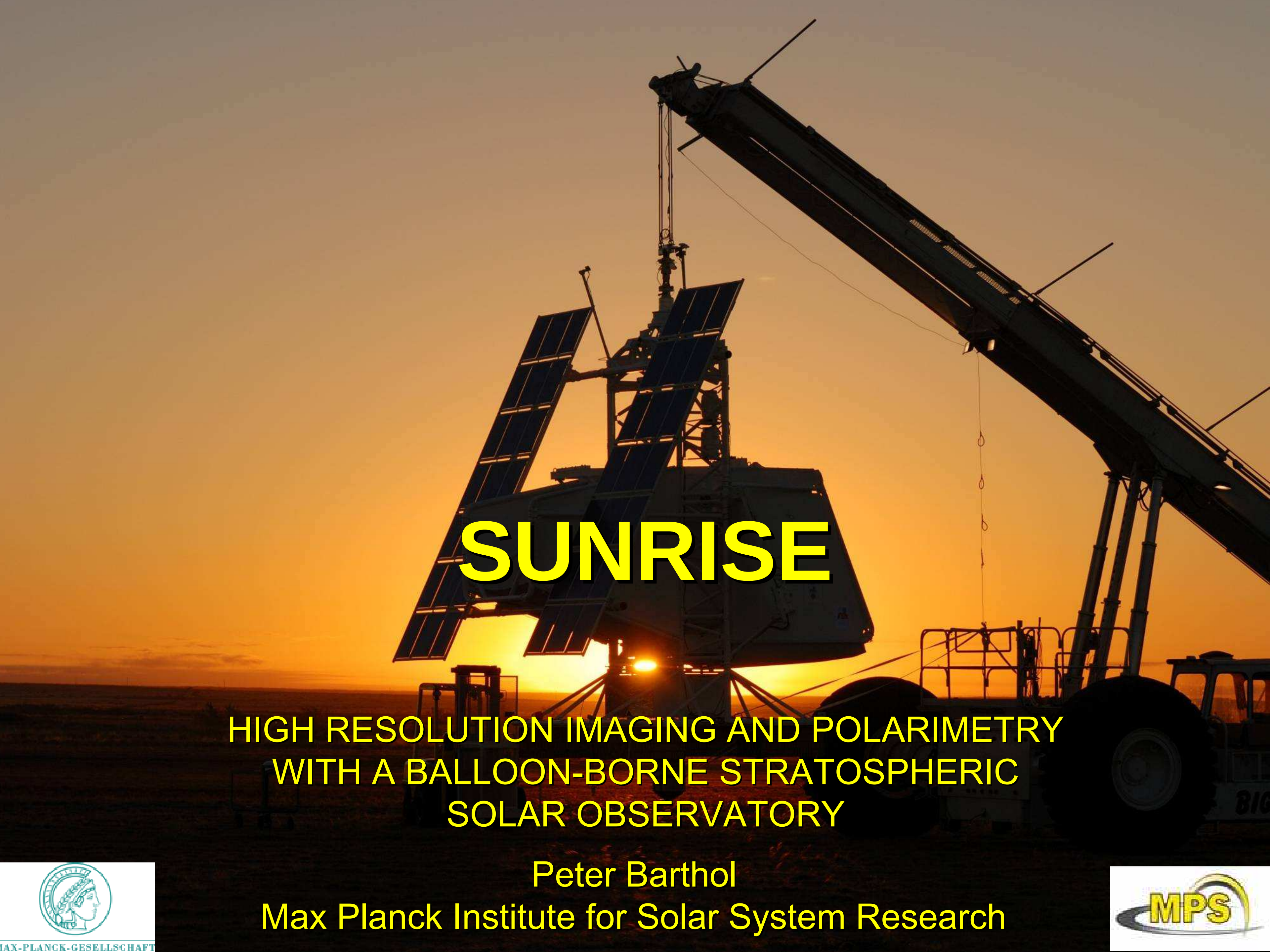


SUNRISE

HIGH RESOLUTION IMAGING AND POLARIMETRY
WITH A BALLOON-BORNE STRATOSPHERIC
SOLAR OBSERVATORY

Peter Barthol
Max Planck Institute for Solar System Research

SUNRISE in Brief

- **Aim:** study magneto-convection at a resolution of ≤ 100 km on the Sun
- **Observables:** time series of near diffraction limited UV images and magnetograms in the visible
- **Instrument:** 1-m balloon-borne telescope, with simultaneously observing postfocus instruments
