Ground-based Solar Optical Observations

A Survey of Present and Future Capabilities

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Survey of Current Capabilities

Bias: imaging and polarimetry
Excluded: full-disk patrol, networks (helioseismic, space-weather), coronographs

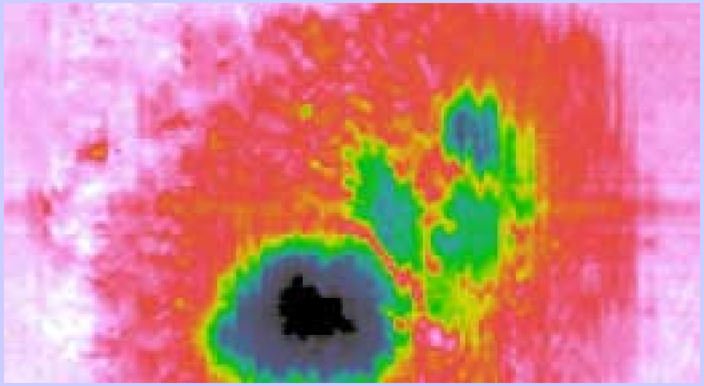
- **KPVT**: Full-disk images and magnetograms
- **McMath Pierce**: 1.52m heliostat all-reflecting telescope
- **VTT**: 0.7m vacuum heliostat reflector, adaptive optics
- **THEMIS**: 0.9m f/16.7 helium pressurized, domed reflector
- **Big Bear:** 0.65m vacuum domed reflector
- **"SVST":** 0.48m f/45 vacuum turret refractor, adaptive optics
- **DST:** 0.76m f/72 vacuum turret reflector, adaptive optics
- **DOT:** 0.45m f/4.4 open-air reflector, speckle imaging

McMath-Pierce

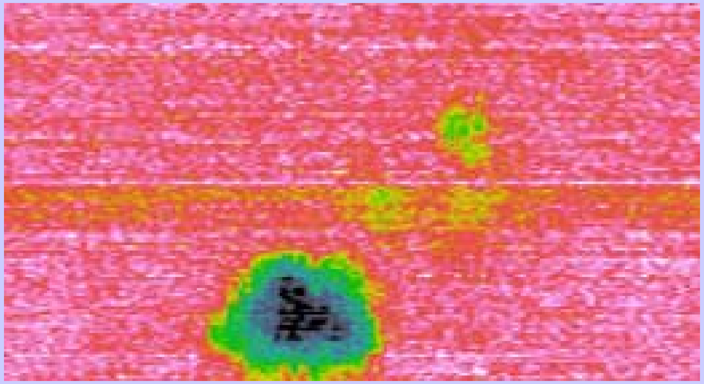
Kitt Peak, Az.

- 1.52m heliostat all-reflecting off-axis
- Commissioned: Sputnik-era
- Main goal: IR imaging and spectroscopy
- Strengths: large aperture, all-reflecting
- Weaknesses: site, telescope seeing
- Instruments:
  - 0.3 to 20 µm FTS
  - ZIMPOL I visible polarimeter
  - 1 to 5 µm imager and polarimeter
  - 1.56 µm imaging vector polarimeter
  - 6 to 15 µm imager (NASA)
  - 12 µm vector polarimeter (NASA)

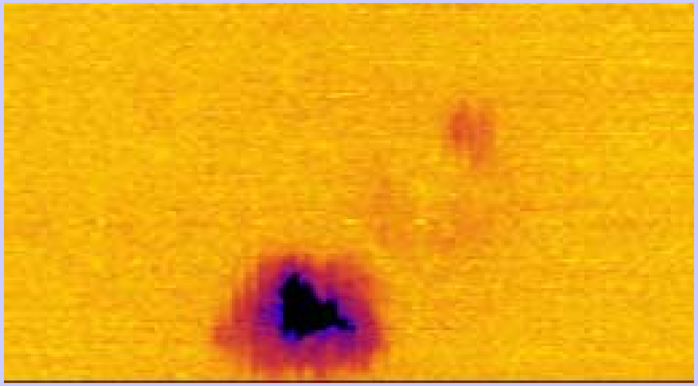
McMath 4 μm IR Imaging Example: Acid Rain



