linear pols.)
- The slit may be moved between observations to map a finite area
  - A wide single scan maps an entire active region
  - Repeated narrow scans study small features with high time resolution
- Processing on the ground produces maps of magnetic field vectors, Doppler shifts, and thermal properties on the Sun

Dual Spectra in SP Focal Plane





This image from the SP focal plane was made in test of the FPP using a light feed from the laboratory heliostat.

SP Observing Modes -1

- Normal Observing Mode
  - Expose/Read/Demodulate for 3 full rotations of waveplate, polarimetric accuracy of 0.001
  - Raw data is 120 x 2 spectral pixels x 1024 spatial pixels x 4 Stokes parameters in 4.8 sec, which is 983 Kpixels or 205 Kpixels/sec
  - Send to MDP for optional compression and downlink
  - Maps area 1.6″ wide in 50″ or 160″ wide in 83 min.
- Fast Map Mode
  - Expose/Read/Demodulate for 1 full rotation of waveplate, step the slit 0.16″, Expose/Read/Demodulate for a 2nd rotation, adding to the previous results
  - Sum 2 pixels in spatial direction on chip => effective pixel size is 0.32 “x 0.32″
  - Raw data rate is 492 Kpixels in 3.6 sec = 137 Kpixels/sec
  - Maps area 1.6″ wide in 18 sec, and 160″ in 30 min

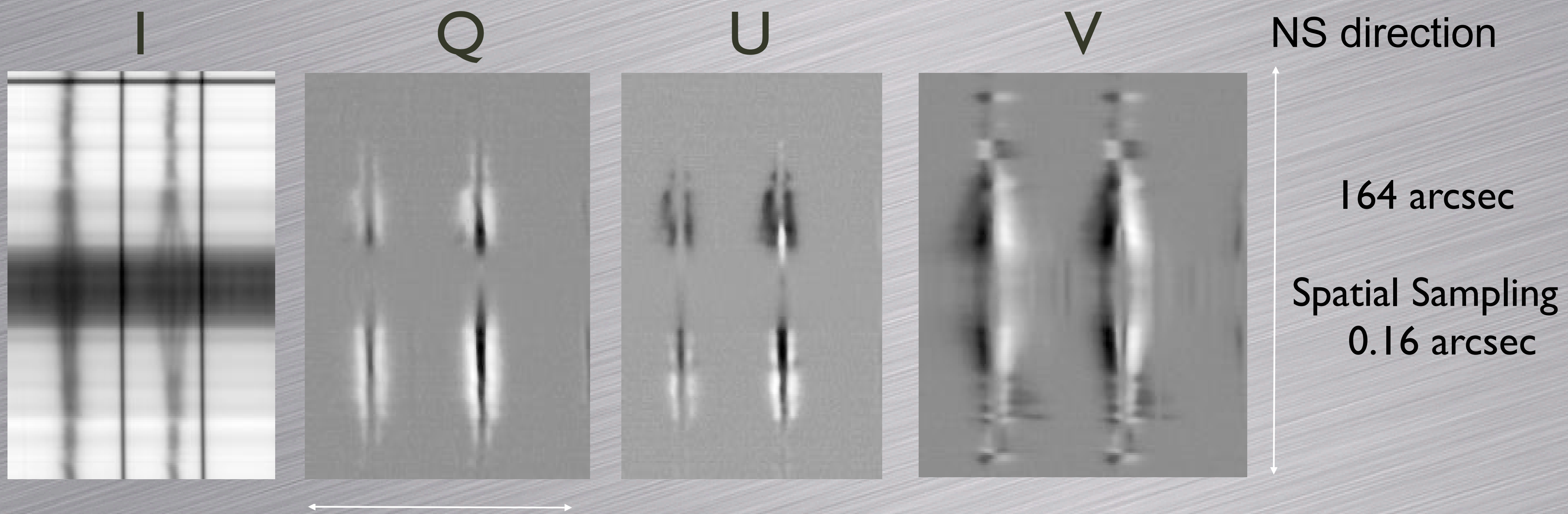
SP Observing Modes - 2

- Dynamics Mode
  - Expose/Read/Demodulate for only 1 full rotation of waveplate
  - Optionally step the slit by 0.16″
  - Must limit spatial FOV to reduce data rate: maybe 32″ typical slit length
  - For 32″along the slit, raw data rate is 192 Kpixels in 1.6 sec or 120 Kpixels/sec
- Deep Magnetogram Mode
  - Expose/Read/Demodulate for many full rotations of waveplate
  - Goal is to detect weakest polarization signals possible
  - Ignore wrap-around of intensity and strong polarization signals
  - Downlink data with no compression to avoid artifacts from wrap-around boundaries

In any mode, Field-of-View and data rate can be restricted by sending to the MDP only spectra from a limited spatial portion of the slit

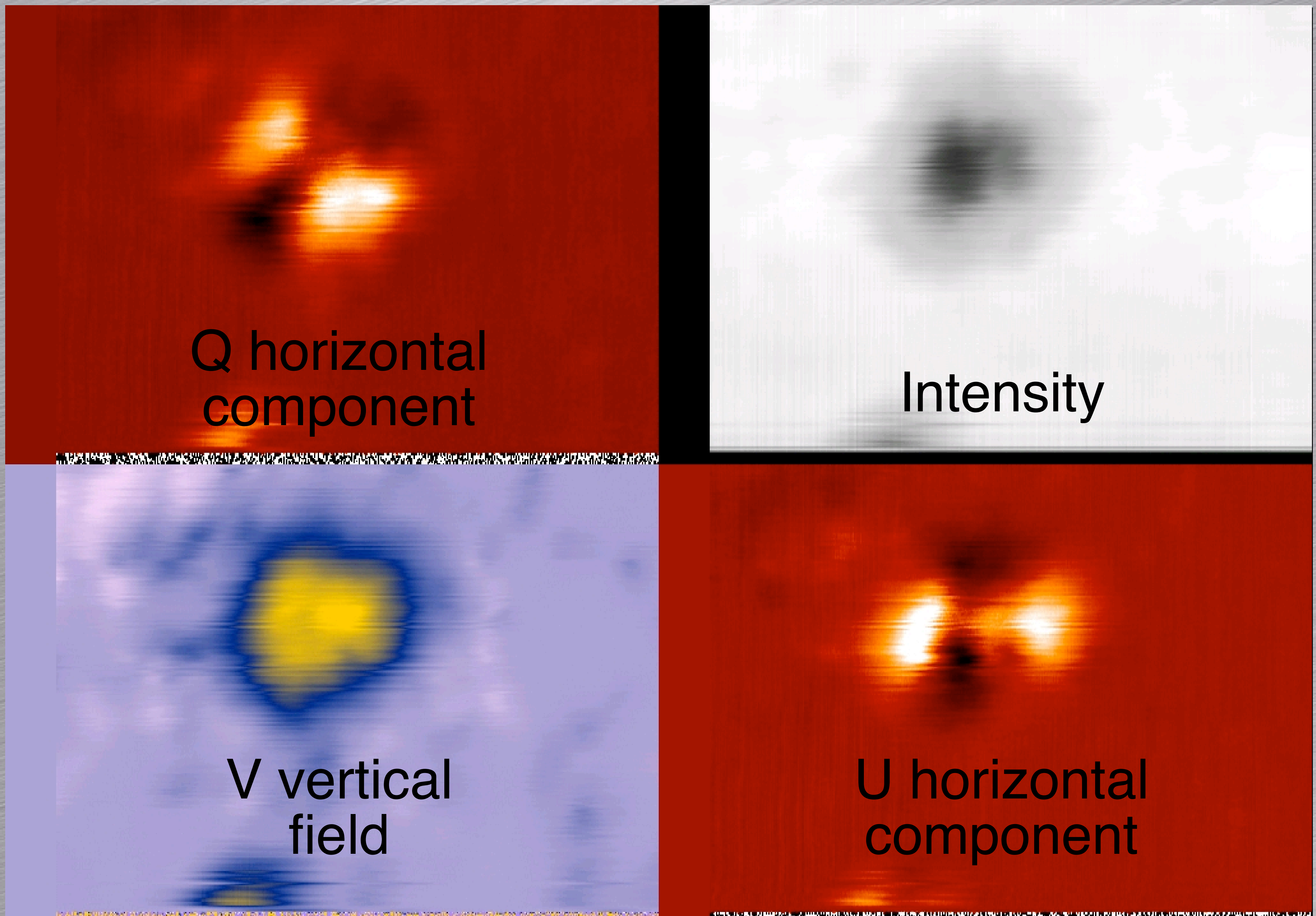
Spectro-Polarimeter (SP)

- Obtains spectra of two Fe lines at 630.15 and 630.25 nm and nearby continuum, with a 0.16 x 164 " slit.
- Spectra are exposed and read out continuously, 16 times per rotation of the Polarization Modulator (PMU) (1.6 sec)
- Raw spectra are added and subtracted onboard in real time to demodulate, forming Stokes I/Q/U/V.