- **Mission:** circumpolar long-duration stratospheric balloon flight(s) at solstice conditions

The SUNRISE Team

S.K. Solanki (PI), P. Barthol (PM), A. Gandorfer (PS), M. Schüssler (Co-I) + MPS Team
Max Planck Institute for Solar System Research, Germany

M. Knölker (Co-I) + HAO Team
High Altitude Observatory, USA

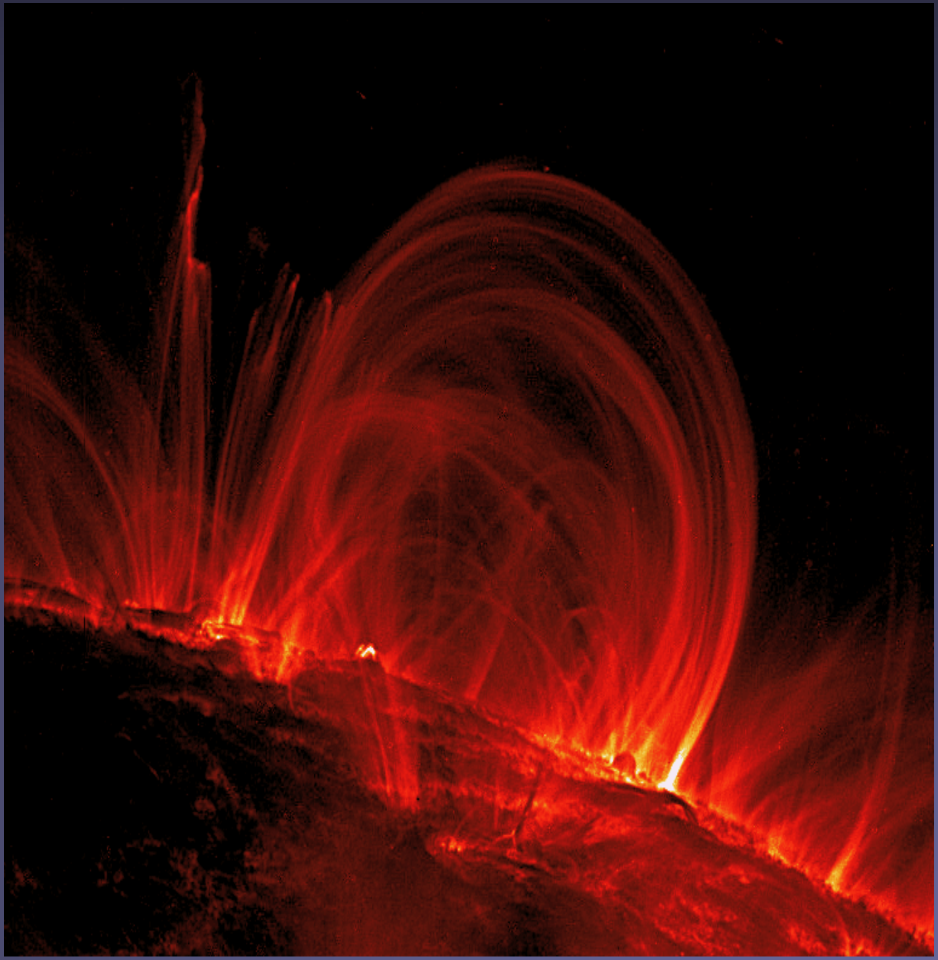
V. Martínez-Pillet (Co-I) + IMaX Team
Instituto de Astrofisica de Canarias, Spain and the IMaX consortium