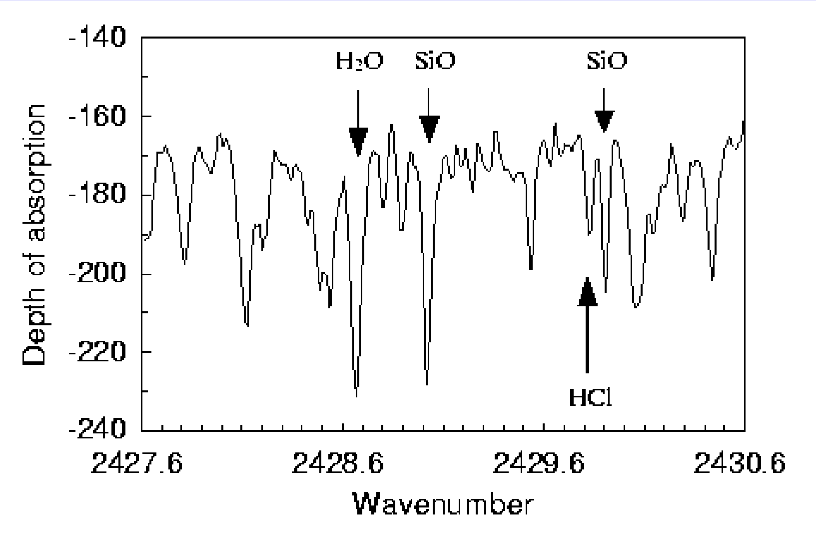
IR Continuum



HCl Molecular Line

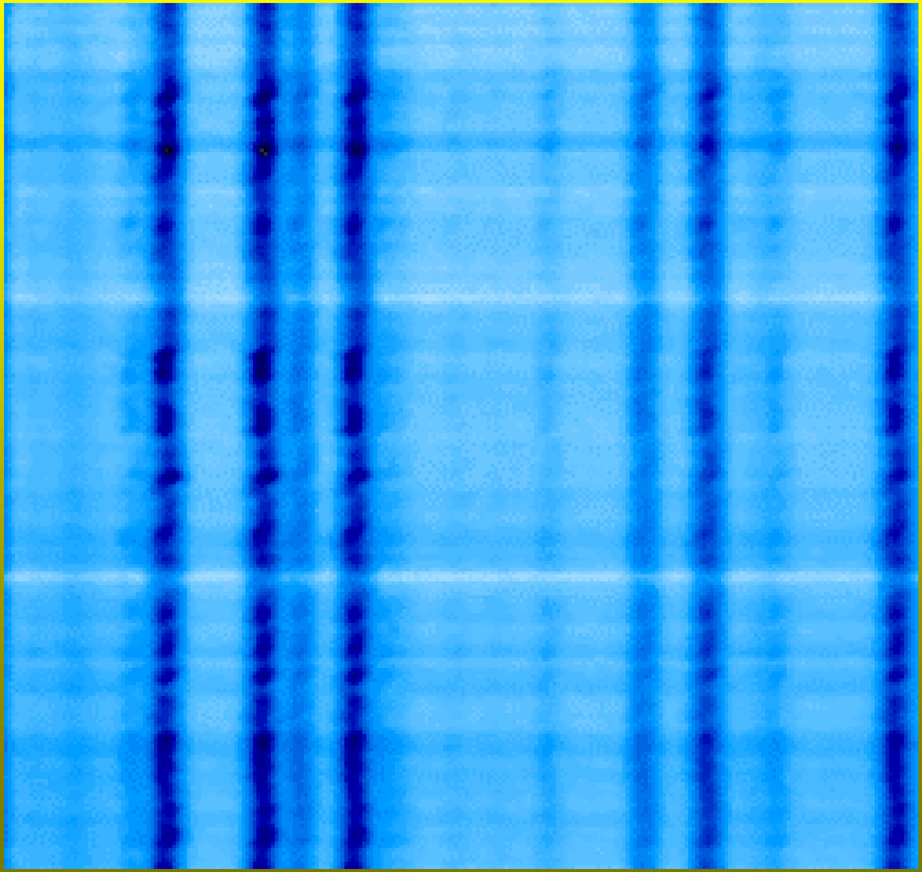


H_20 Molecular Line



Courtesy C. Keller

CO 4.67 μm IR Lines: McMath-Pierce FTS



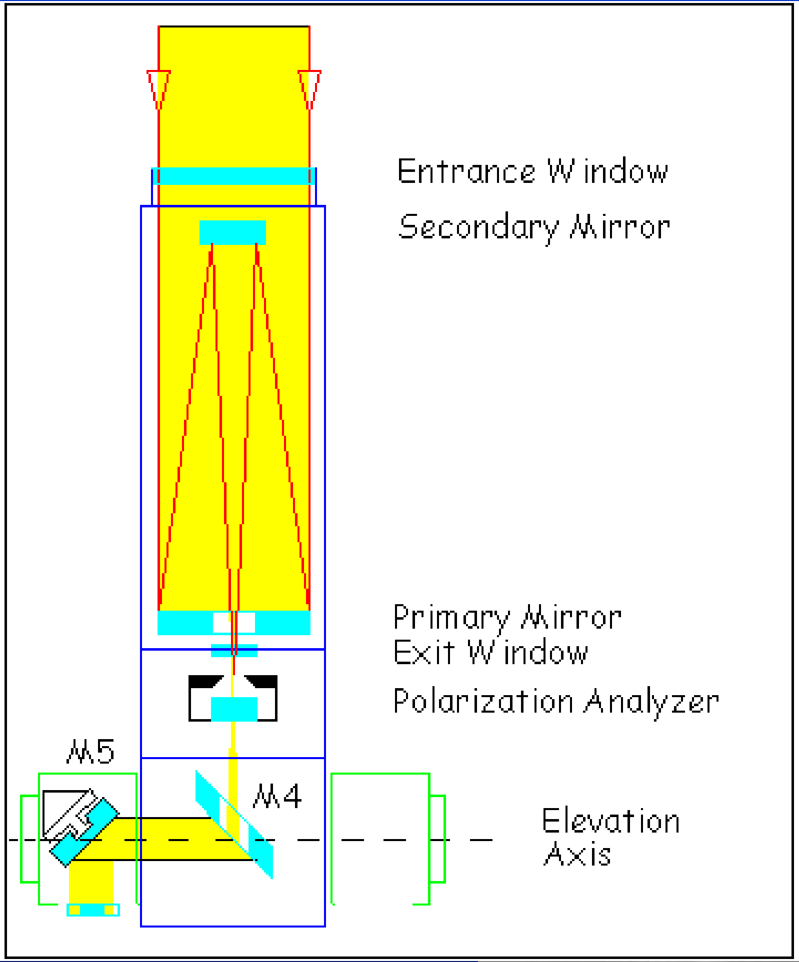
Courtesy H. Uitenbroek

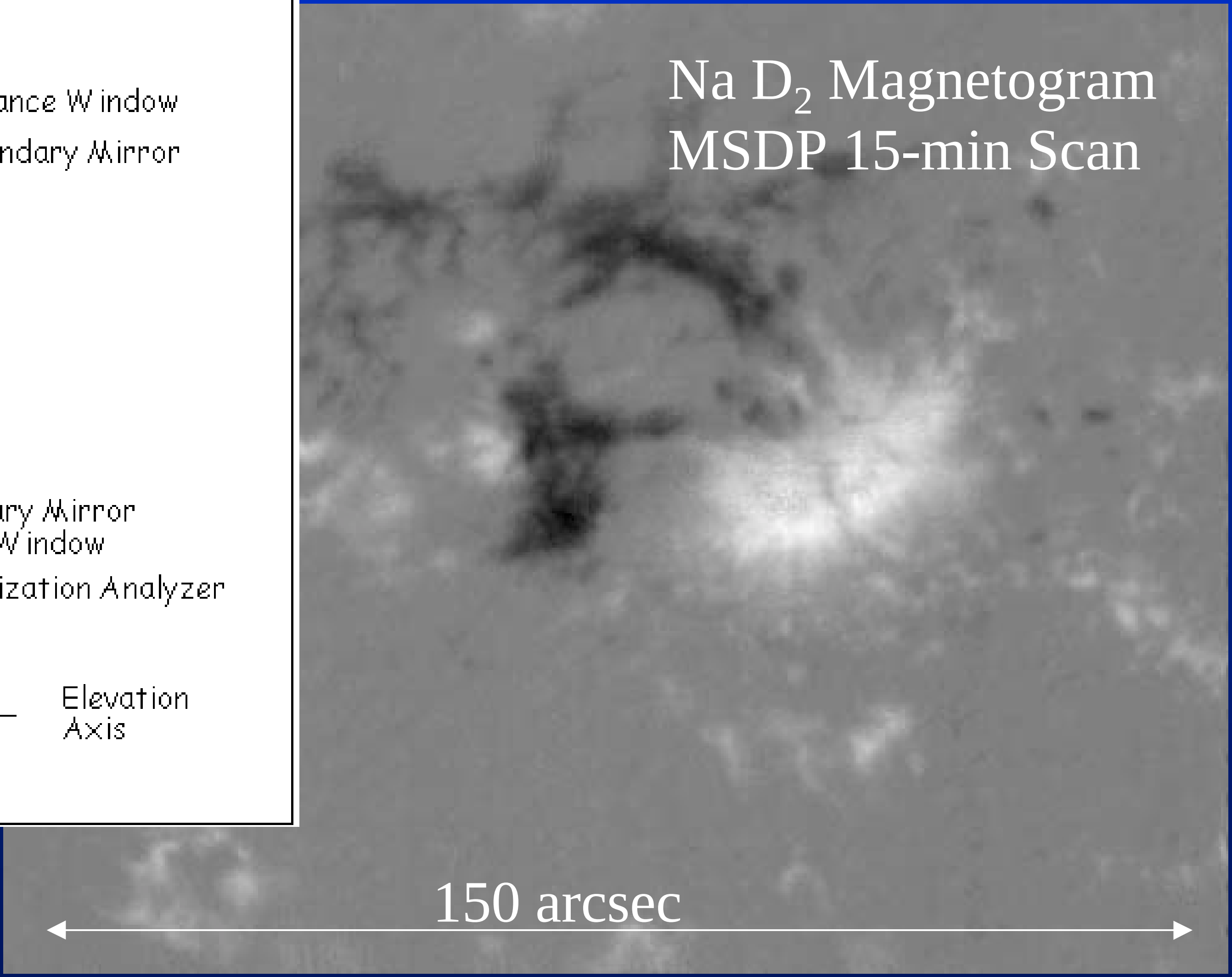
THEMIS

Tenerife, Esp.

- 0.9m f/16.7 helium pressurized reflector
- Alt-az integrated dome mounting
- Commissioned: March 2000
- Main goal: high precision spectropolarimetry
- Strengths: good site, low instrumental polarization
- Weaknesses: vertical optical bench/complex optical paths
- Instruments:
  - MTR: multi-line spectroscopy
  - MSDP: double-pass imaging spectrometer
  - IPM: birefringent/Fabry-Perot imaging filter system

THEMIS

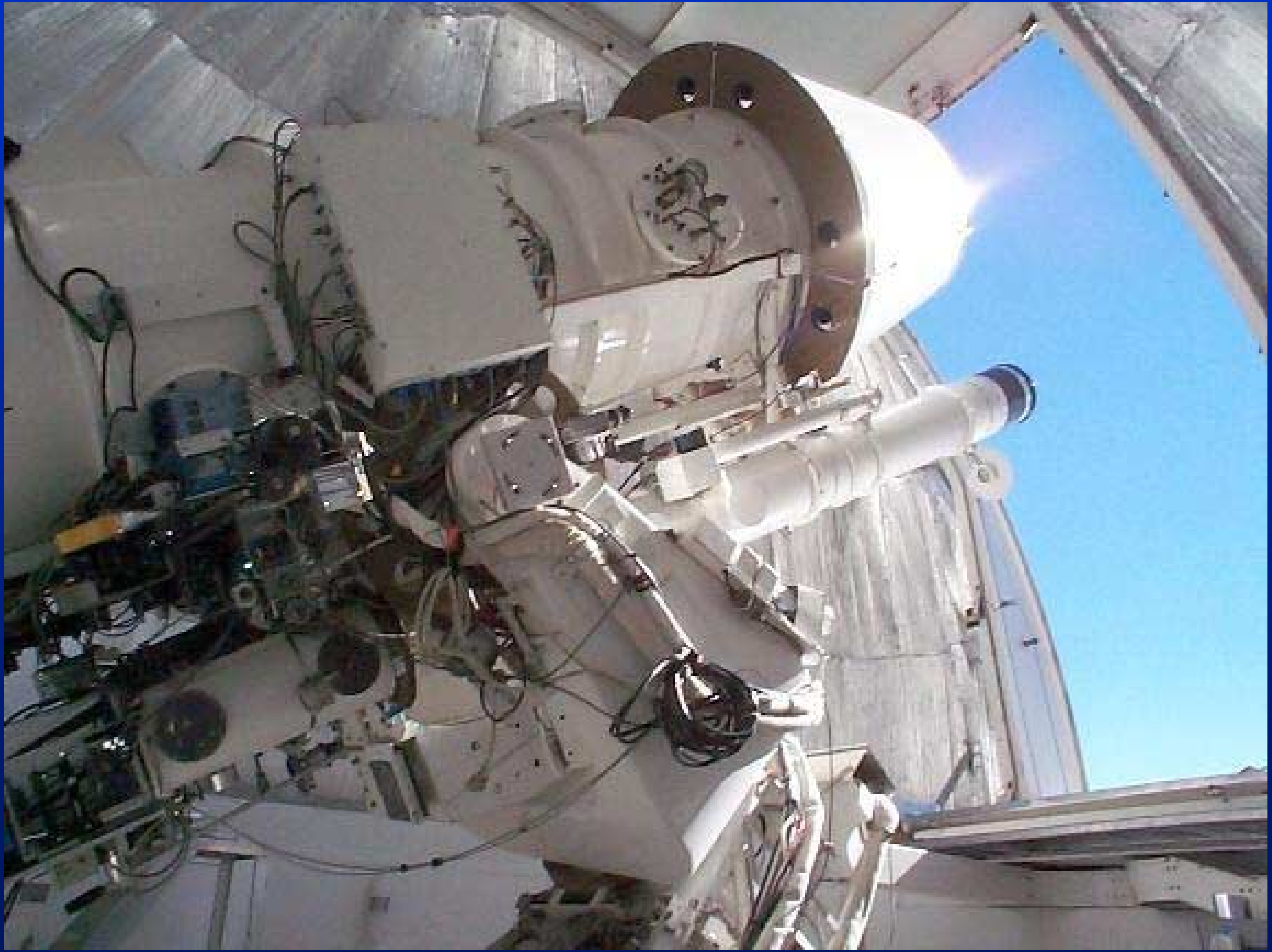

Entrance Window
Secondary Mirror
Primary Mirror
Exit Window
Polarization Analyzer
M5
M4
Elevation Axis

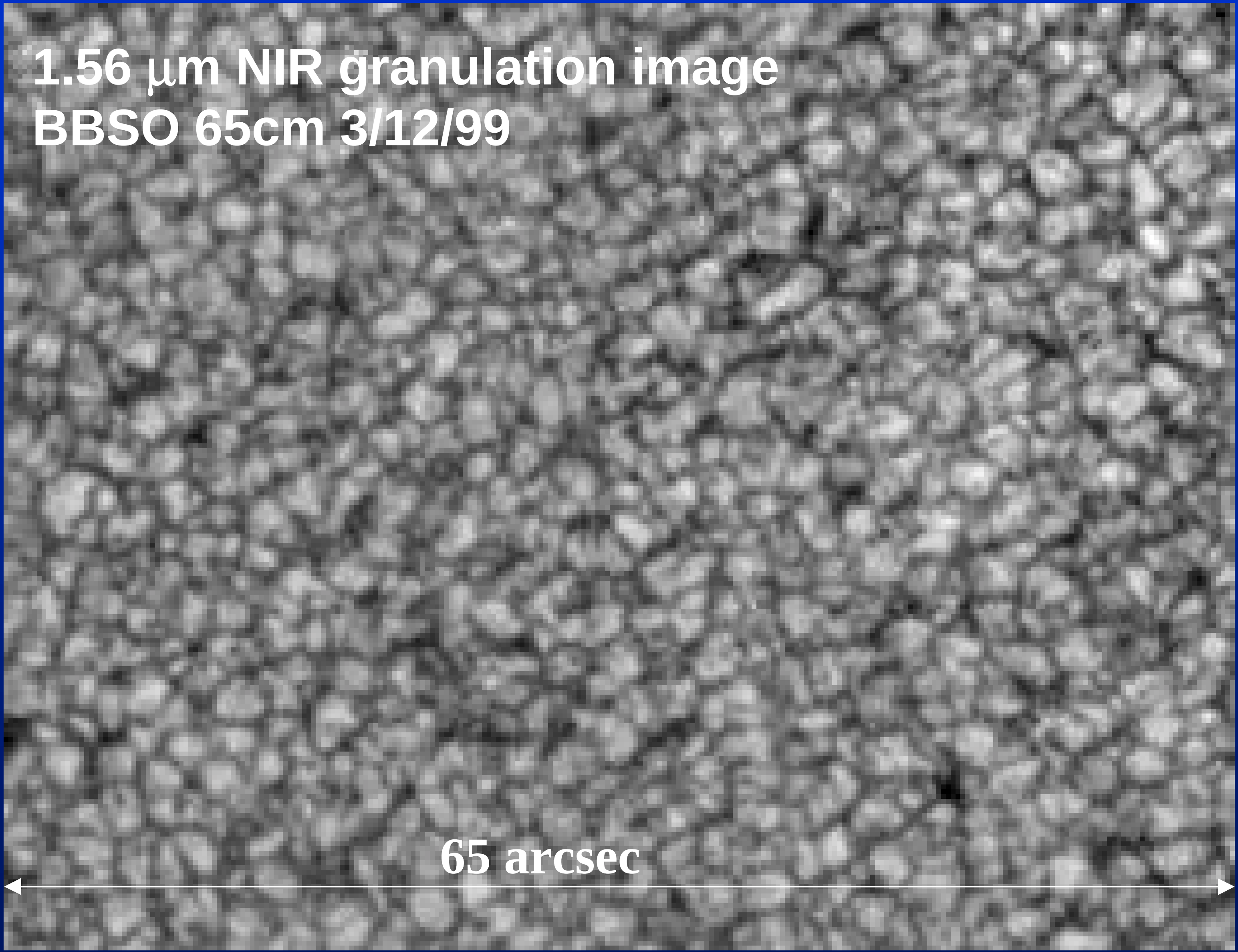

Na D_2 Magnetogram
MSDP 15-min Scan
150 arcsec

Big Bear
Solar Observatory
Big Bear, Ca.

- 0.65m vacuum reflector
- Equatorial mount
- Commissioned: 1969
- Main goal: high resolution imaging and magnetograms
- Strengths: very good site, low instrumental polarization
- Weaknesses: dome seeing, instruments on telescope
- Instruments:
  - Video magnetograph
  - Birefringent narrow-band tunable filter
  - 0.2m full-disk Hα telescope

Big Bear



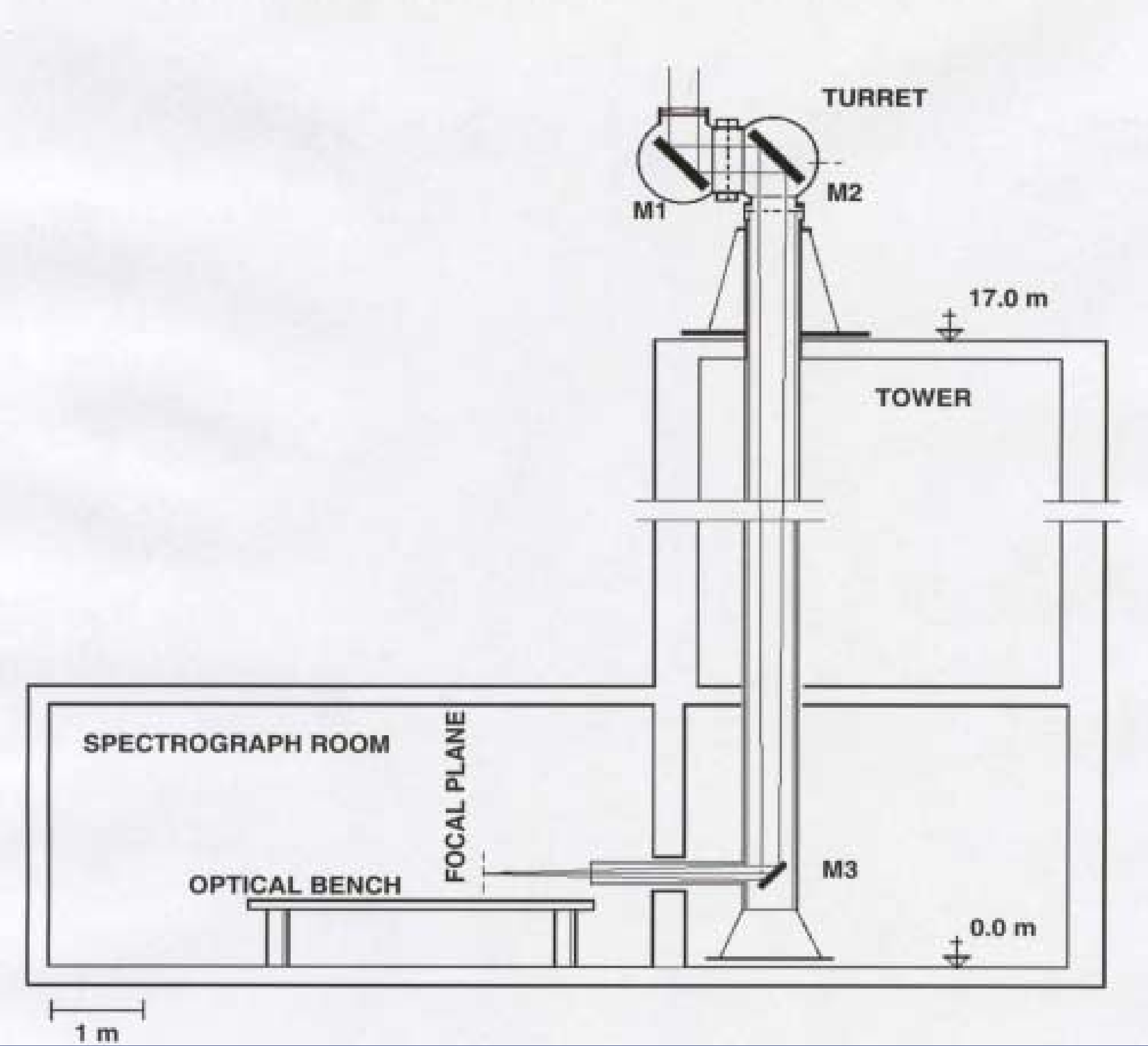

1.56 μm NIR granulation image
BBSO 65cm 3/12/99
65 arcsec

Swedish Vacuum Solar Telescope

La Palma, Esp.