Spectral direction: resolution 0.0030 nm/sampling 0.00215 nm

SP maps of Sunspot Region



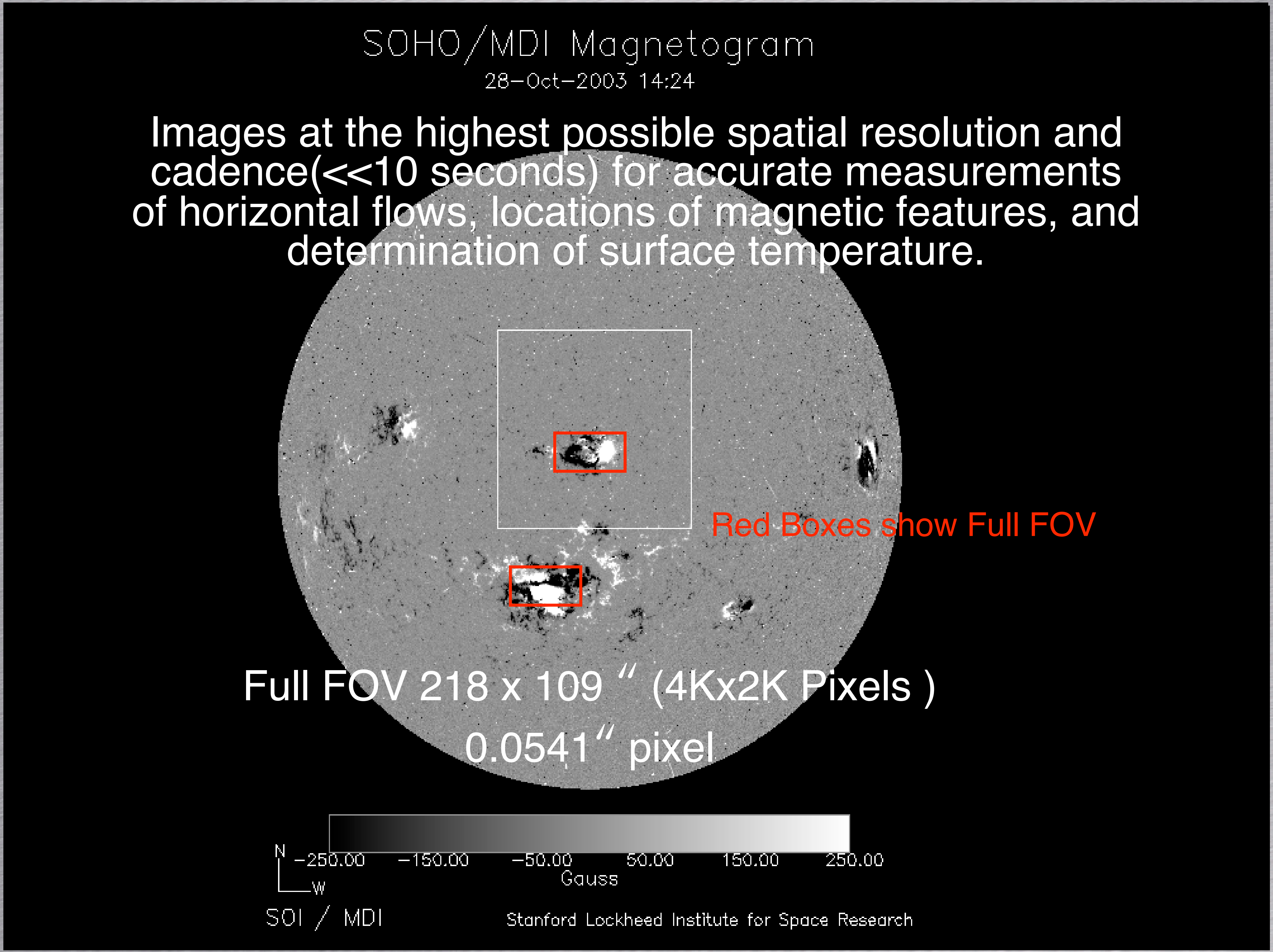
Filtergraph Observables

- Filtergrams
  - Broadband Filter Imager: all bands, only observable made by BFI
  - Narrowband Filter Imager: all lines & nearby continuum
- Dopplergrams
  - Images of the Doppler shift of a spectral line => line of sight velocity
  - Derived from narrowband filtergrams at several wavelenghts
- Longitudinal Magnetograms
  - Give the location, polarity and crude estimate of flux of magnetic field components along the line-of-sight
  - Derived from narrowband filtergrams converted to Stokes I & V
- Stokes Parameters I, Q, U, V
  - Analysis of IQUV at multiple wavelengths in a spectral line yields vector magnetic field information ("vector magnetograms")
  - I, Q, U, V images made onboard from narrowband filtergrams at different polarization modulator positions

Filtergrams (NFI & BFI)

- Shutter open/close always synchronized with Polarization Modulator
- Exposure times 0.1 - 1.6 sec in NFI, .03 - .8 sec in BFI
- Full readout in 3.4 sec, 2x2 summing in 1.7 sec
- Partial readout possible for faster cadence & reduced data volume: several discrete sizes from 192 to 2048 rows
- Reconfigure time (filterwheels, TF) < 3 sec
- No onboard processing in FPP, optional data compression in MDP

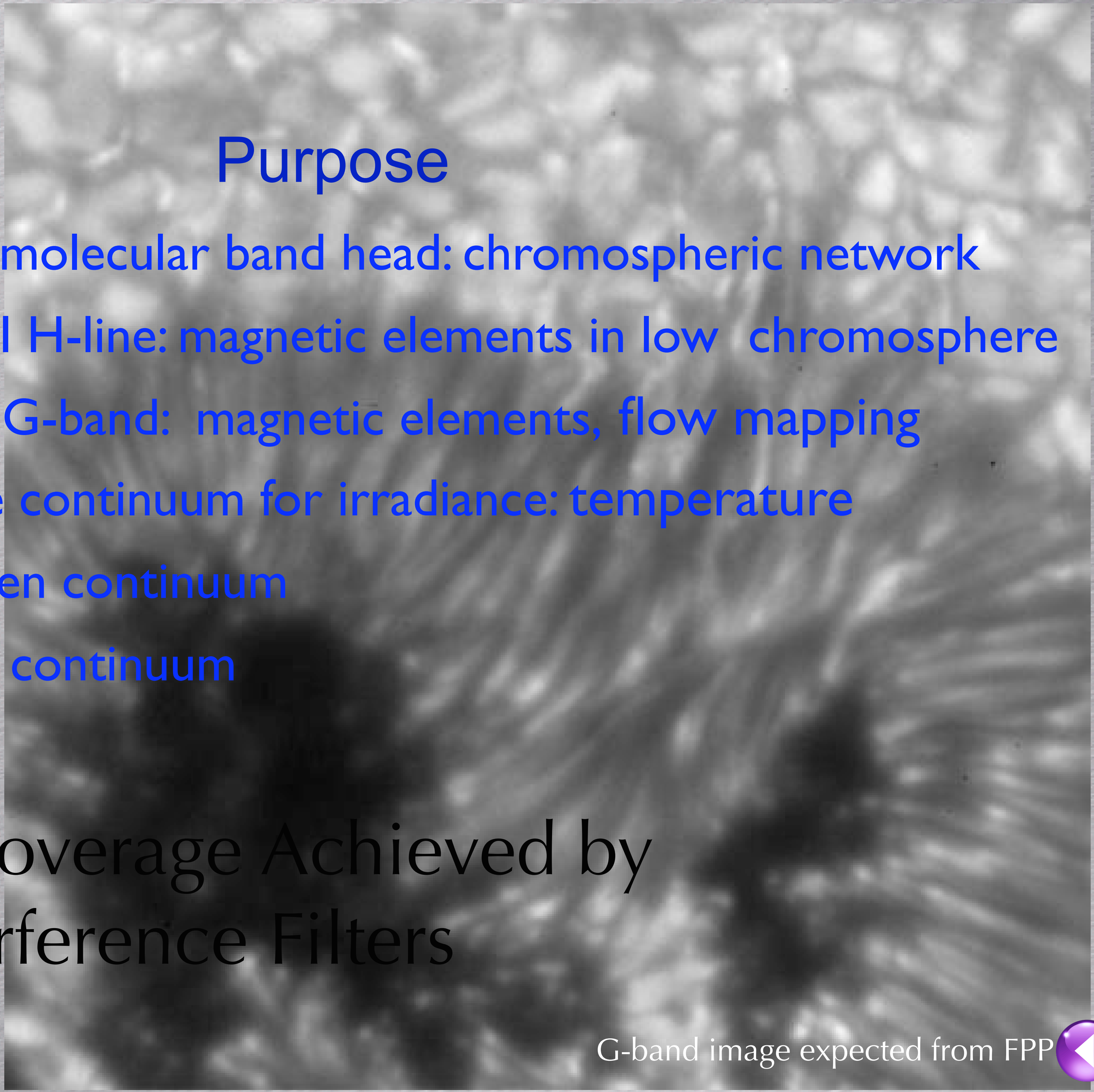
Broadband Filter Imager (BFI)