W. Schmidt (Co-I) + KIS Team
Kiepenheuer Institut für Sonnenphysik, Germany

A.M. Title (Co-I)
Lockheed-Martin Solar and Astrophysics Laboratory, USA

SUNRISE Key Science Questions

- Study of solar magnetic field
- Investigation of photospheric and chromospheric phenomena
- How is the magnetic field brought to and removed from the solar surface (emergence, concentration, cancellation)?
- How much magnetic flux is there in the quiet Sun?
- How is momentum and energy transported to the outer solar atmosphere?
- What is the underlying physics of solar UV irradiance variability?
- Test of MHD predictions



SUNRISE Basic Requirements

- Analyze small scale interaction of convective flows and magnetic field (≤ 100 km, ~ 0.05 arcsec) with sufficient field of view
  → Diffraction limited telescope with 1 meter aperture
  → Above atmosphere to cancel seeing effects and to access the UV
  → High precision pointing + image stabilization

- Resolve time dependent characteristics of magneto-convective patterns (≤ 5 sec) and cover (hours - days) their evolution
  → High cadence + uninterrupted observations

- Measure 3D-distribution of B vector, plasma velocity and temperature
  → Polarization sensitive spectroscopy in photospheric and chromospheric line(s)

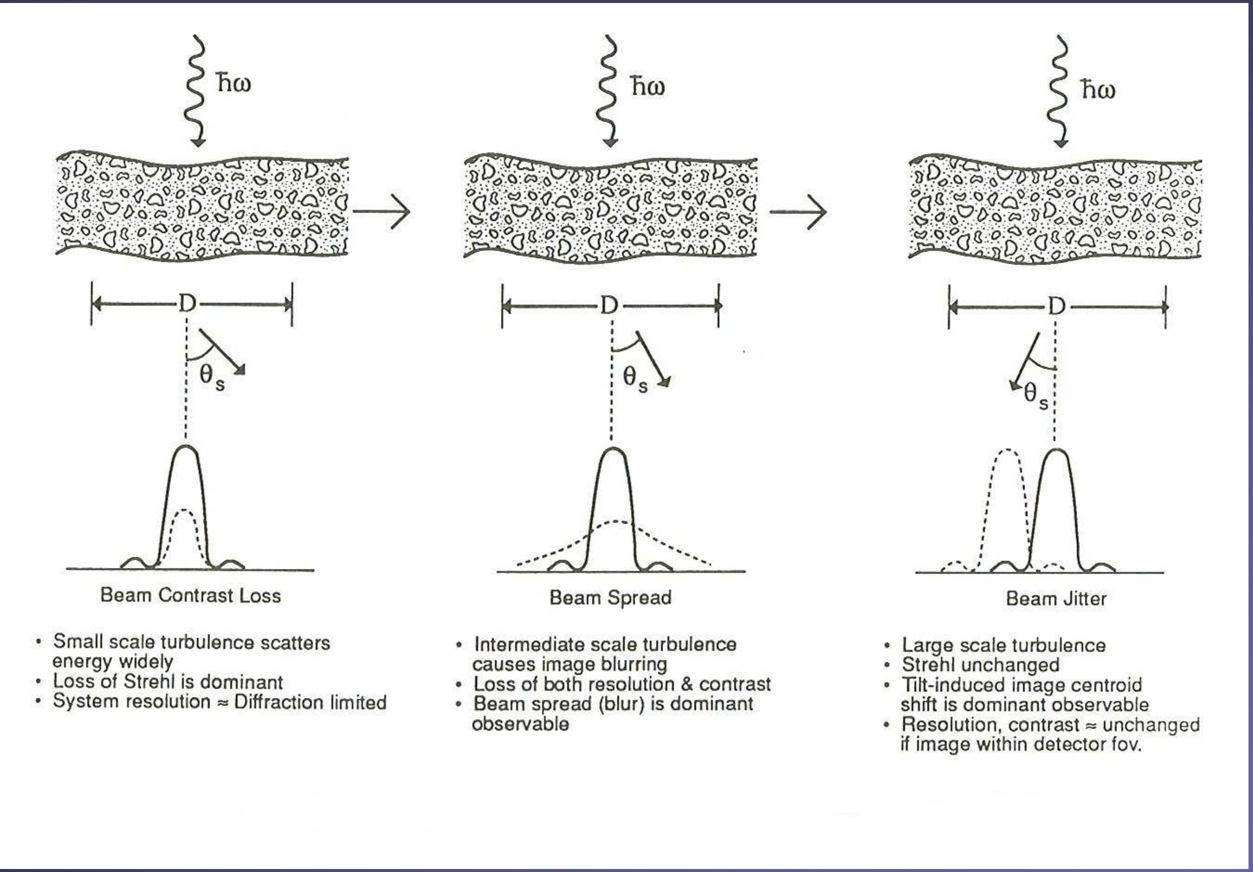
- High-cadence imaging of different layers
  → Visible + UV filtergrams