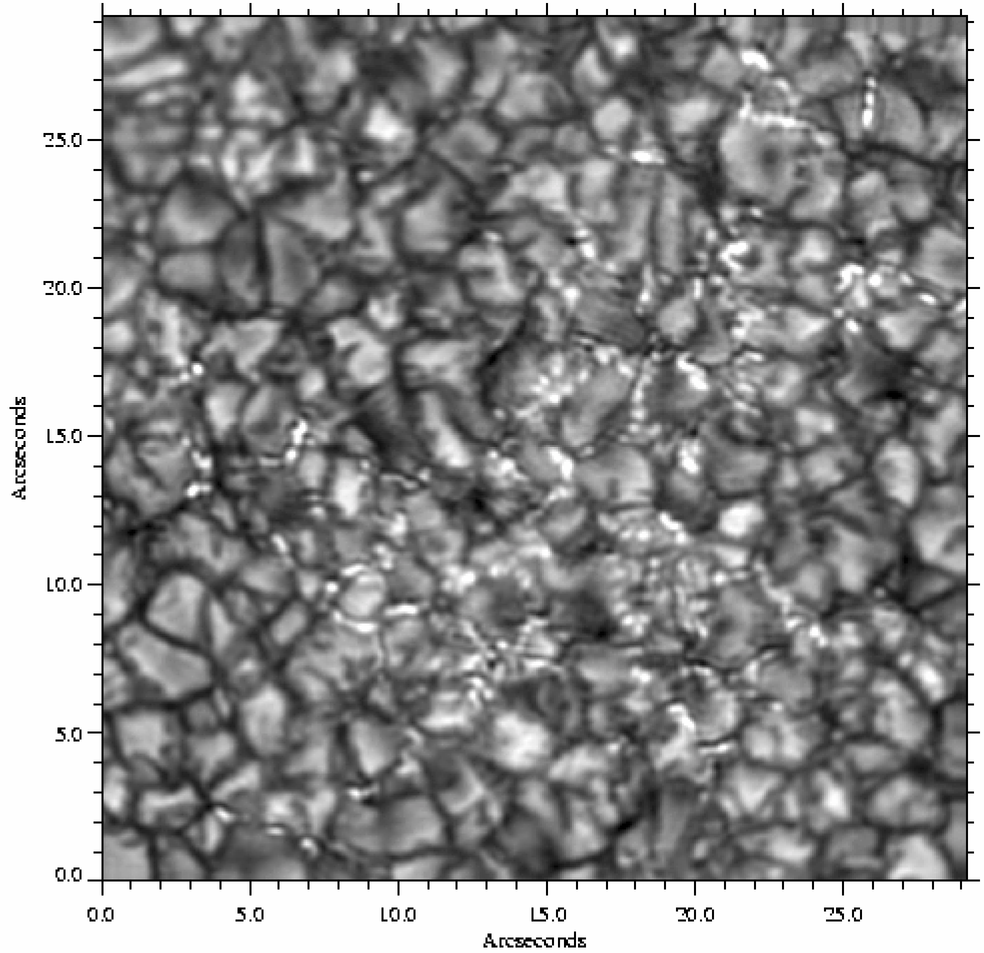
- 0.48m f/45 vacuum refractor
- Alt-az turret mount
- Commissioned: 1986
- Decommissioned: 2000
- Main goal: high resolution imaging
- Strengths: excellent site, simple optical paths and lab area
- Weaknesses: none – well, okay: image rotation, inst. polarization
- Instruments:
  - 3m Littrow spectrograph
  - SOUP: birefringent tunable narrow-band imaging filter
  - La Palma Stokes Polarimeter
  - Wide-band imaging filters (G-band, Ca II, etc.)