Broadband Filter Imager (BFI)

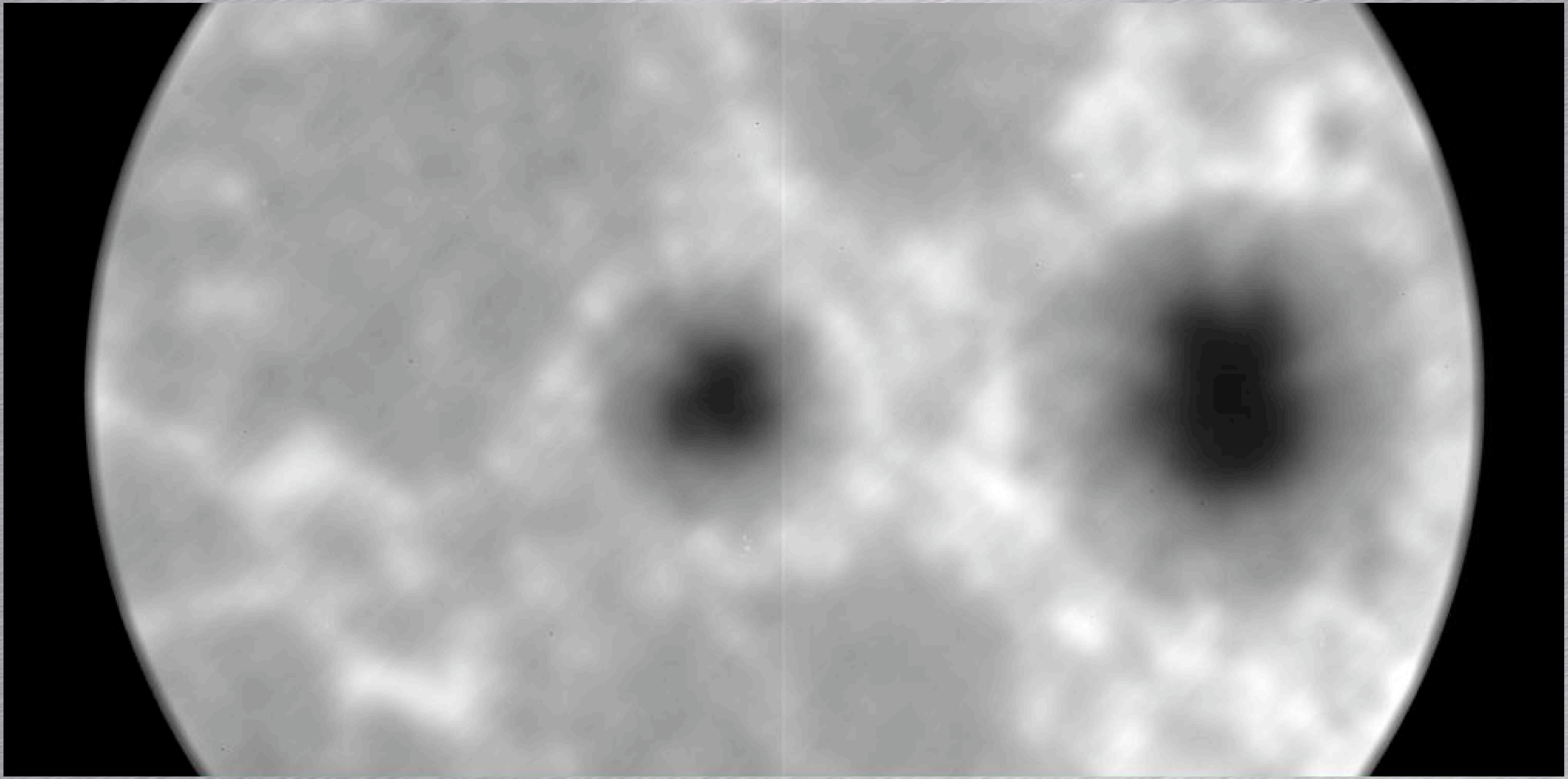
Center	FWHM	Purpose
388.35 nm	0. 7 nm	CN molecular band head: chromospheric network
396.85 nm	0.3 nm	Ca II H-line: magnetic elements in low chromosphere
430.50 nm	0.8 nm	CH G-band: magnetic elements, flow mapping
450.55 nm	0.4 nm	Blue continuum for irradiance: temperature
555.05 nm	0.4 nm	Green continuum
668.40 nm	0.4 nm	Red continuum