Why so far above Ground?

- Reduction of “Seeing”:
- Ground based observations have limited resolution due to air turbulence
- Angular resolution typically not better than 1 arcsec

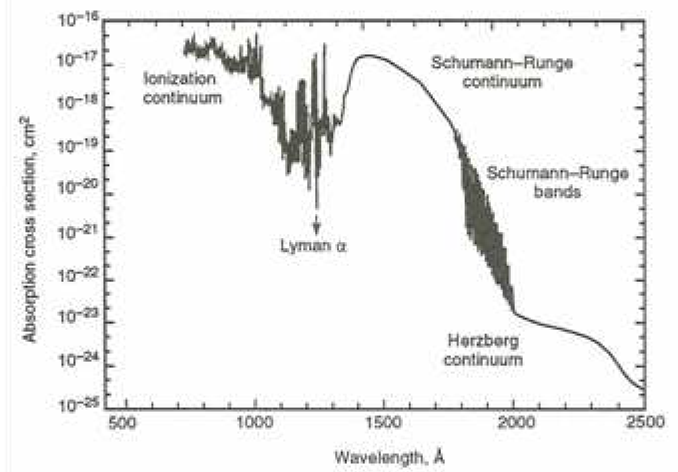
- Sometimes (at specific places) resolution is ~ 0.2 arcsec, but you have to be extremely lucky !

- SUNRISE aims at ≤ 0.05 arcsec !!!