SVST
Optical Layout

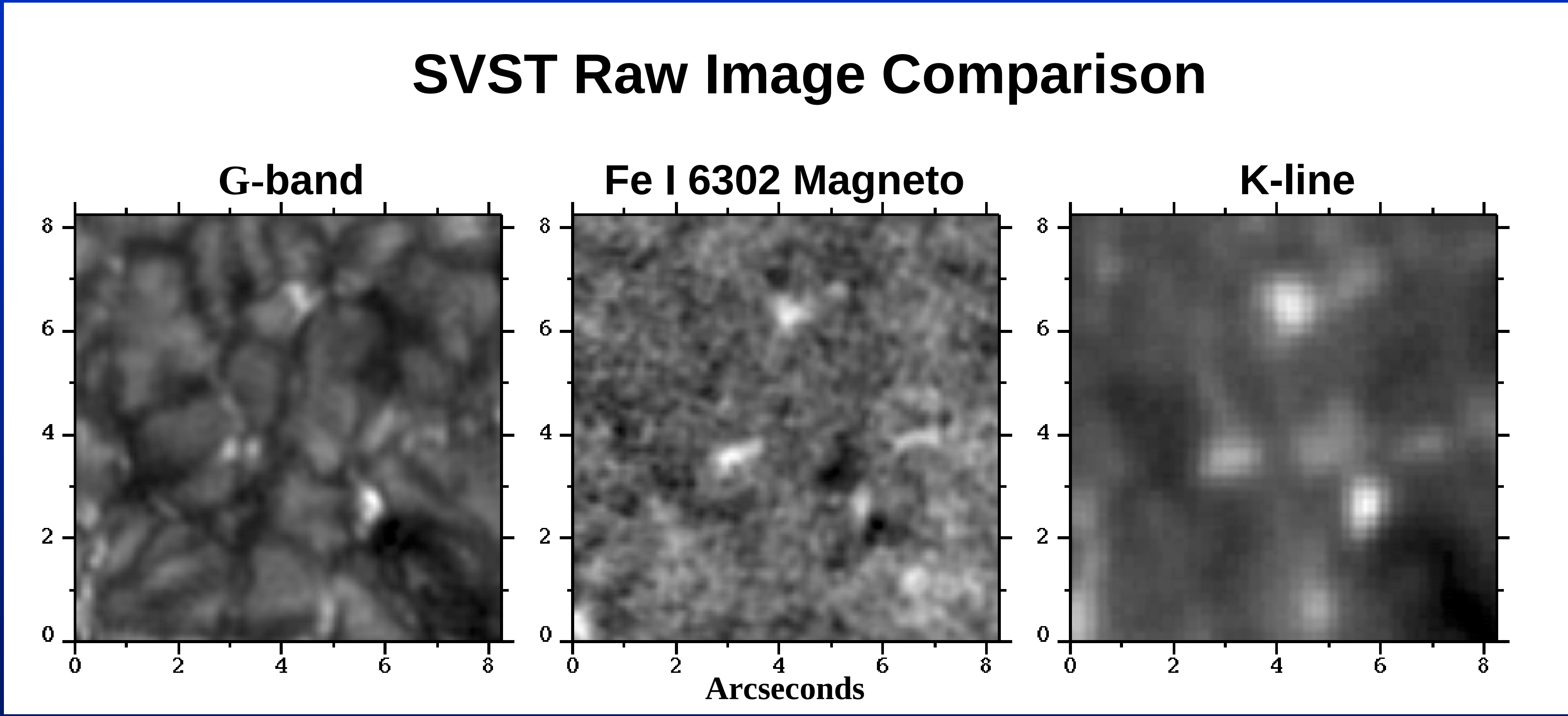


SVST Phase Diversity Imaging

SVST 05-Oct-95 11:08 UT 4305A G-band Image



SVST


SVST Raw Image Comparison
G-band
Fe I 6302 Magneto
K-line
0
2
4
6
8
Arcseconds

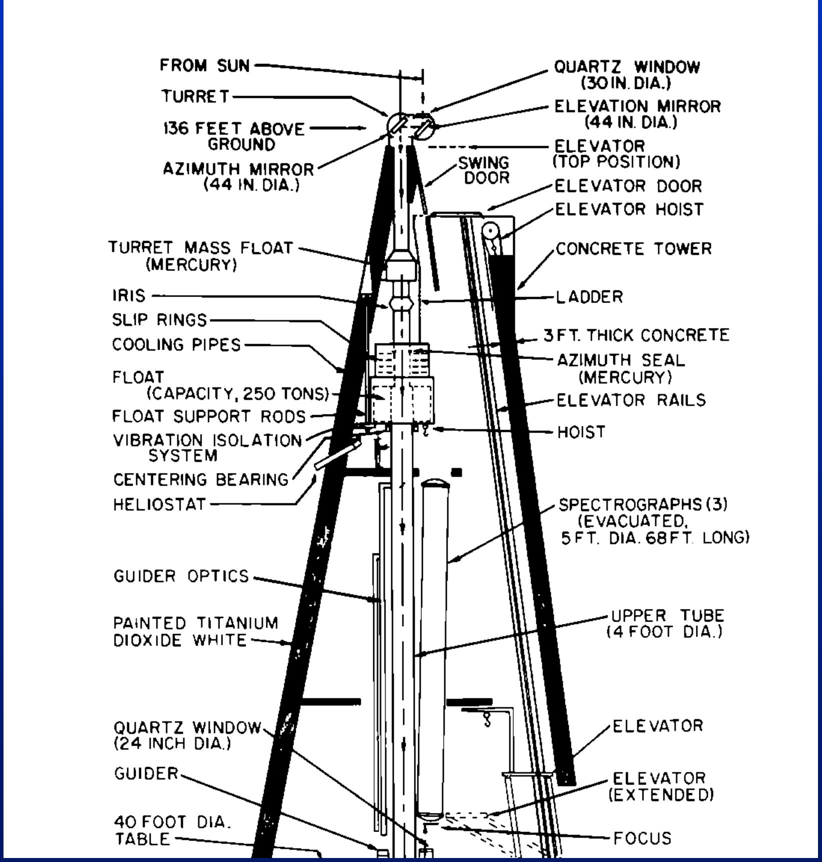
Dunn Solar Telescope

Sacramento Peak, NM

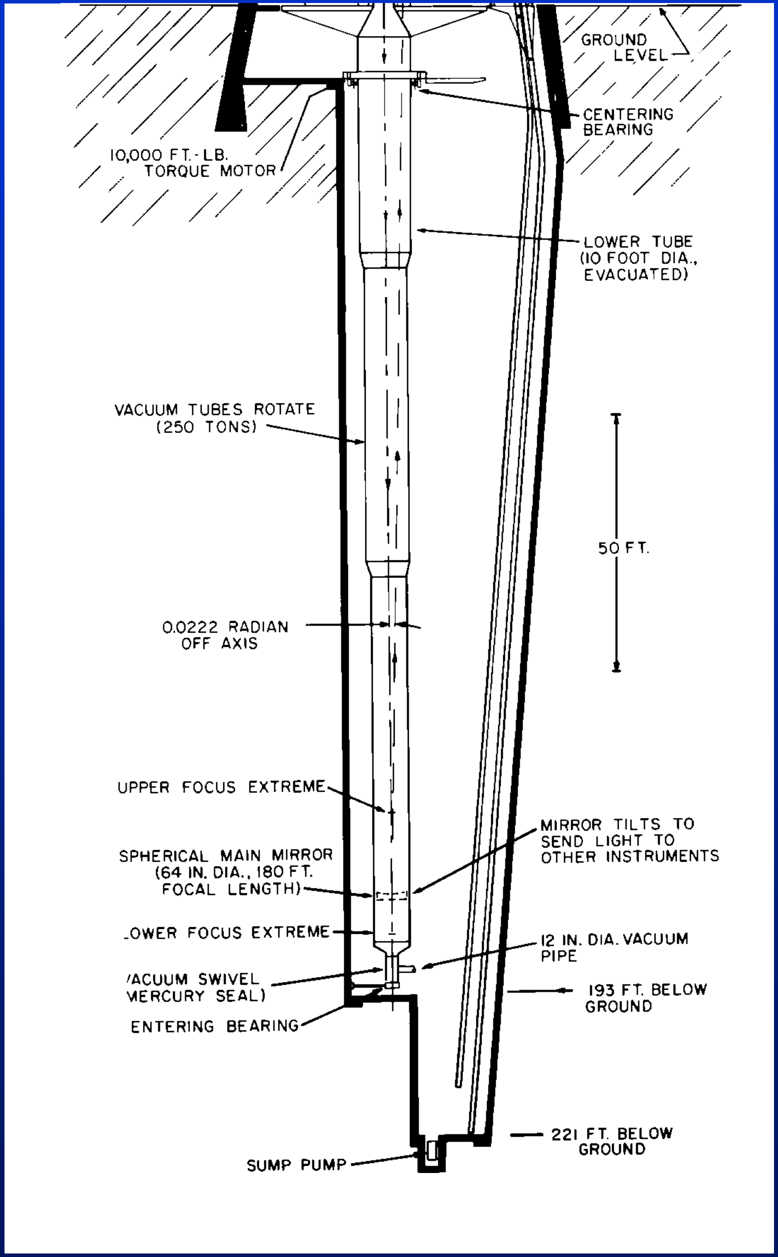
- 0.76m f/72 vacuum reflector
- Alt-az turret mount
- Commissioned: 1972
- Main goal: high resolution imaging and polarimetry
- Strengths: good site and design, adaptive optics
- Weaknesses: complex instrumentation
- Main Instruments:
  - Advanced Stokes Polarimeter: spectropolarimeter
  - UBF: birefringent tunable narrow-band imaging filter
  - Wide-band imaging filters (G-band, Ca II, etc.)