Spectral Coverage Achieved by
Interference Filters



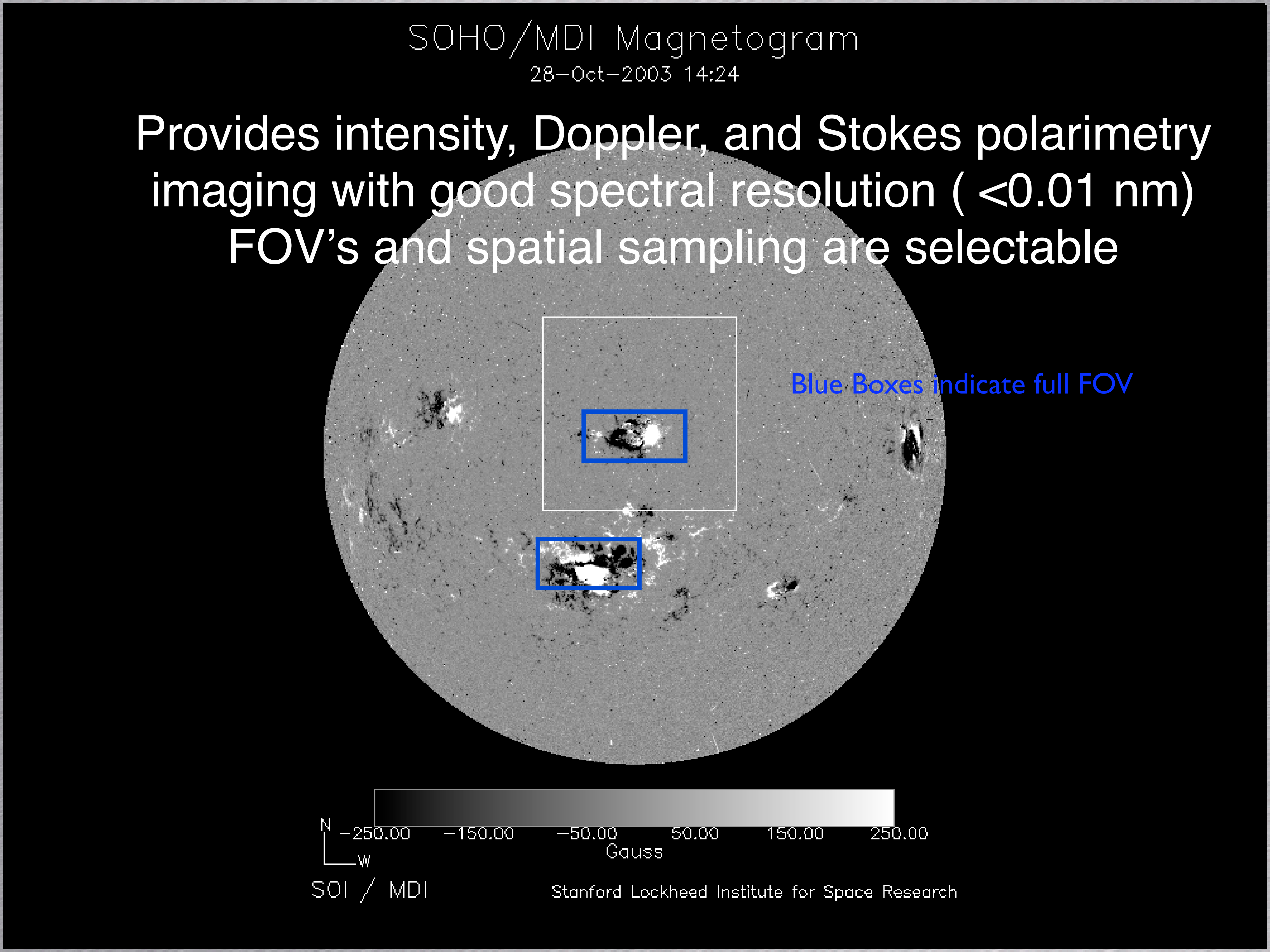
G-band image expected from FPP

CaH 393.3 nm Image from BFI System



(The fine line in center is caused by missing line pair. The circular cutoff is caused by the CCD cold trap. The cold trap has since been replaced and cutoff now longer occurs)

Narrowband Filter Imager (NFI)

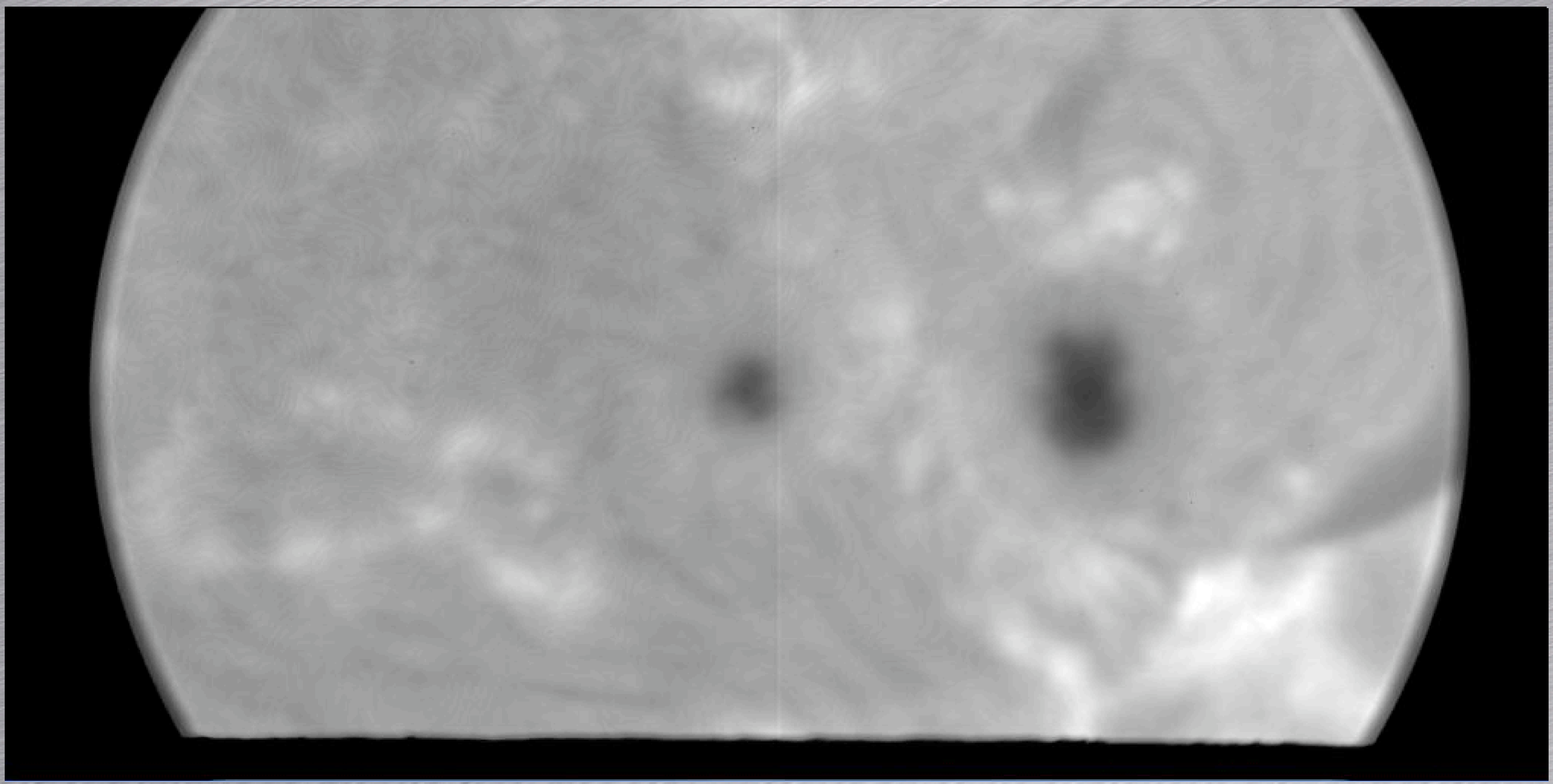


Narrowband Filter Imager (NFI)

Spectral lines in Lyot filter

Ion	Wavelength	g eff	Purpose
Mg I b	517.27 nm	1.71	Magnetograms and dopplergrams in low chromosphere
Fe I	524.71 nm	2.00	PhotoMagnetograms
Fe I	525.02 nm	3.00	Line ratio Magnetograms with 525.06
Fe I	525.06 nm	1.50	
Fe I	557.61 nm	0.00	Photospheric Dopplergrams
Na D	589.6 nm	1.50	Weak Fields - Chromospheric Fields
Fe I	630.15 nm	1.67	Photospheric Magnetograms
Fe I	630.25 nm	2.50	Photospheric Magnetograms
Ti I	630.38 nm	0.92	Sunspot Umbra Magnetograms
Hα	656.3 nm		Filtergrams and Dopplergrams