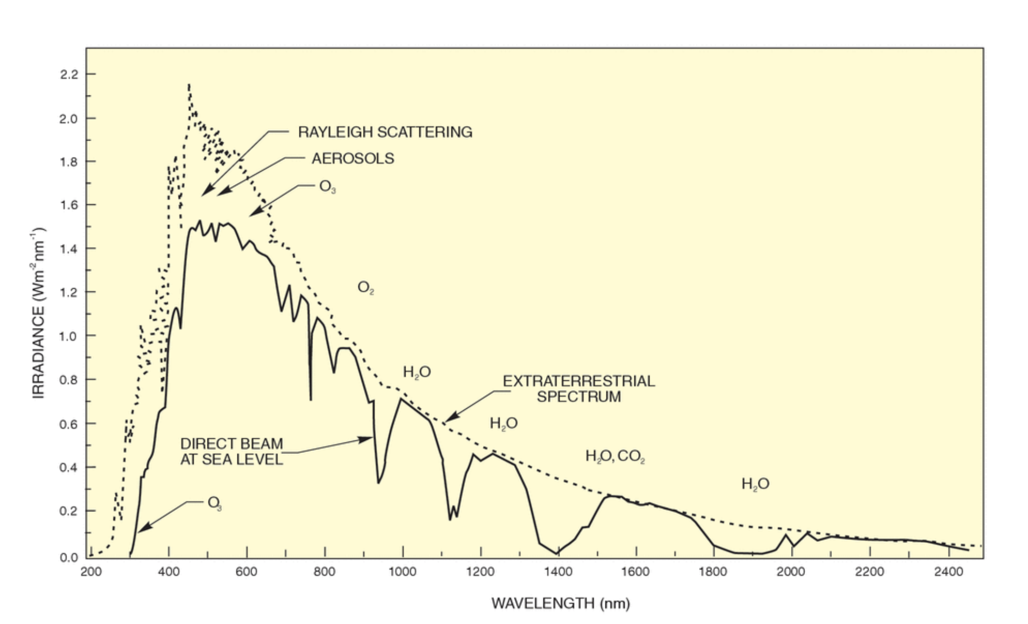


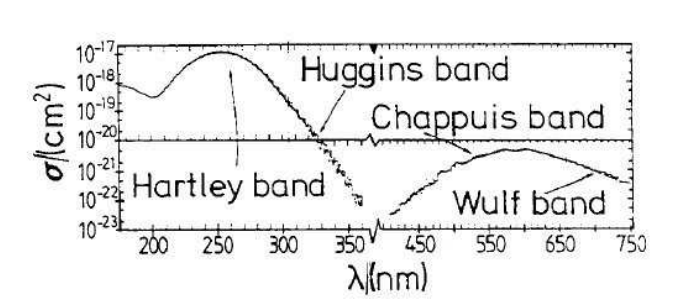
Why so far above Ground?

- Access to the Ultraviolet Spectral Domain:
- Thermospheric Oxygen and stratospheric Ozone absorbs virtually all UV radiation <300 nm at sea level
- Shorter wavelengths can give higher spatial resolution !



Electronic transitions of oxygen in the ultraviolet



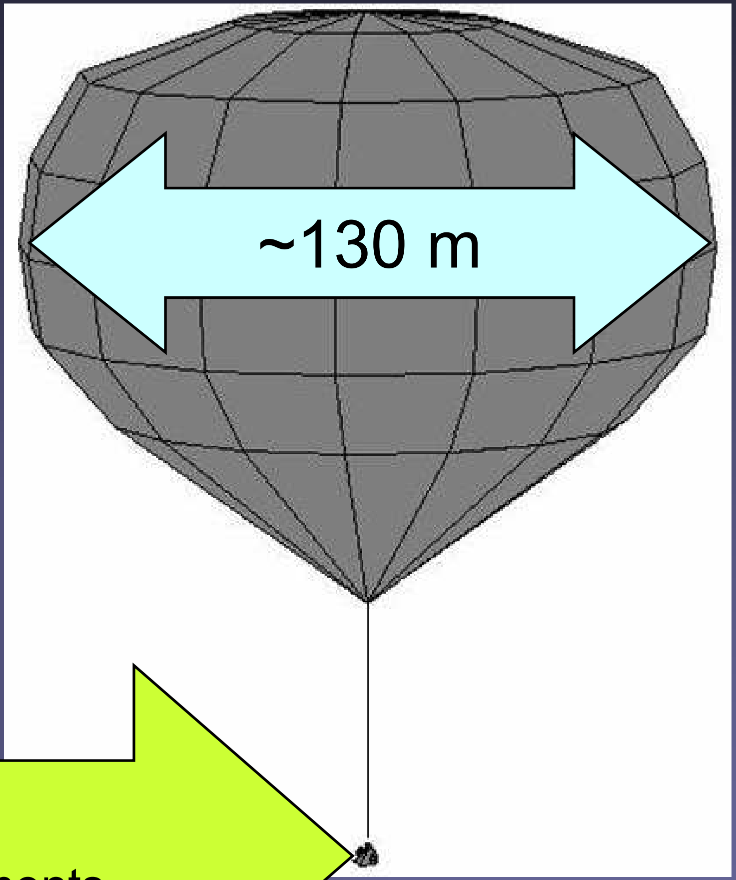


The photo-absorption cross-section of ozone from 180 to 750 nm showing the main absorption bands (Banichevich *et al.* 1993).