DST

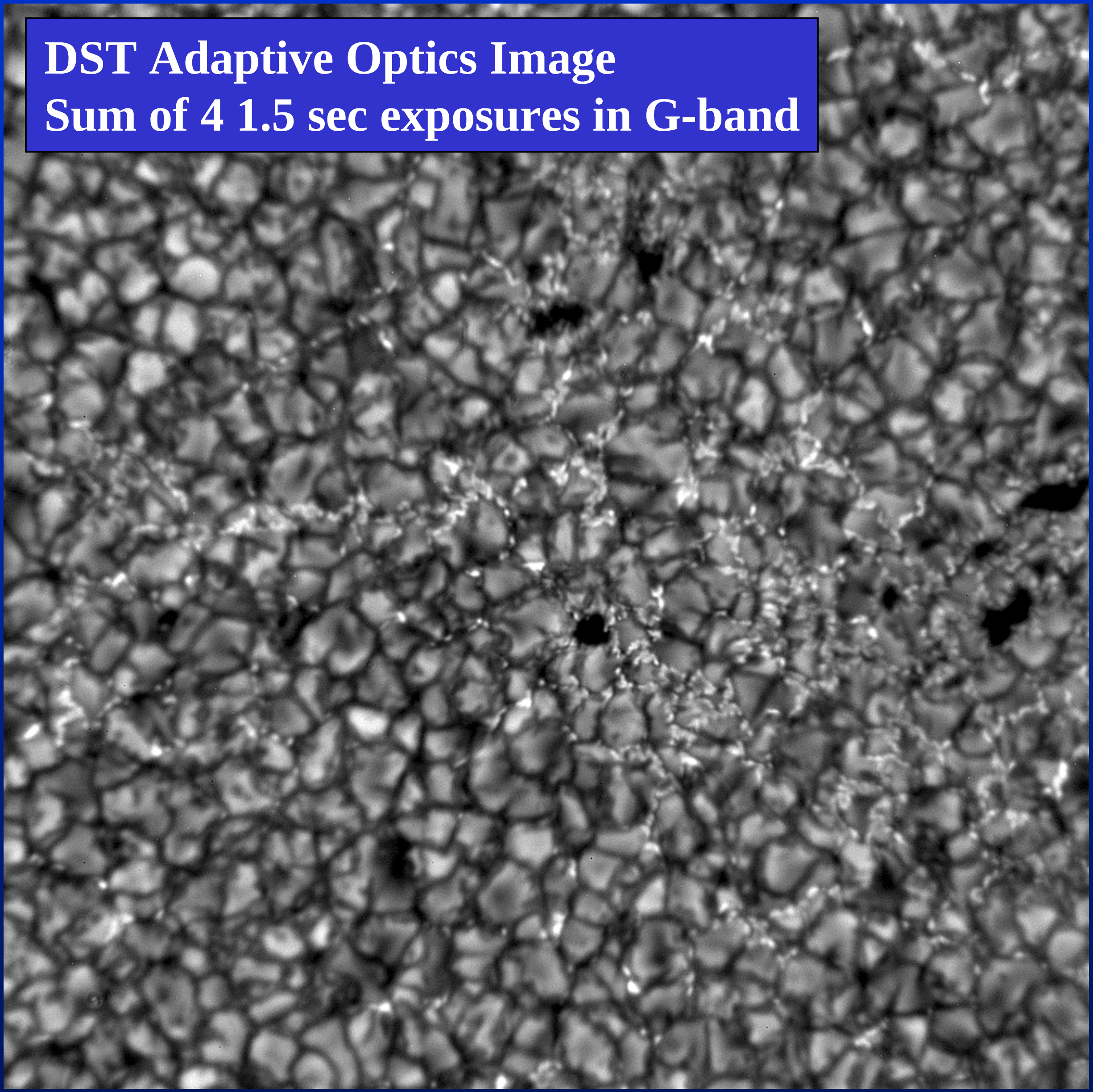
Optical Layout

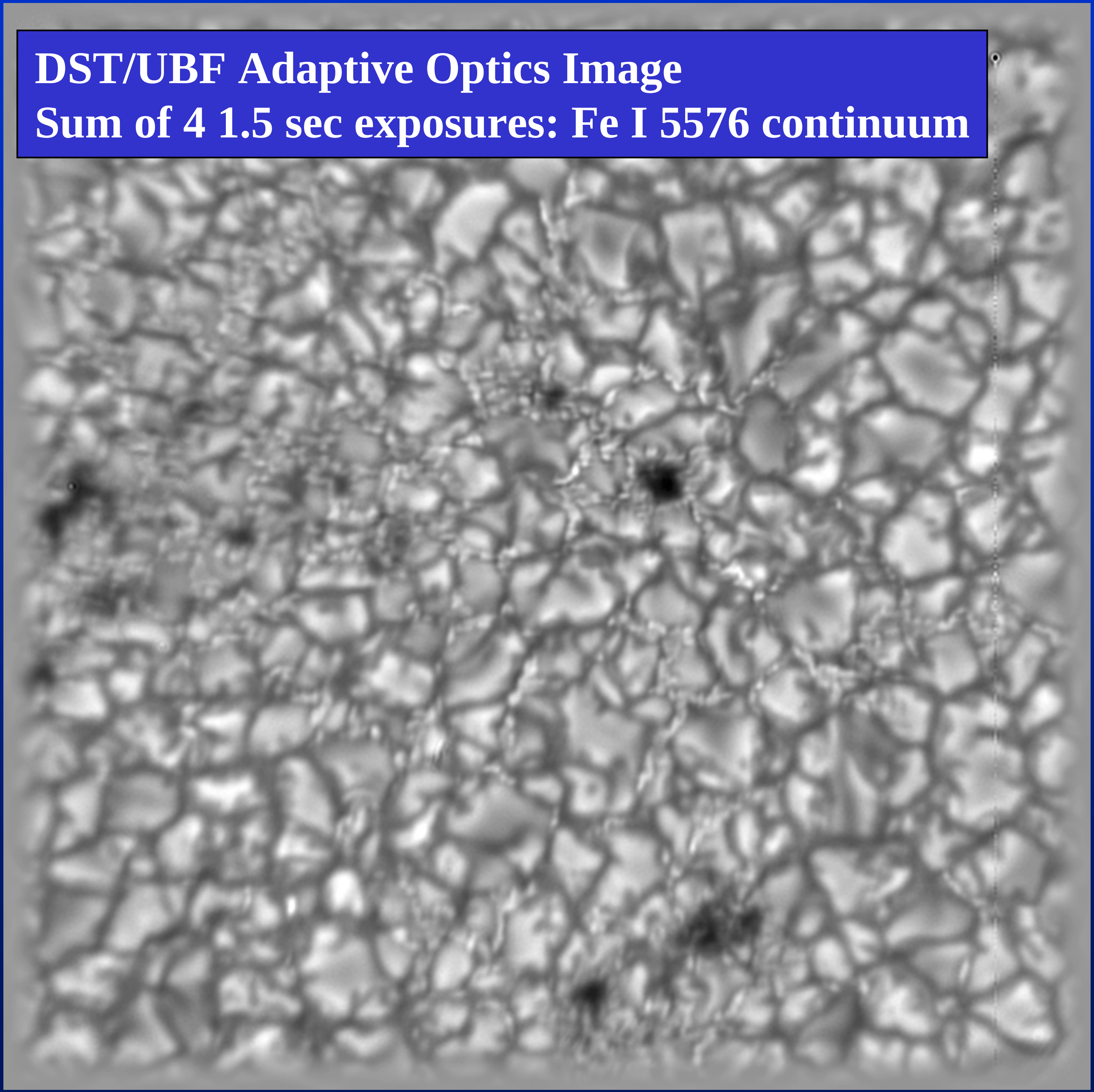


Above Ground



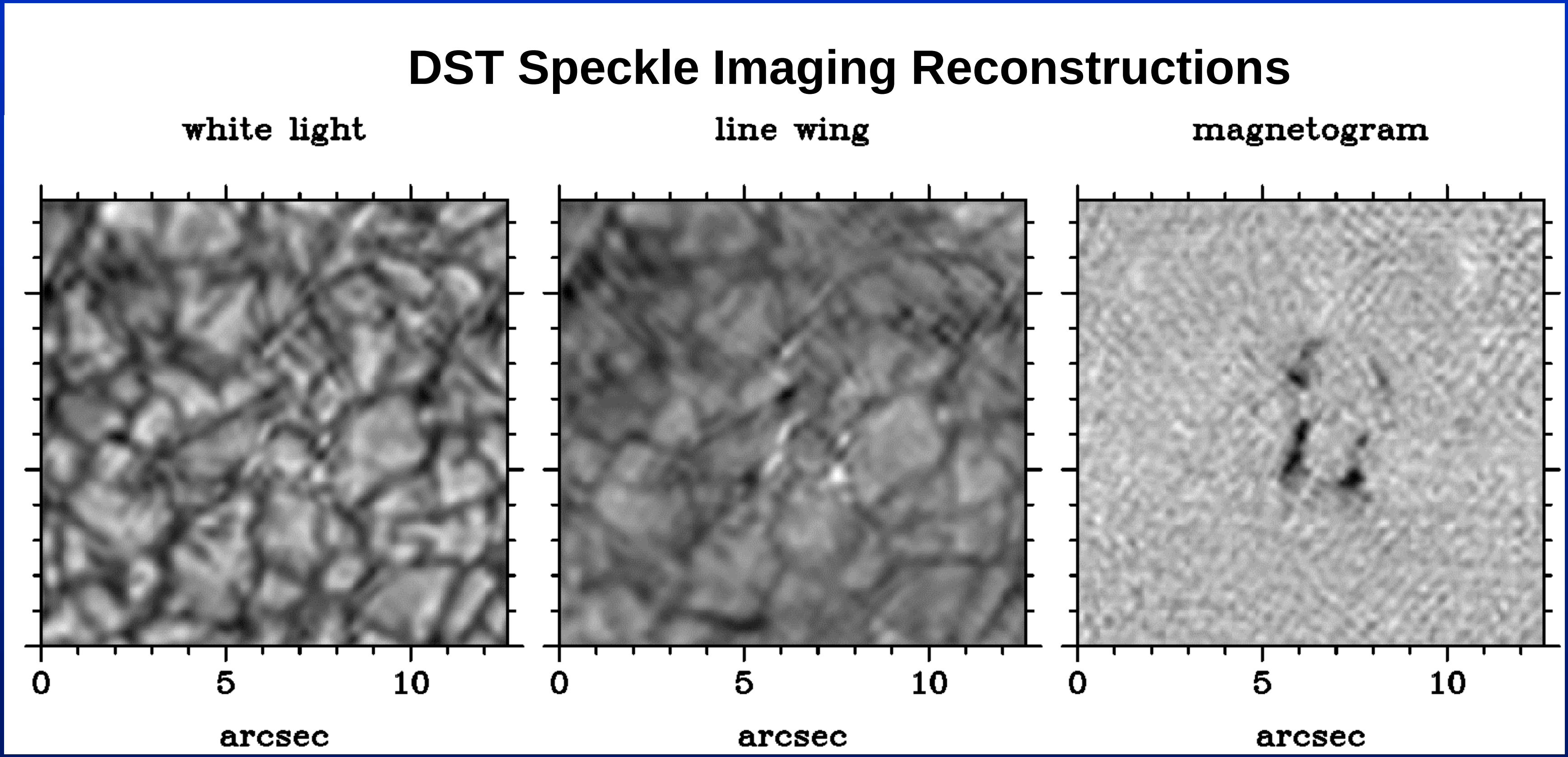
Below Ground


DST Adaptive Optics Image
Sum of 4 1.5 sec exposures in G-band


DST/UBF Adaptive Optics Image
Sum of 4 1.5 sec exposures: Fe I 5576 continuum

solar and astrophysics lab

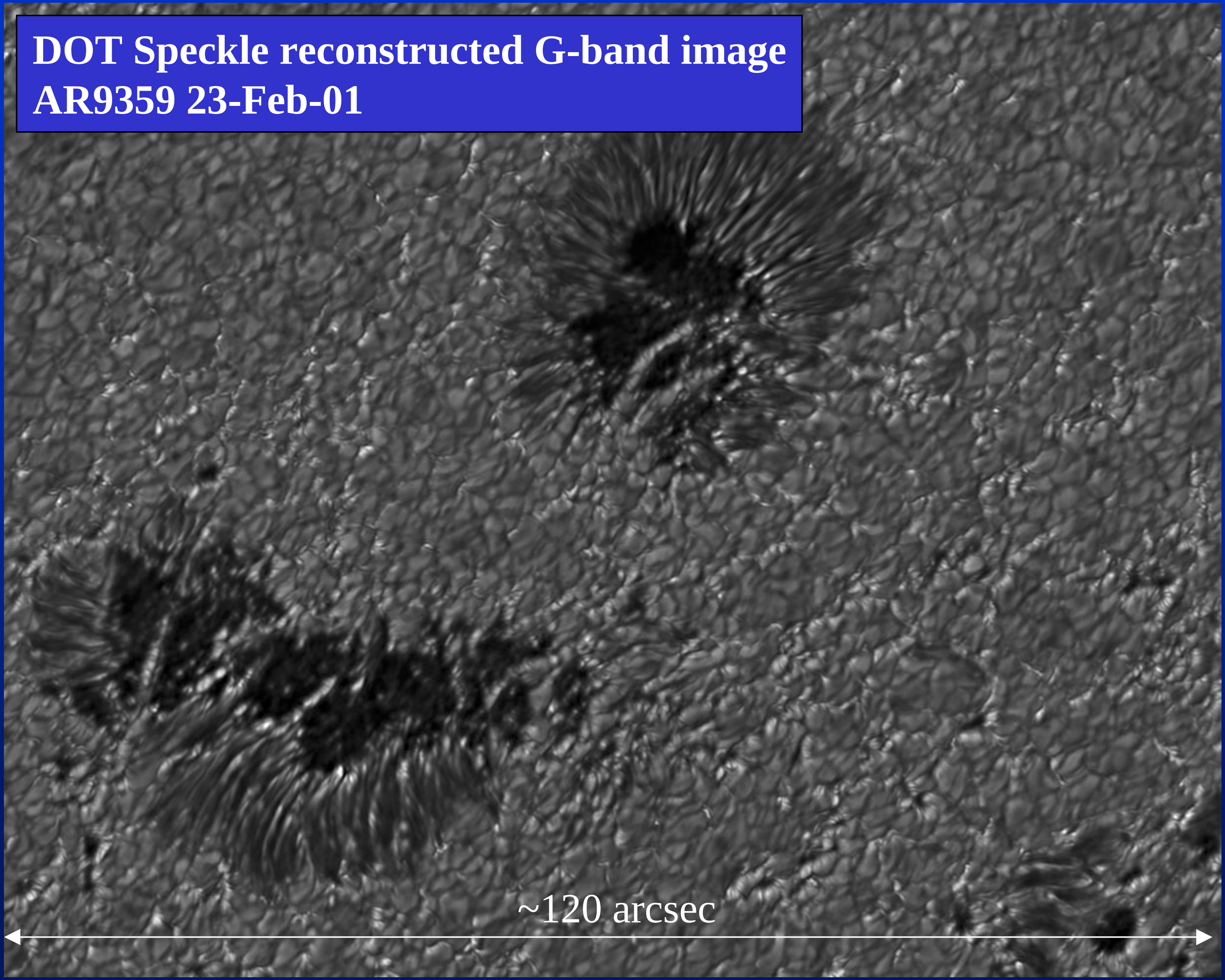
DST



Dutch Open Telescope

La Palma, Esp.

- 0.45m f/4.4 open-air reflector
- Equatorial mount
- Commissioned: 1998
- Main goal: high resolution imaging
- Strengths: excellent site, open design
- Speckle imaging reconstruction
- Weaknesses: inst. Mount on telescope
- Main Instruments:
  - Focal-plane CCD camera


DOT Speckle reconstructed G-band image
AR9359 23-Feb-01
~120 arcsec

DOT

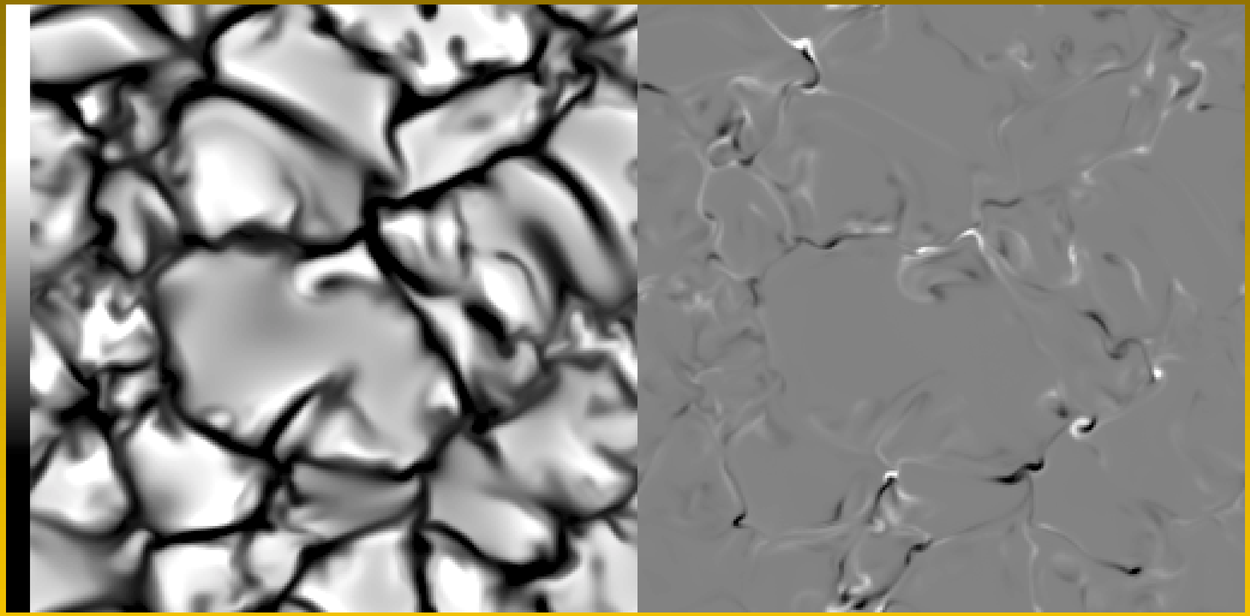
Speckle imaging movie: 22-Sep-99 Sunspot in G-band

Why We Need to do Better

- **Still not resolving the details of convection-flux interactions**
  - Spatial and temporal resolution of current telescopes is inadequate to capture the smallest scale dynamics of
    - Granulation
    - Sunspot penumbrae
    - Filaments
- **Polarimetry is photon starved**
  - Vector magnetogram resolution is compromised by need to integrate over several seconds to get adequate S/N
- **Progress in solar science requires "movie processing" not just image processing**
  - Need to have uniform high resolution time series in order to track formation and dispersal of magnetic flux