Hα 656.3 nm Image from NFI System



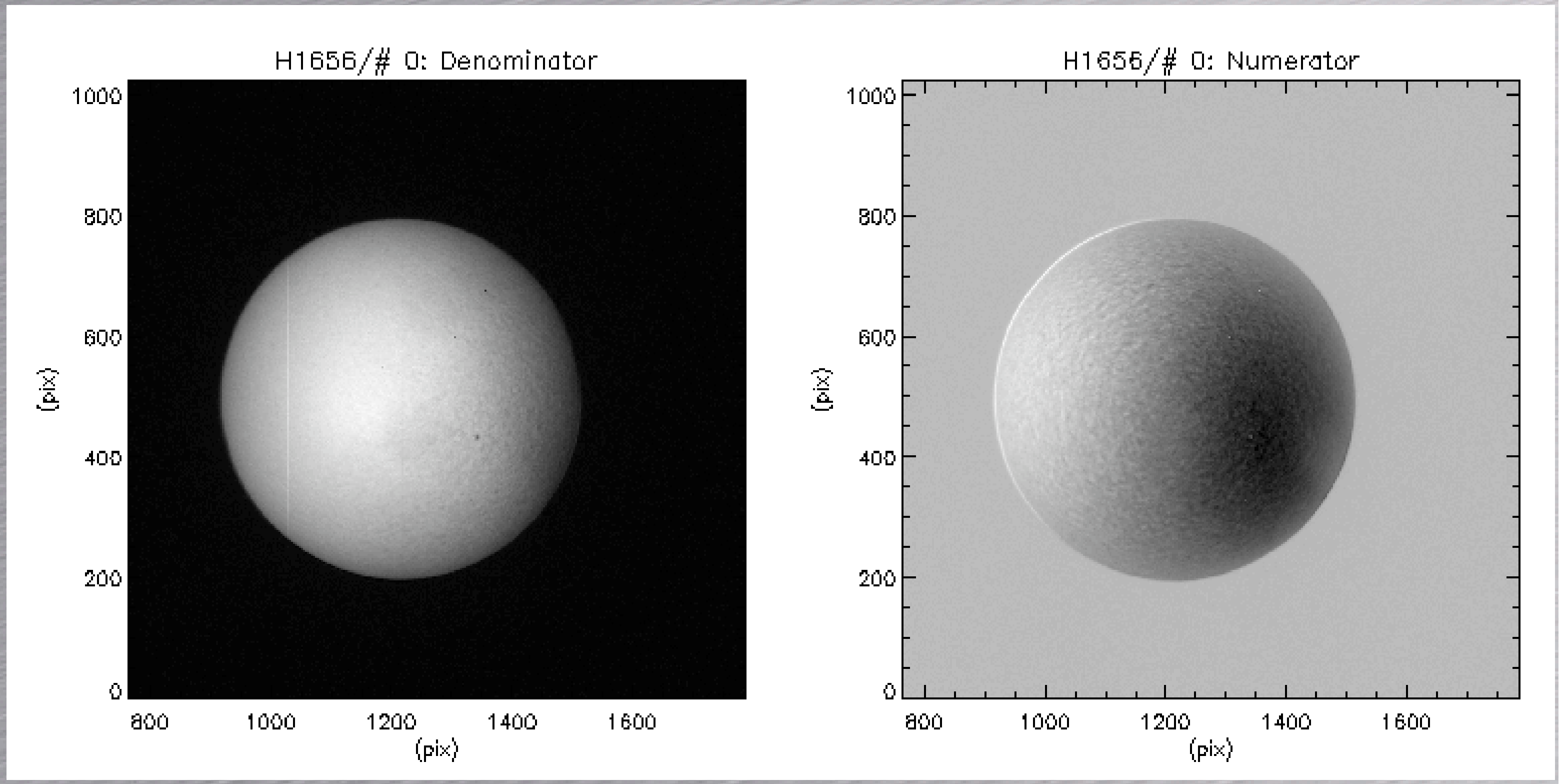
(Black band at bottom is cause by misalignment cause by instrument leg mounting. This has been corrected.)

Dopplergrams

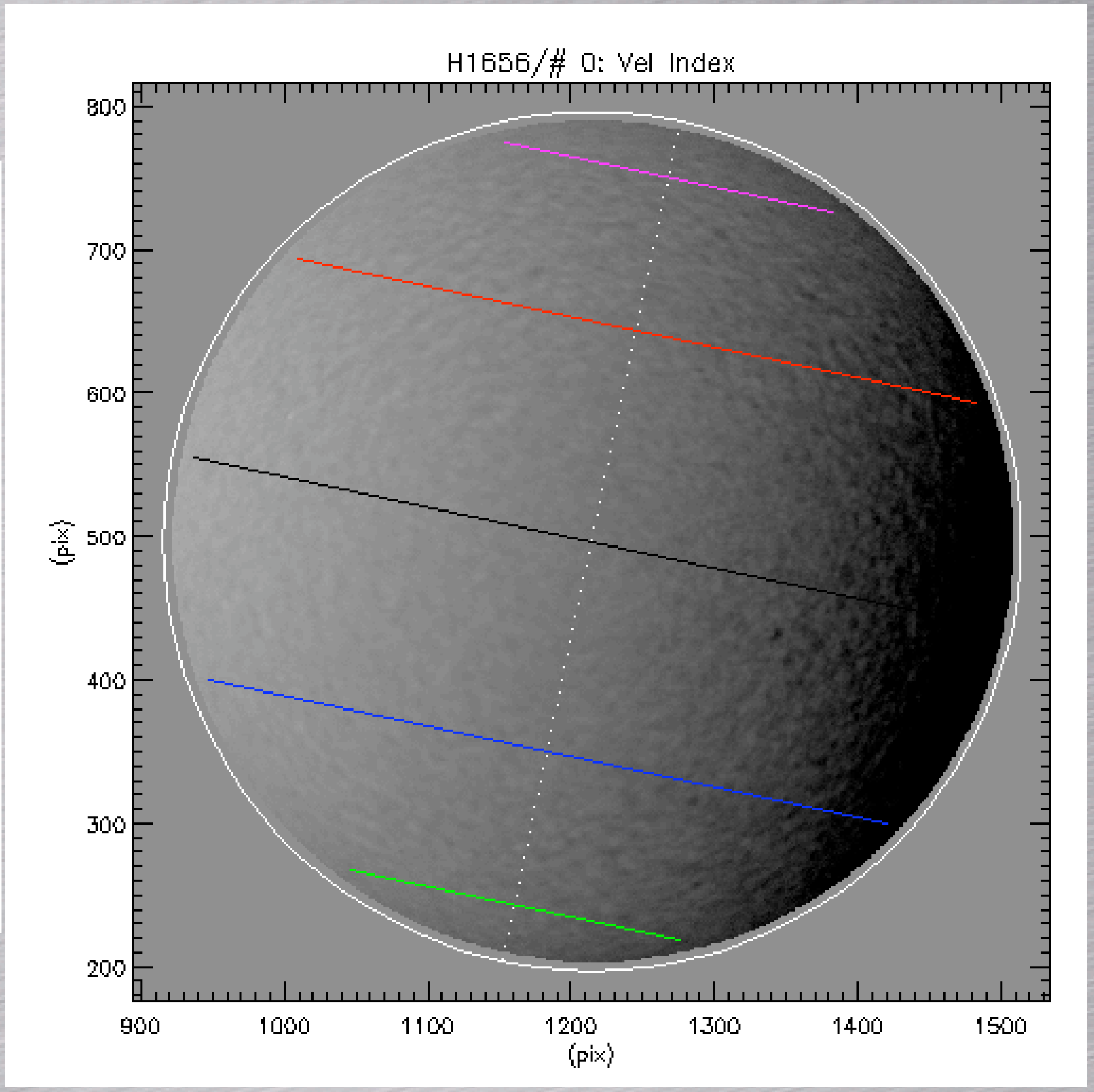
- Maps of line-of-sight component of velocity
  - Baseline is simplified version of algorithm used by MDI instrument on SOHO
  - Derive central wavelength from 4 images uniformly spaced in the line, F1 ... F4
  - R = (F1 + F2 - F3 - F4) / (F1 - F2 - F3 + F4)
  - Use 2 smart memories to make numerator & denominator
  - Velocity = V(R), implemented on the ground by lookup-table
  - Two wavelength dopplergrams possible for higher cadence
- Best photospheric line is Fe I 557.6 (non-magnetic, g=0)
  - 1-sigma noise of 30 m/s with 4 images, 2x2 summing, 0.16″ px, 0.2 sec exposure,
- Low chromospheric velocity measured in core of Mg I 517.3 line
  - Very dark line, but higher velocities expected
  - 1-sigma noise ~ 100 m/s with 0.16″ px, 1.6 sec exposures

Quantitative Evaluation with Solar Rotation

- The data were obtained in April 19-20, 2005 at Palo Alto.
- 2x2 summing mode, 1Kx1K partial images
- The solar diameter is around 600 pixels.
- The Doppler velocity is evaluated along the latitude