SUNRISE Balloon

NASA LDB Flight Program:

- 34 MCF, ~ 1.000.000 m^3
  Zero pressure balloon
- Science payload weight ~2000 kg
- Float altitude 34 km – 37 km
- Air pressure at float 3 – 7 hPa



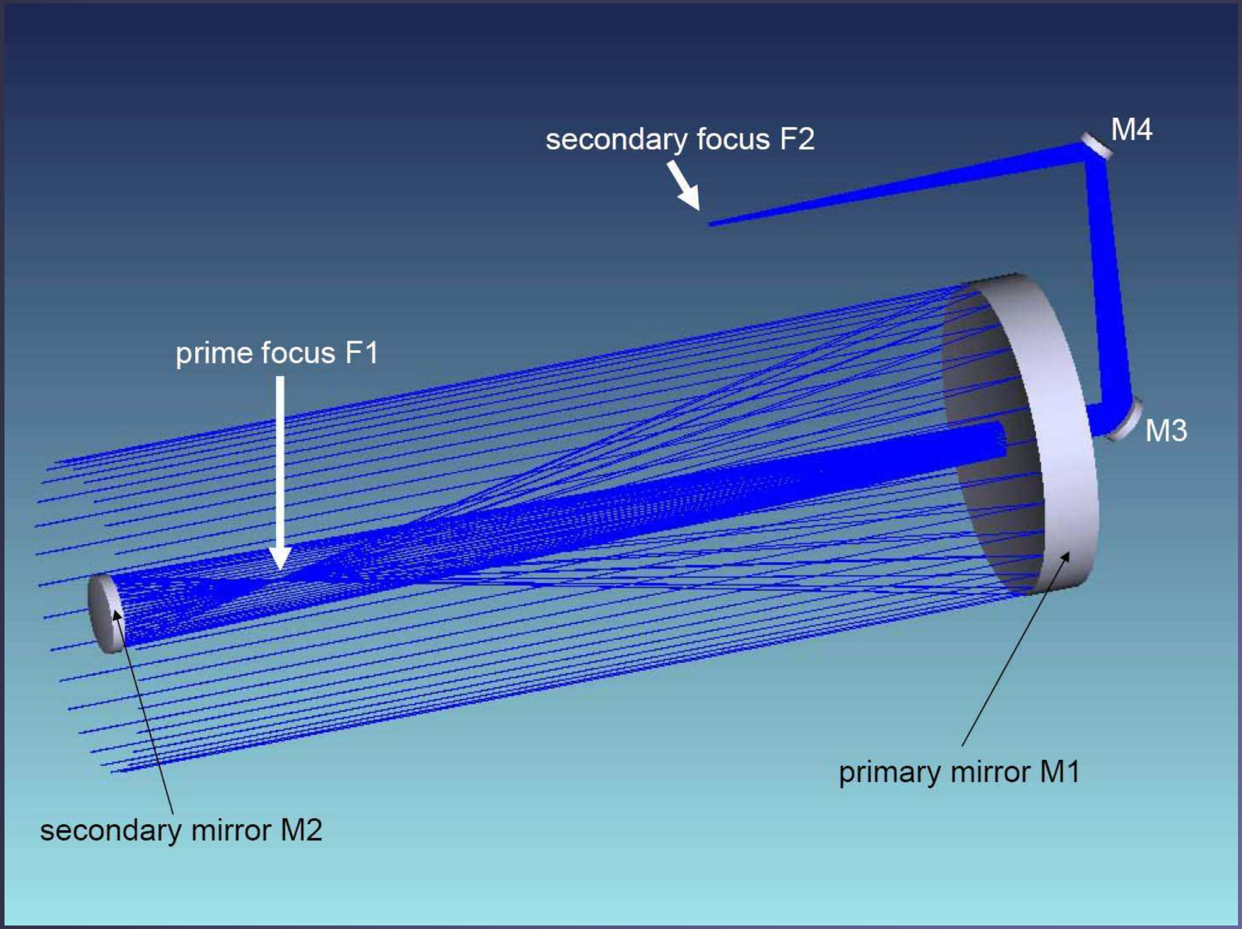
SUNRISE Gondola

- Provides stable platform for telescope and instrumentation
- Power supply (batteries and solar panels)
- Azimuth and elevation pointing and tracking to few arcsec accuracy