Numerical MHD Simulation

1 gauss horizontal field at box bottom
23 km grid resolution



6 Mm

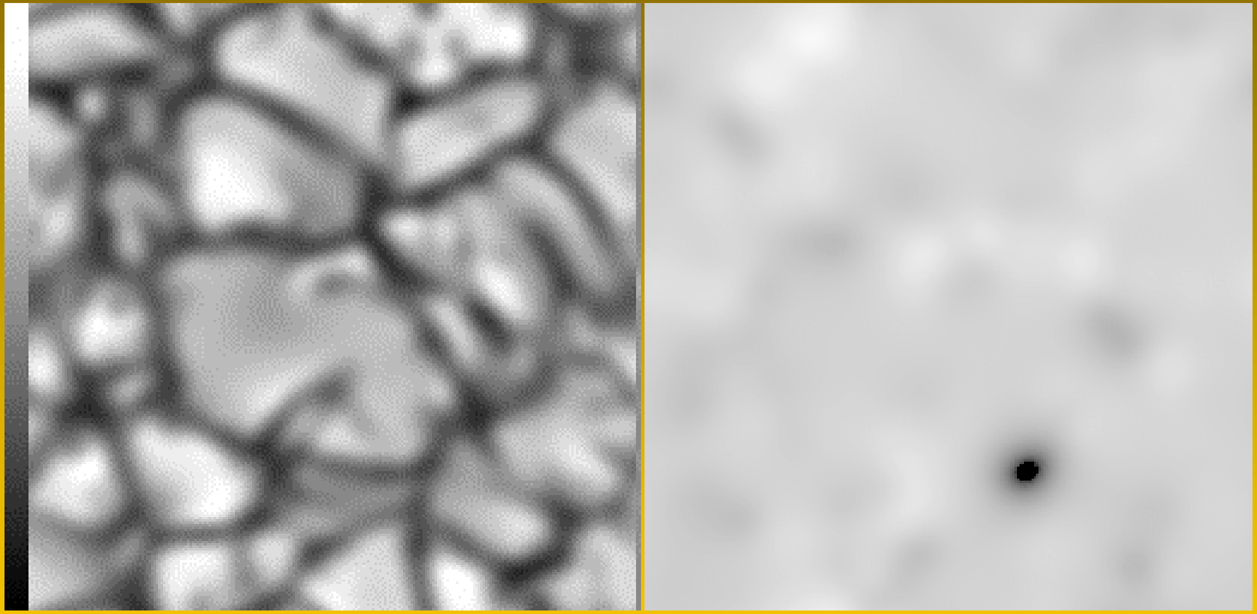
50 gauss P-P
3 gauss RMS

Courtesy Åke Nordlund

Numerical MHD Simulation

1 gauss horizontal field at box bottom

200 km FWHM PSF | 300 km FWHM PSF



6 Mm

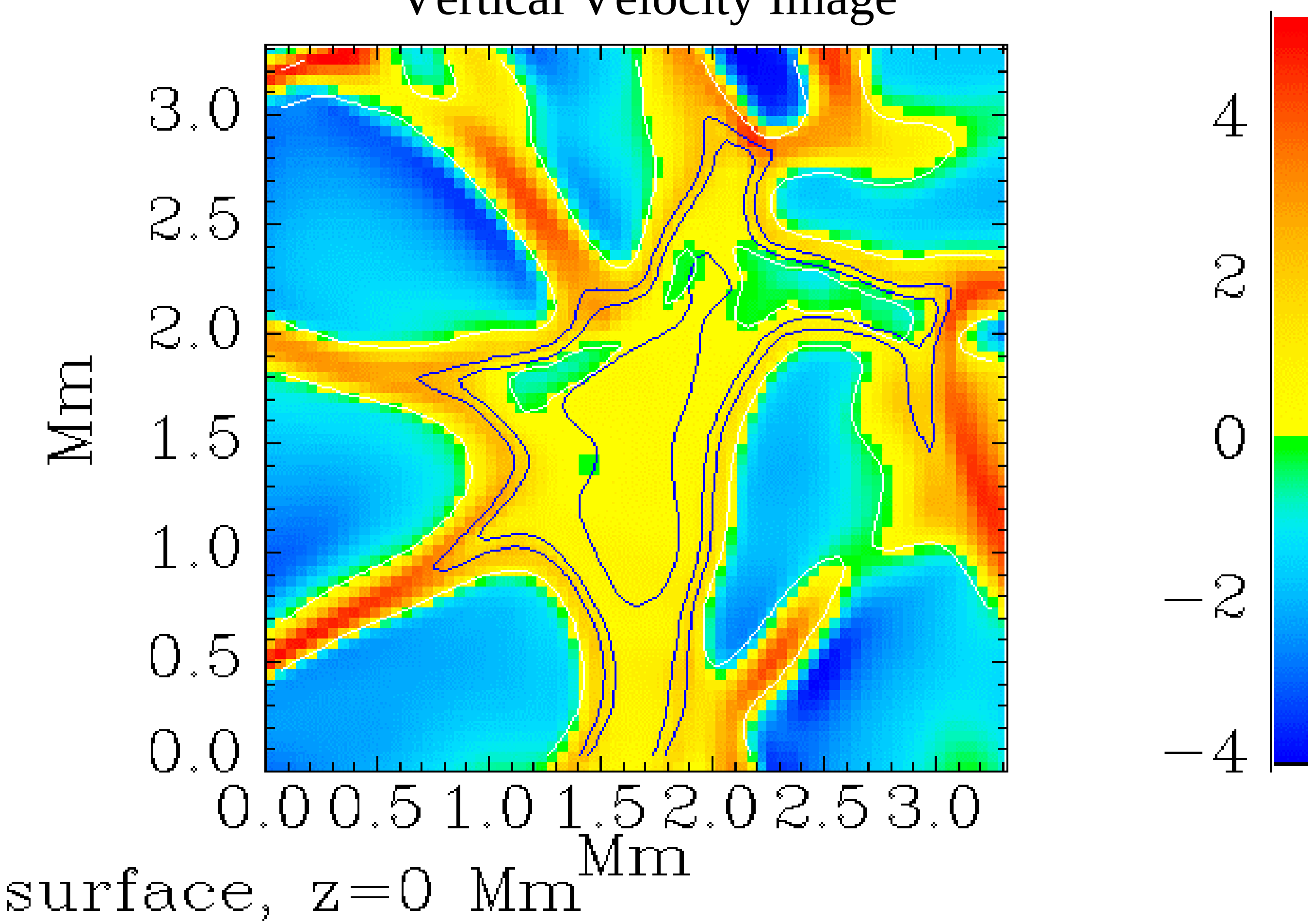
~10 gauss noise floor

Courtesy Åke Nordlund

Numerical MHD Simulation

Micropore Formation Case: 1.5 kgauss field

Vertical Velocity Image



Courtesy Bob Stein

Why We Need to do Better

High spatial resolution polarimetry is photon starved

- **Some simple calculations with a few assumptions**:
  - Unobscured aperture
  - 10% overall efficiency (including detectors)
  - Maximum horizontal motion of 5 km/s
  - Solar image is not allowed to evolve more than half a pixel
  - Spectral resolution of 150,000
  - Nyquist sampled in space (diffraction-limited) and spectrum
  - Look at a single spatial and spectral pixel
- **Need photons for high sensitivity:**
  - 10^{-5} requires 10^{10} photons: typical CCD exposure 10^5, need 10^5 exposures
- **Need photons for high spatial resolution:**
  - $3 \cdot 10^8$ photons/Å/s per diffraction-limited resolution sampling element
  - high spatial resolution magnetic field studies: 0.1 Å, 0.02s, 1% efficiency: only 6000 photons per exposure
  - high spatial resolution polarimetry is rarely very sensitive

Courtesy C. Keller

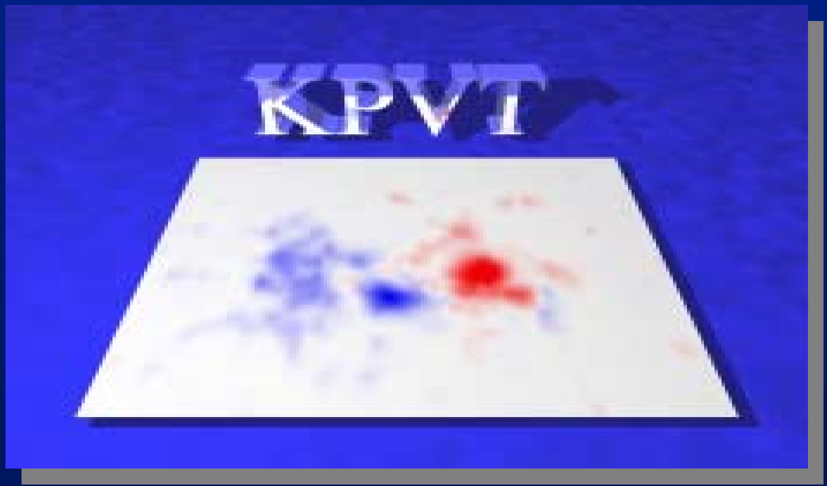
The Future

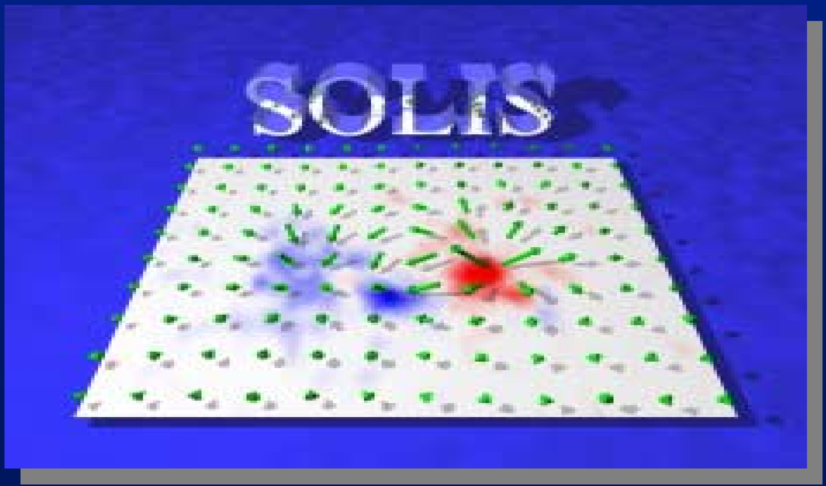
- **SOLIS**: Synoptic Optical Long-Term Investigations of the Sun
  - Replacement for the KPVT
  - Full-disk 1 arcsec vector magnetograms, several per day
- **NSST**: New Swedish Solar Telescope
  - Replacement for the SVST: 1m refractor
  - Very high resolution imaging and polarimetry, adaptive optics
- **GREGOR**: Gregorian Telescope on Tenerife
  - Replacement for the Gregory Coude Telescope: 1.5m reflector
  - Very high resolution imaging and polarimetry, adaptive optics
- **ATST**: Advanced Technology Solar Telescope
  - Completely new instrument and site: 4m off-axis reflector, adpative optics
  - Extremely high resolution imaging
  - Very high sensitivity polarimetry
  - NIR imaging and polarimetry
  - Limited coronagraphic capability

SOLIS

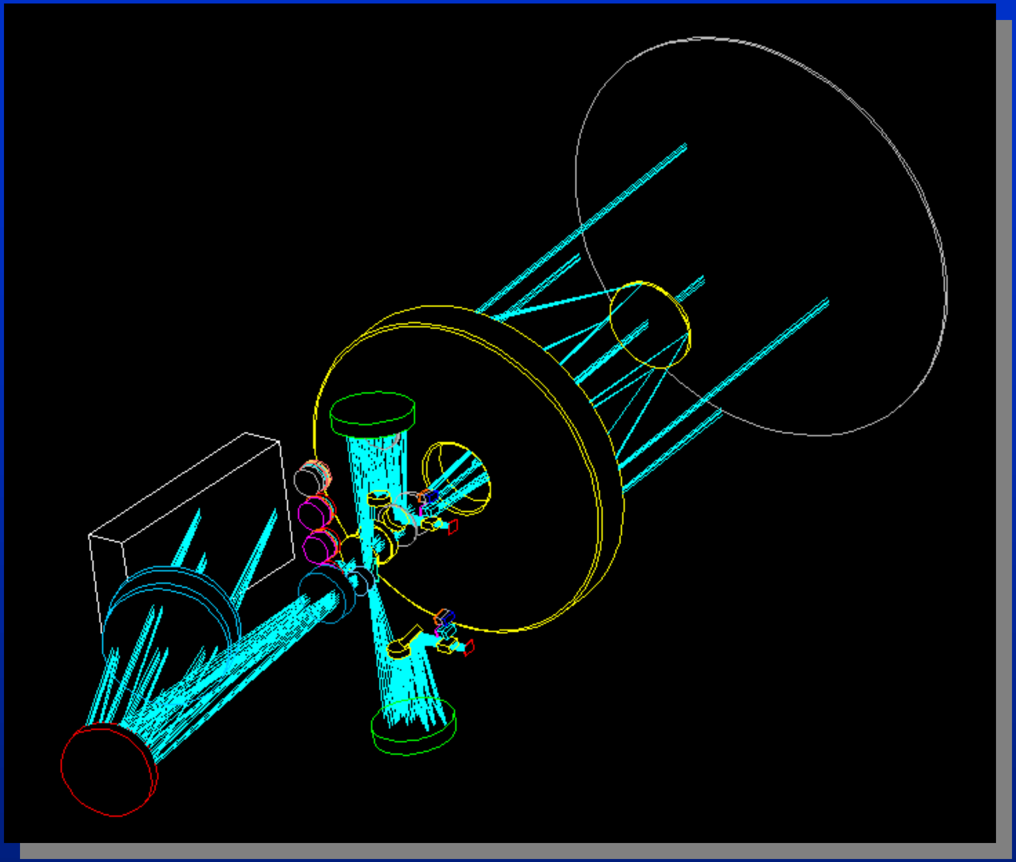
Synoptic Optical Long-term Investigations of the Sun

- 0.5m Vector Spectromagnetograph
- 0.1m Full-disk patrol
- Integrated sunlight spectrometer
- Kitt Peak site
- Equatorial mount
- Status: mount complete, optics in fab, cameras in test





SOLIS/VSM



- Capabilities
  - Full-disk scan in 900 sec
  - Spatial resolution: 2 arcsec
  - Spectral resolution: 200,000
  - Polarimetric sensitivity: 2×10^{-4}
- Polarimetry: 3/day each of
  - Fe I 630.15, 630.25nm: I,Q,U,V
  - Ca II 854nm: I,V
  - He I 1083nm: I
- Instrument Features
  - 0.5m f/6.6 modified RC telescope: low instrumental polarization
  - Active secondary, helium cooled
  - Active Littrow grating, 79 lines/mm
  - Offner reimaging optics: splits spectrum to two cameras
  - 1024 x 256 16µm pixel CCD, backside illum, <35 e- read noise @ 300 f/sec

NSST

New Swedish Solar Telescope*

- 0.92m f/21 refractor
- La Palma site
- Alt-az turret on 17m tower
- Vacuum beam path
- Wavelength range: 390 – 900 nm
- Adaptive optics on the lab bench
- Simplest possible optical paths
  - Only 3 elements between atmosphere and adaptive optics
  - Field lenses/mirrors allow flexible observing modes
- Lead Institution: Swedish Royal Academy, Stockholm Observatory
- Status: turret installed, optics in final figuring; First light: 2002