Raw data of FG Dopplergram

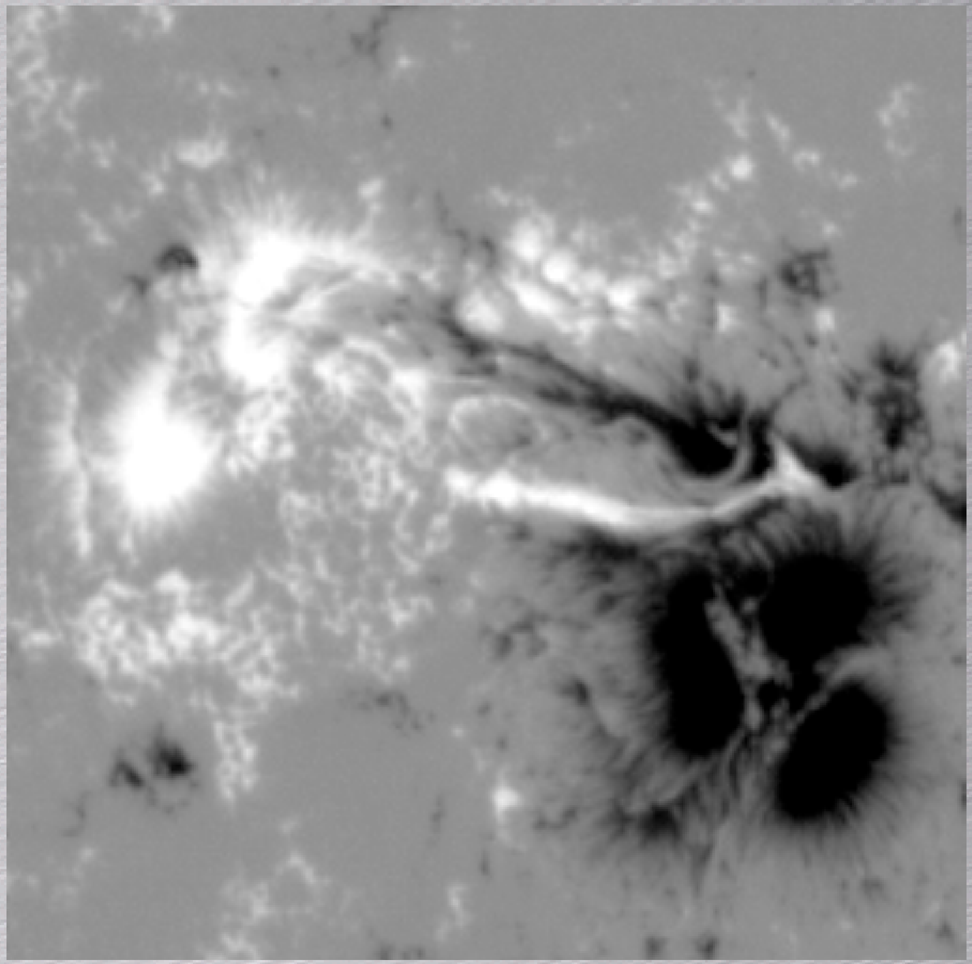


Velocity index (R)

FG Longitudinal Magnetogram

- Constructed from multiple NFI filtergrams in a magnetic sensitive line
- Onboard real-time processing makes numerator & denominator
- 630.2 nm magnetogram with 1x1 summing has RMS noise of ~1 10^{15} Mx/pixel

Map of Stokes V / Stokes I



$$Mgram = \frac{\sum_{i=1}^{n} a_i V(\lambda_i)}{\sum_{i=1}^{n} b_i I(\lambda_i)}$$

$$\text{where } a_i,\ b_i = 0,\ \pm 1,\ or\ \pm 1/2$$

Fe 630.2 nm Magnetogram from NFI

Partial field images taken to rapidly make image pairs in order to minimize seeing effects

Stokes Parameters

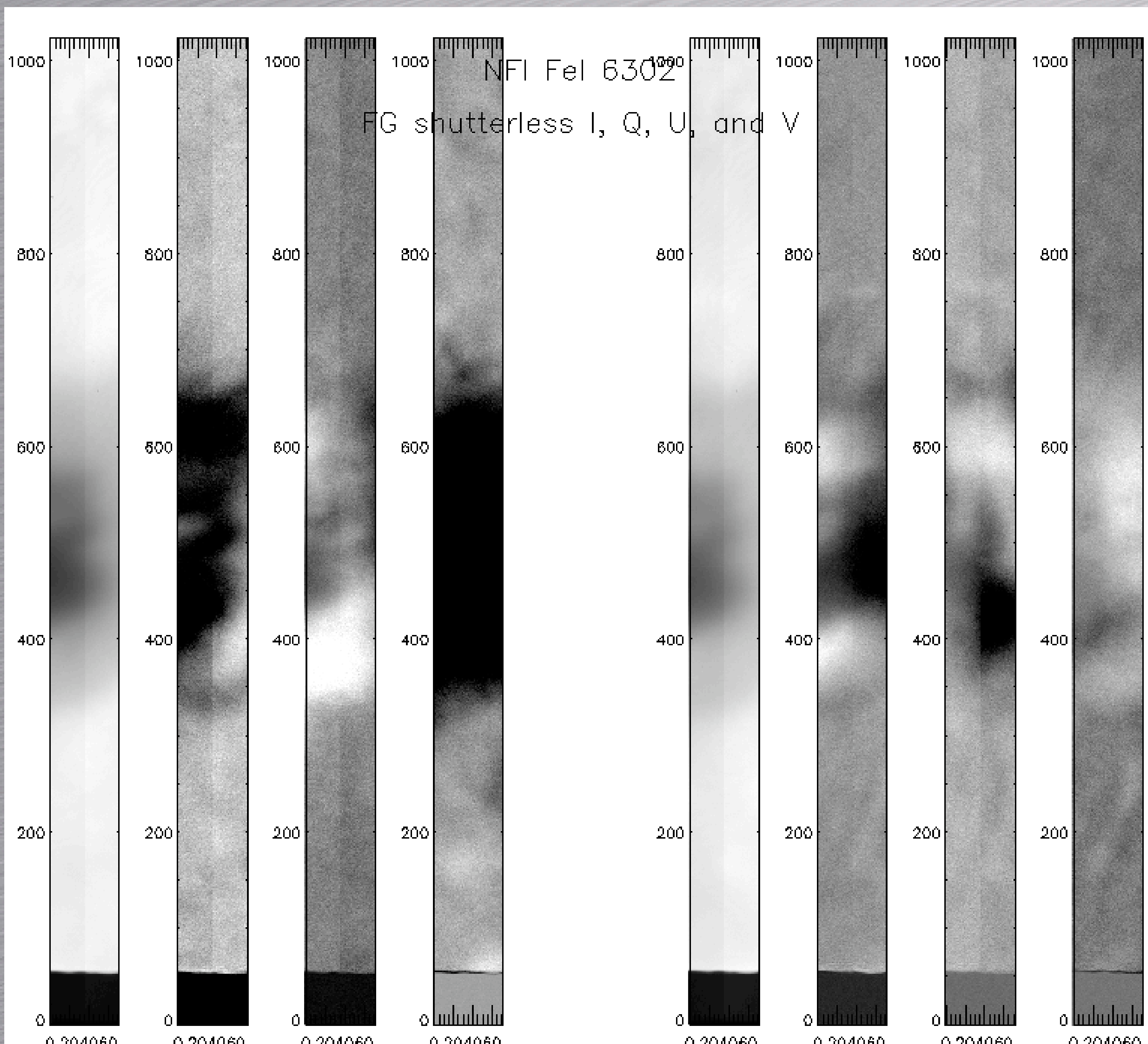
- Shutterless imaging with FOV restricted by focal plane mask
  - 0.1 sec exposure and readout time: IQUV all measured simultaneously
    - FOV = 8 x 164 for 0.08″ pixels, 16 x 164 for 0.16″ pixels
    - Processing in smart memories identical to that for SP, to make spatial maps of I, Q, U, and V
  - 0.2 sec exposure and readout time: I & Q or I & U, measured separately
    - FOV = 16 x 164 for 0.08“ pixels, 32 x 164 for 0.16″ pixels
    - Measure I & Q first, then I & U by shifting phase of exposure wrt Pol. Mod.
  - 0.4 sec exposure and readout time: I & V only
    - FOV = 32 x 164 for 0.08″ pixels
- Stokes Parameters using shutter
  - 0.4 sec exposures possible for V, 0.2 sec for Q & U
  - Additional noise sources due to time between frames & cross-talk between polarizations will appear