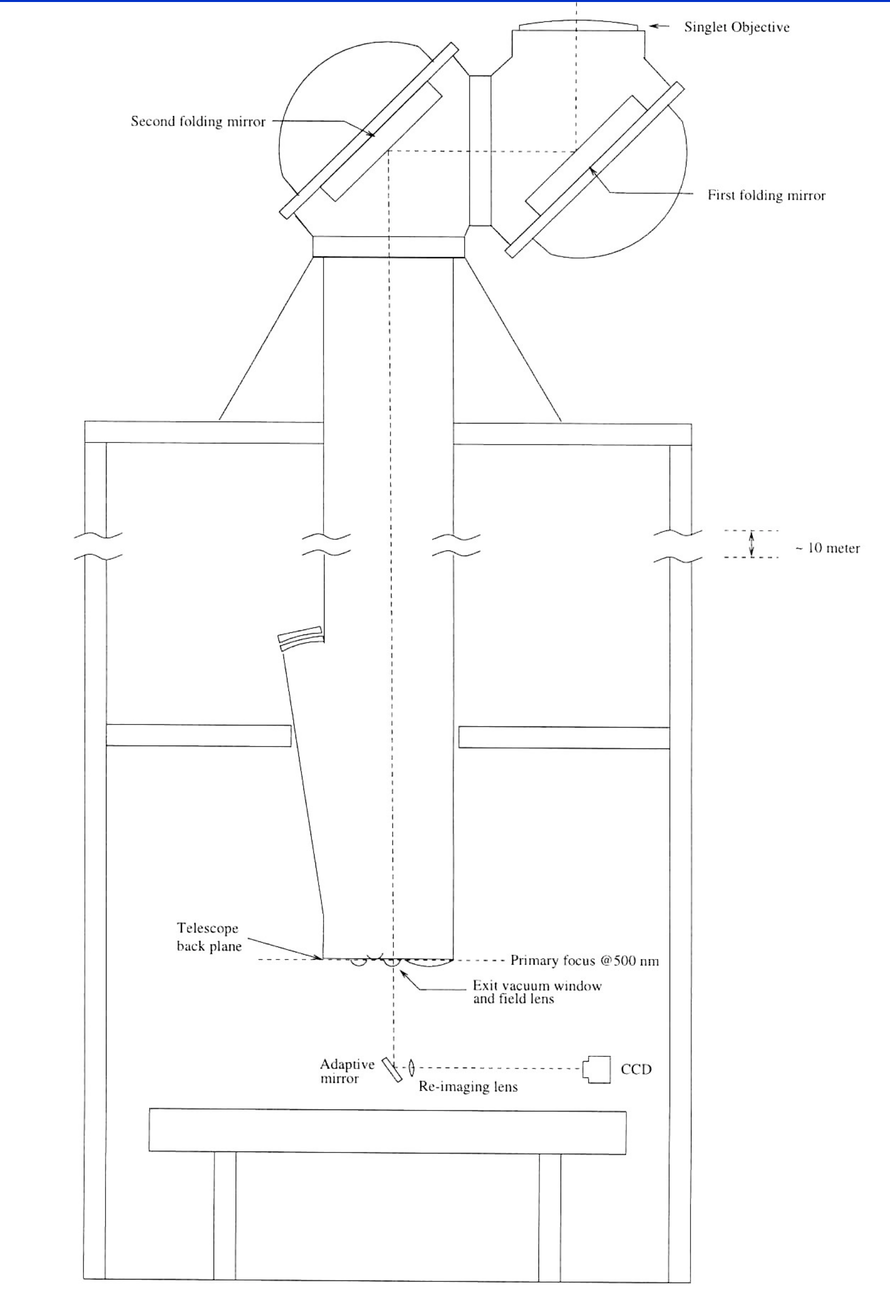
* Provisional name

NSST

- **Capabilities**
  - Singlet primary lens and relay mirrors: $\lambda/40$ – $\lambda/30$ wavefront error
  - Adaptive optics corrects up to 15^{th} Zernike mode
  - 390nm PSF HWHM: 0.10 arcsec = 72 km
  - 900nm PSF HWHM: 0.21 arcsec = 145 km
- **Observing modes**
  - High-resolution narrow-band
  - High-resolution achromatic Schupmann
  - Low-resolution full-disk patrol
- **Instruments**
  - Wide-band imaging filters
  - SALAD: imaging vector polarimeter
  - LPSP: La Palma Stokes Polarimeter on 2m Littrow spectrograph
  - ZIMPOL II

NSST
Narrow-band Observing Mode

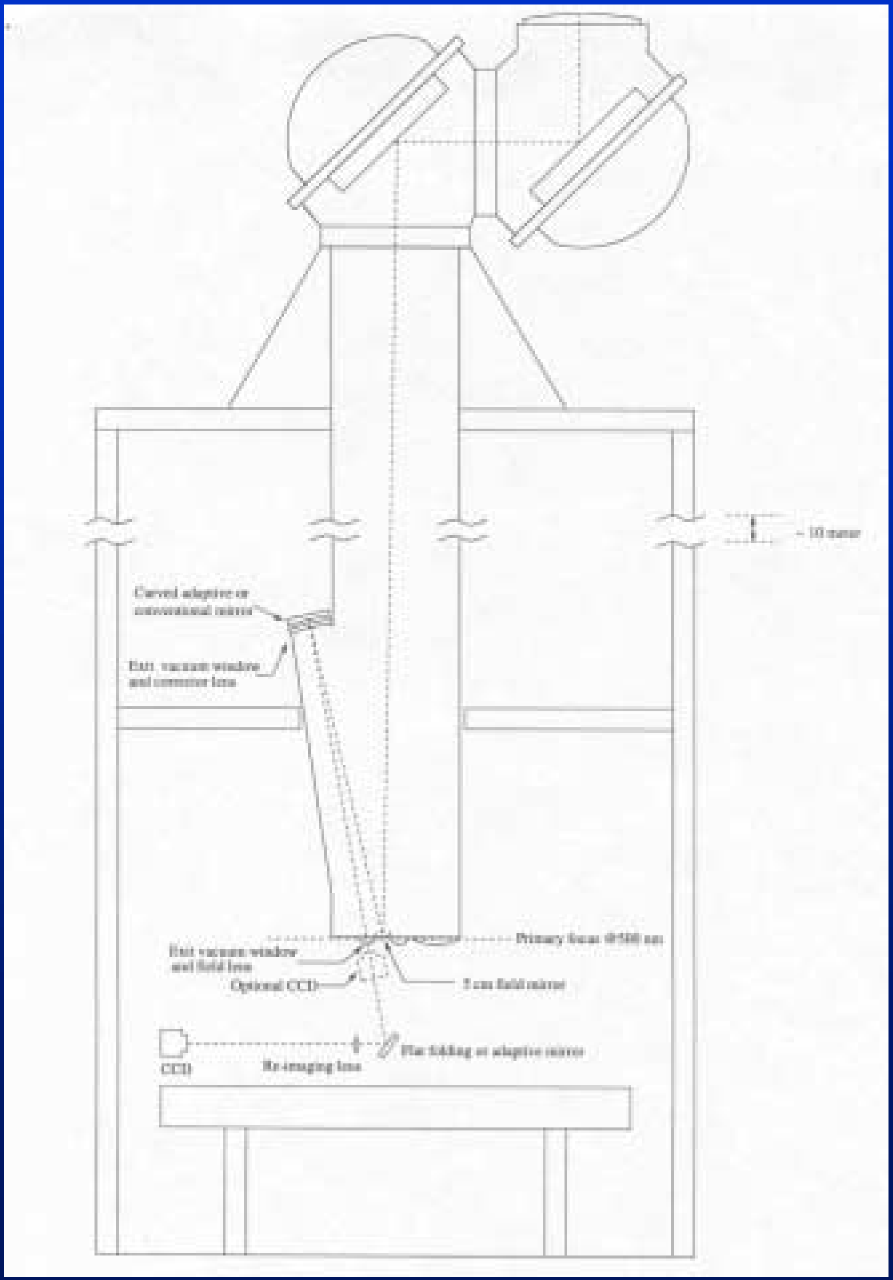
- Advantages
  - Simplest possible optical path gives maximum image quality at camera
- Disadvantages
  - No correction for singlet primary lens chromatic aberration: only one wavelength in focus at camera and no spectrographic capability



NSST

Wide-band Observing Mode

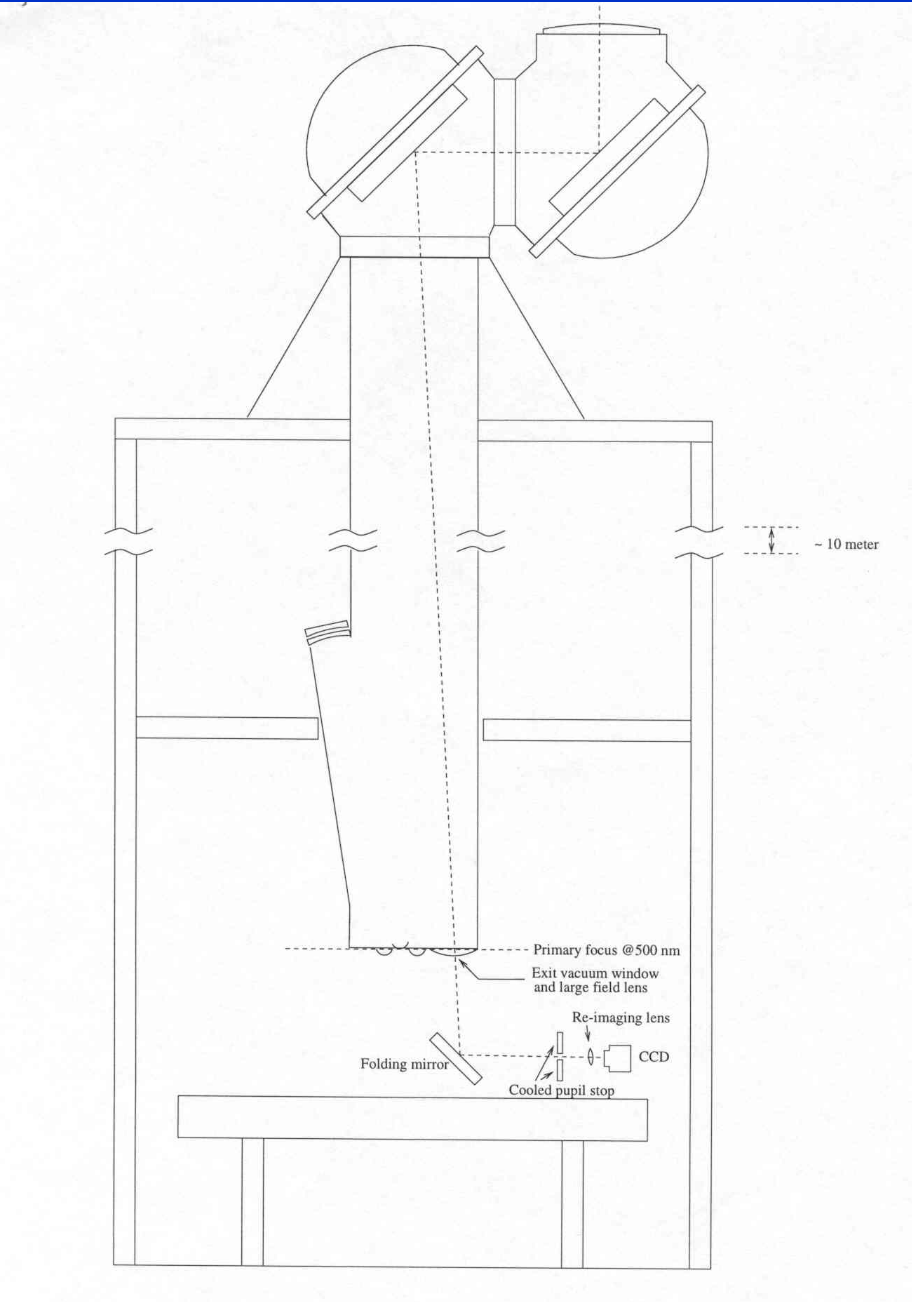
- Schupmann mirror completely corrects chromatic aberration of singlet primary and moves focus out of vacuum (1.5% magnification).
- Advantages
  - Allows multiple cameras imaging different wavelengths at same focal plane or use of spectrograph
  - Schupmann mirror can be adaptive
- Disadvantages
  - FOV restricted by strong power on corrector system
  - Adds 6 optical surfaces to beam path



NSST

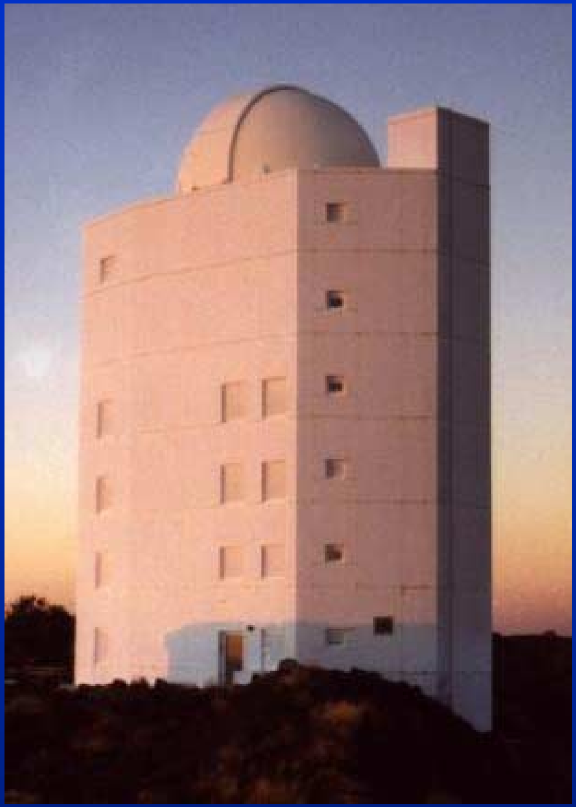
Full-disk Observing Mode

- Large field lens reimages primary at cooled aperture stop
- Aperture stop of 10cm and reimaging lens give full-disk FOV with ~1 arcsec/10 µm pixel
- Uses:
  - Full-disk patrol
  - "Poor-seeing" coordination with satellites
  - Fast Stokes maps of active regions