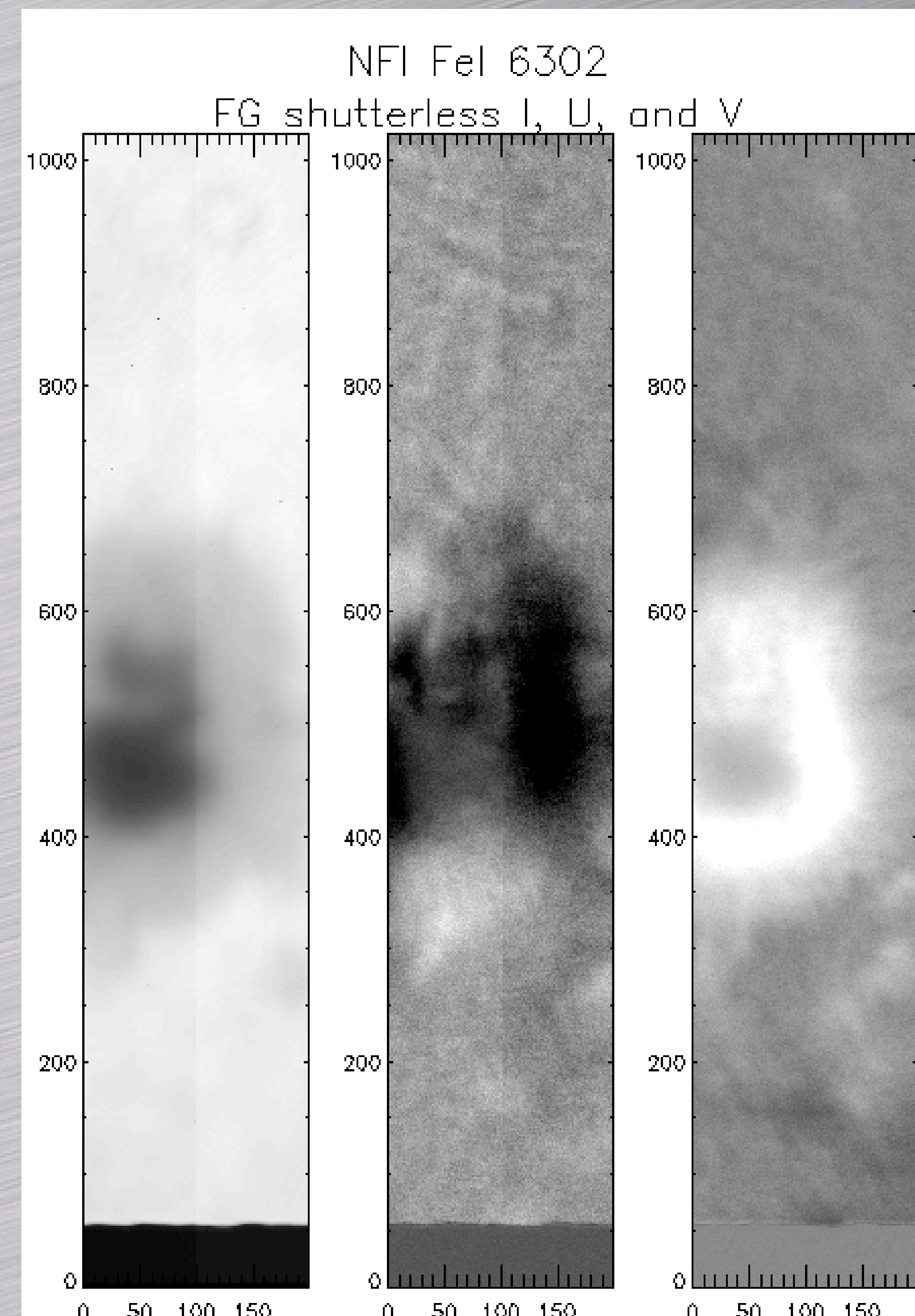
Shutterless (I, Q, U, V) & (I, U, V)

2004/08/20 01:01 UT

2004/08/20 01:01 UT

2004/08/20 01:03 UT





Assembled Tunable Filter

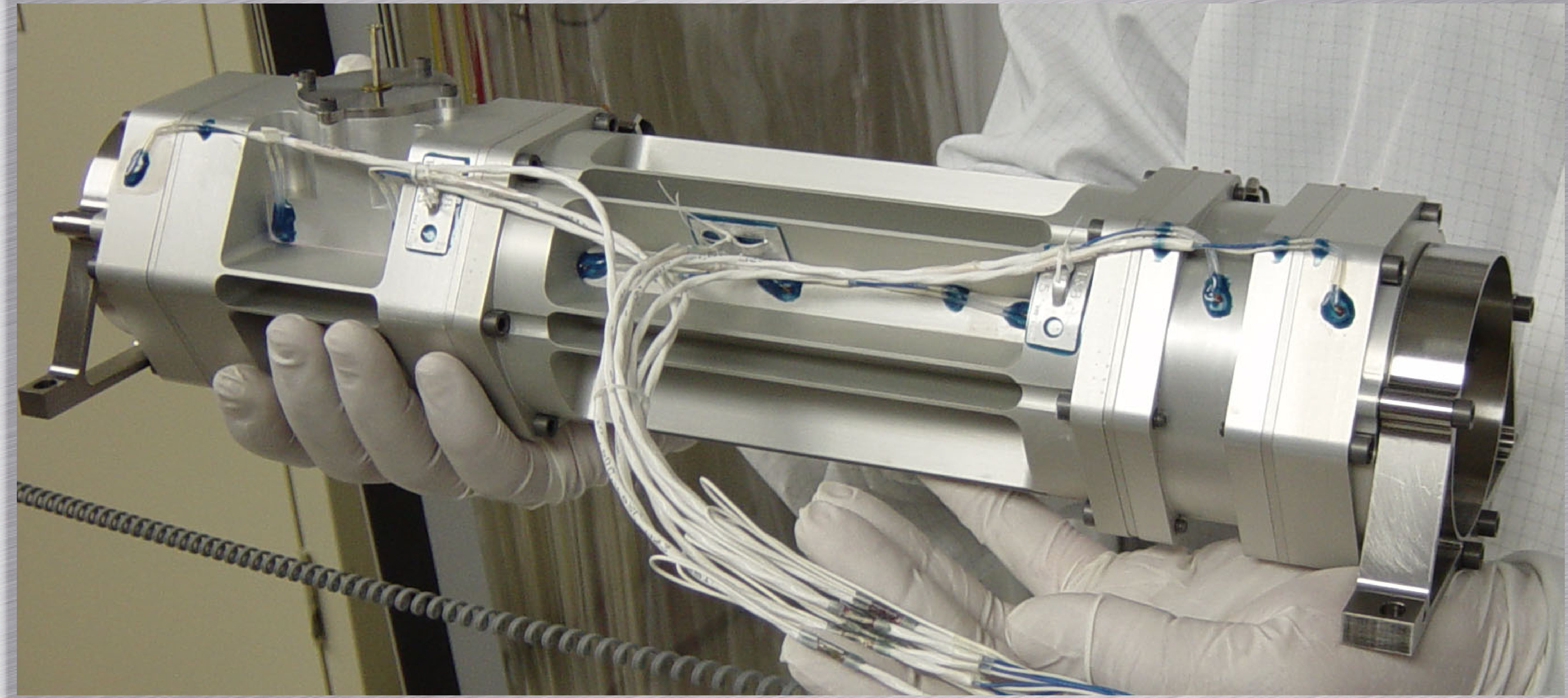
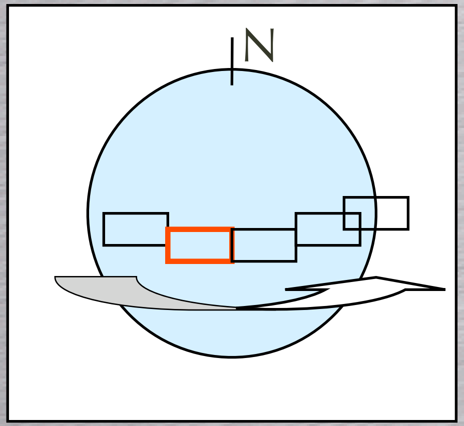


Image Stabilization System

- The SOT ISS consists of correlation tracker (CT) in FPP and tip-tilt mirror in OTA (CTM).
  - The CT is a separated system with its own special processor and 50 x 50 pixel CCD.
  - The correlation tracker target is an 11 x 11" region in the target FOV.
  - The laboratory measured stability is < 0.02" for a 30 second period
- Additionally the Solar-B attitude system tracks a target continuously at the local speed of the solar differential rotation.