GREGOR

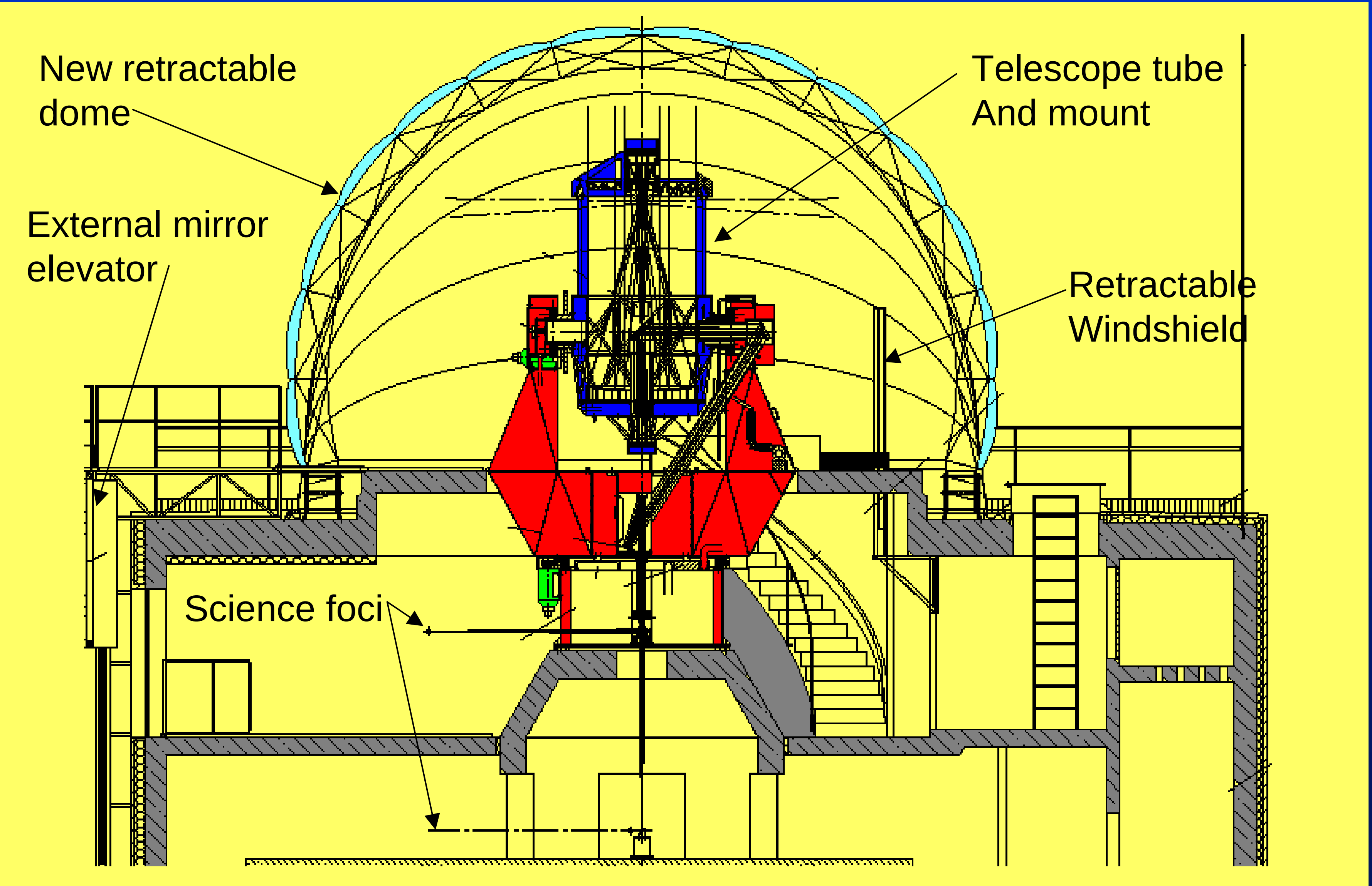
- 1.5m “Triple Gregorian”
- Site: Izaña, Tenerife
- Open Telescope tube, fully retractable dome (thanks to DOT)
- Alt-az mount
- Lightweighted structure
- Integrated adaptive optics system
- Focus redirectable to two laboratories
- FOV 300 arcsec, f_{eff} = 75m, F_{sys}/50
- Low Instrumental Polarization
- NIR and possibly TIR capability
- Dead reckoning pointing and tracking
- Lead Institution: Kippenheur Institut for Sonnenphysik
- Status: proposal accepted?



Gregory Coude Telescope
Site of the new GREGOR

GREGOR

Cross Section

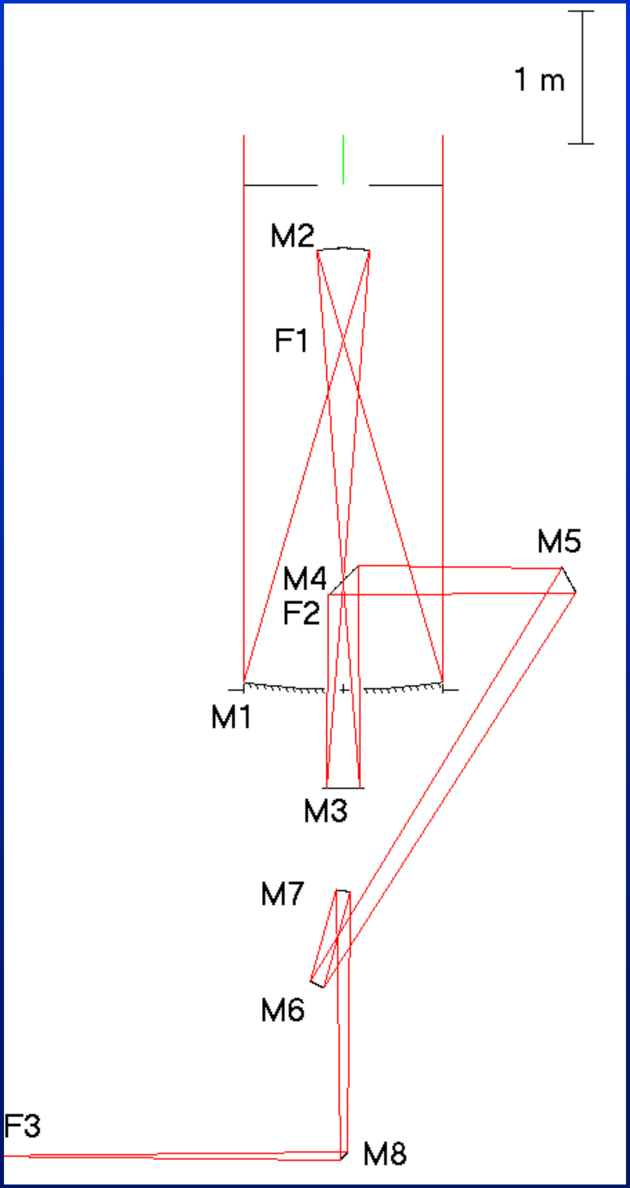


GREGOR

Optical Layout

- Triple Gregorian optics
- F/1.75 1.5m SiC primary
- 300 arcsec FOV at F1
- Polarimetric calibration optics at F2
- 110mm pupil at M6 and M7 for adaptive optics
- F/50 tertiary focus, F_{eff} = 75m
- 400nm PSF HWHM: 0.06 arcsec = 41 km
- 1.56µm PSF HWHM: 0.22 arcsec = 160 km

- AO system
  - 66 degrees-of-freedom (corrects to Z10) @150Hz
  - Goal: Strehl ratio > 0.5 for 20% of time

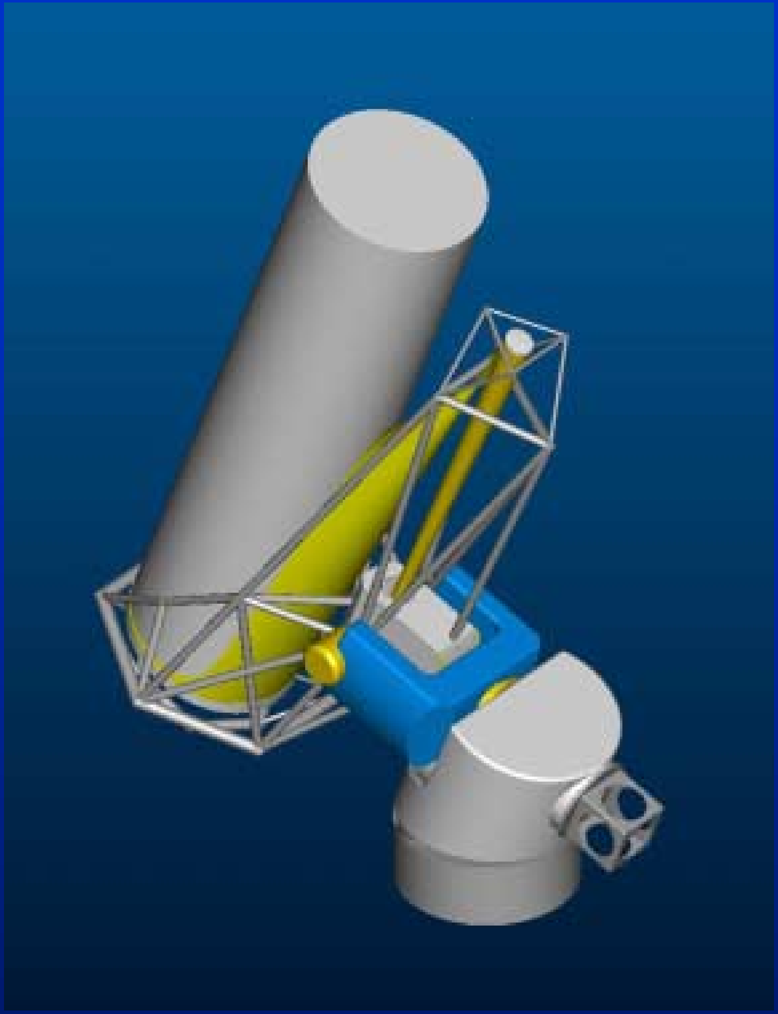


GREGOR
Instrumentation

- **Filtergraph**
  - Redeployment of Gottingen FPI from VTT
  - Installation in main observing room
- **UV Spectropolarimeter**
  - Redeployment of Freiburg POLIS from VTT
  - Installation in main observing room
- **General Purpose Grating Spectrometer**
  - Refurbishment of present Czerny-Turner from GCT
  - Installation in spectrograph room

ATST

Advanced Technology Solar Telescope



- 4m f/4 active off-axis parabolic primary
- Gregorian secondary (and cooling tower)
- Site: ??
- Open telescope structure, retractable dome
- Alt-az mount (not equatorial as shown!)
- Very low scattered light (no spiders)
- FOV goal: 5 arcmin, min = 3 arcmin
- Actively cooled optics: ambient temps.
- Integrated AO
- Wavelength coverage: 350nm – 35µm
- Coronagraphic capabilities (off pointing)
- Lead institute: National Solar Observatory
- Status: proposal to NSF for design study in final draft

ATST

- Capabilities/Goals
  - Scattered light < 10^{-5} at $r/R_{sun} = 1.1$ and $\lambda > 1\mu m$
  - 400nm PSF HWHM: 0.02 arcsec = 15 km
  - 4μm PSF HWHM: 0.21 arcsec = 153 km

- Observing Modes
  - Ultra-high resolution imaging
  - 10^{-4} Polarization sensitivity with <1 second integrations
  - High resolution NIR imaging and spectroscopy
  - NIR coronagraphic imaging and polarimetry (if offpointing is ok)

- Baseline Instruments
  - Tunable filter visible imager
  - Visible vector spectropolarimeter
  - NIR imager
  - NIR spectrograph

ATST
Major Challenges

- Everything
- But especially
  - Thermal control: Primary focus heat stop has ~2.4 MW/m^2 irradiance
    - Active liquid or air cooled optics is a must
    - TIR capability requires ambient temperatures on all telescope structure
  - Contamination control: open design has high particulate loading
    - Scattered light and IR emissivity may require frequent cleaning of mirrors
  - Site: needs very large r_0 (~20-30cm) for significant periods of time
  - Adaptive Optics:
    - DOF ~ $(D/r_0)^2$: r_0 20cm -> 400 DOF adaptive mirror -> 1200 actuators
    - Off-axis design puts skewed pupil on AO mirror
    - Alt-az mount + off-axis optics rotates a variable phase pupil across the AO mirror
    - Multi-conjugate AO required to correct over full FOV