Sequence Control and Compression

- Sequence control of observations is managed by observing tables in Mission Data Processor (MDP).
  - One table for filter observation, the other for SP observation
  - The table is the list of macro-commands for observables with time interval.
- FPP science data can be compressed in MDP
  - To reduce the data volume in telemetry
  - MDP has an ASIC chip for 12bit JPEG/DPCM
    - Pixel data is bit-compressed from 16 bit-pixel to 12 bit; 8 look-up tables
    - 12bit JPEG (DCT): lossy
      - ~3 bits/pixel for FG data
      - ~1.5 bits/pixel for SP data

      , when compression noise is comparable to photon noise level
    - 12bit DPCM: lossless, 6-8 bits/pixel
    - Compression ratio depends on images and required quality

Data Recorder and Data Rates

- Solar-B Data Recorder and Data Downlinks
  - Capacity: 8 Gbits
  - 5.6 Gbits for FPP data with assumption of ~70% allocation.
  - 4 Mbps high telemetry (X-band) downloads ~1.7 Gbits FPP data in one station pass (10 min duration).
- Allocated telemetry rate for FPP compressed data
  - Possible maximum rate ~1.3 Mbps (in nominal)
    ~1.8 Mbps (in SOT dominant)
    → ~70 min to occupy 5.6 Gbits in data recorder
    The rest of the time is in idle.
  - Rate averaged per day
    25.5 Gbits (3.2 Gbytes) in a day, assuming 15 downlinks in a day
    or ~300 Kbps

Example Observation

Goal: The magnetic/dynamical nature of micro-flare associated small emerging fields in AR.

Telemetry: 300 Kbps continuously for several days

- ***SP observation***
  - Fast mapping, 80″ wide scanning, NS size = 80″, 0.32″ resolution
  - One map completed every 15 min
  - Data size: 229 Kpixel every 3.6 sec.
  - Telemetry: 96 Kbps with 1.5 bits/pixel compression.
- ***FG observation***
  - G-band, 3 wavelengths in Hα, Longitudinal magnetogram, Dopplergram, repeated every ~ 45 seconds.
  - 80″x 80″ FOV, 0.08″ resolution for G-band and magnetogram, 0.16″ for Hα and Dopplergram
  - Data size: 3.25M pixel every 45 seconds
  - Telemetry: 222 Kbps with 3 bits/pixel compression

Example Observation-Spicules

JOP 2b: by DePontieu (SOT/FPP), Landi (EIS), Weber (XRT)

Goal: Opposite polarities and reconnection at footpoints of spicules, and their impact on the transition region and corona

Telemetry:~360 Kbps total for 4 hours on each target region

- ***SP observation***
  - Normal map mode, 1.9 x 64" FOV, 60 second cadence
  - 360 Kpixel every 5.0 sec, 72 Kbps at 1bit/pixel compression
- ***FG observation***
  - Longitudinal magnetogram & Dopplergram in both 630.25 (photosphere) and 517.3 (low chromosphere) & 2 wavelengths in H-alpha every 30 sec
  - 64 x 64" FOV, 0.08" pixels, 215 Kbps at 1 bit/pixel compression
- ***EIS observation***
  - One wide slit exposure for coalignment, 5 x 70 " rasters of spectra
- ***XRT observation***
  - LogT = 6.1 images at full resolution, 128 x 128 " FOV, 30 second cadence

See the complete JOP description including the other instruments' details at

http://hea-www.harvard. edu/solarb/documents/MODA/

SOT/FPP Science Plan

Science objectives

A. The Origin and Dynamics of the Solar Magnetic Field

A.1 Large-scale active region structure and dynamics
A.2 Sunspot formation, dynamics, and decay
A.3 Small-scale magnetic fields

B. Magnetic Modulation of Solar Luminosity and Irradiance

B.1 Active region irradiance contributions
B.2 Photospheric network irradiance contributions
B.3 Physics of small-scale magnetic element irradiance
B.4 Chromospheric irradiance variations

C. Heating of the Upper Solar Atmosphere

C.1 Coronal heating
C.2 Spicules, jets, and microflares
C.3 MHD waves and atmospheric seismology
C.4 Connectivity of photospheric magnetic field to coronal structures

D. Flares and Transient Phenomena

D.1 Magnetic topology and evolution in flares
D.2 Prominences, filaments, and transient initiation
D.3 CME initiation and development
D.4 Photospheric and chromospheric response to flares

Each objective has one or more “Observing Programs” or “JOPs” assigned to it.

SOT/FPP Science Plan

Sample Abbreviated Observing Plan

A.1.a. Active region formation: The “flux history” of active regions

Scientific objective and requirement. The primary objective of this program is to measure the magnetic flux emergence and decay rates of one or more active regions. This requires vector magnetic field maps of entire active regions (3 – 5 arcmin field-of-view) over time periods of several days. Etc…

Target selection and FOV. The targets must be emerging active regions of moderate to large size on the eastern hemisphere within 60º longitude of the central meridian. This allows tracking of the active region over an area on the disk without excessive line-of-sight angles to the magnetic field. The FOV must encompass the entire active region. Minimum requirement: 2048x2048 center region of BFI/NFI for 164”x164” FOV.

Spatial resolution. 0.05 – 0.08” spatial resolution in BFI/NFI filtergrams. Chromospheric filtergrams can be binned 2x2 for 0.16”. SP vector magnetogram resolution no more than 0.5” over entire region; 0.3” for sub-region scans of sunspot formation and decay.

Duration and cadence. The active region should be tracked across the disk for at least 10 days. Cadence for filtergrams is one per minute. Cadence for vector magnetic field mapping is one per orbit (approx. 90 minutes).

SOT/FPP Science Plan

Sample Abbreviated Observing Plan (cont.)

A.1.a. Active region formation: The “flux history” of active regions

SOT/FPP Observations.

Emergence phase

NFI: Fe I 630.25nm Stokes-V magnetogram. Cadence **1min**. 1x1bin: 0.08” pixels.
Fe I 557.6nm dopplergram. Cadence 2 min. 1x1 bin: 0.08” pixels.
Hα 656.3nm filtergram. Cadence 2 min. 2x2 bin: 0.16” pixels.

BFI: Gband 430.5nm filtergram, cadence 1 min. 1x1bin: 0.05” pixels.

SP: Fast map mode. 164”x320” (full slit scanned over 320”). 1000 spatial steps at 0.32” per step. Cadence 42 min. Repeat once per orbit.

Tracking phase

NFI: Fe I 630.25nm Stokes-V magnetogram. Cadence **5 min**. 1x1bin: 0.08” pixels.
Fe I 557.6nm dopplergram. Cadence **5 min**.

etc.

XRT Observations.

EIS Observations.

Supporting Observations. Other space instruments, ground-based support, *etc.*

Database/Analysis requirements.

SOT/FPP Science Plan

Status of the SOT/FPP science plan

- Outline/basic structure is complete.
- Current format is Microsoft Word document.
- A few observing plans/JOPs completed.
- ***Many others need to be defined and completed***.
- Future:
  - Web-based "Wiki" document will be installed at LMSAL by January 2006.
  - Allows modification via web-browser by any and all Investigators and Collaborators.
  - SOT/FPP Science Team Meeting in April at NAOJ