- Protects instruments during launch and landing
- Carries telemetry and commanding systems

Designed and built by HAO

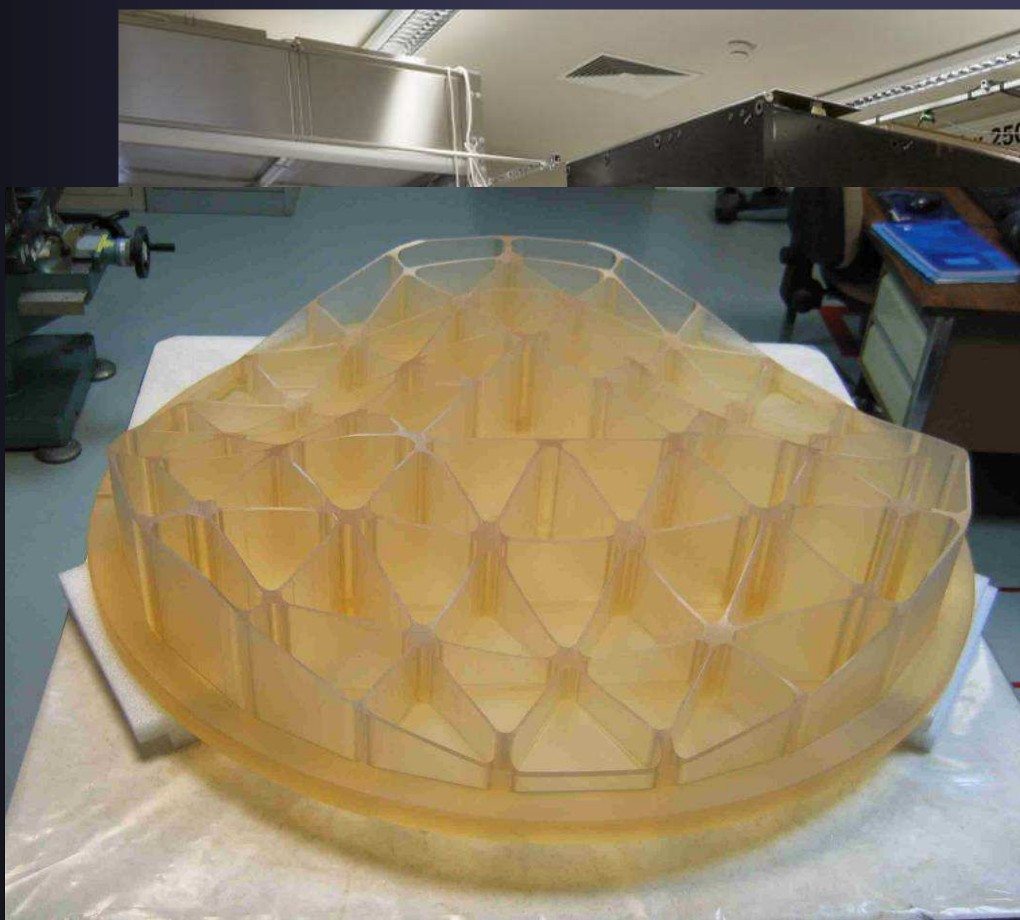
Telescope

- Gregory configuration (f/25, primary focus field stop)
- M2: 3 degrees of freedom, controlled by wavefront sensor
- Two plane fold mirrors (M3, M4) feed postfocus instruments (movable for fine focus)



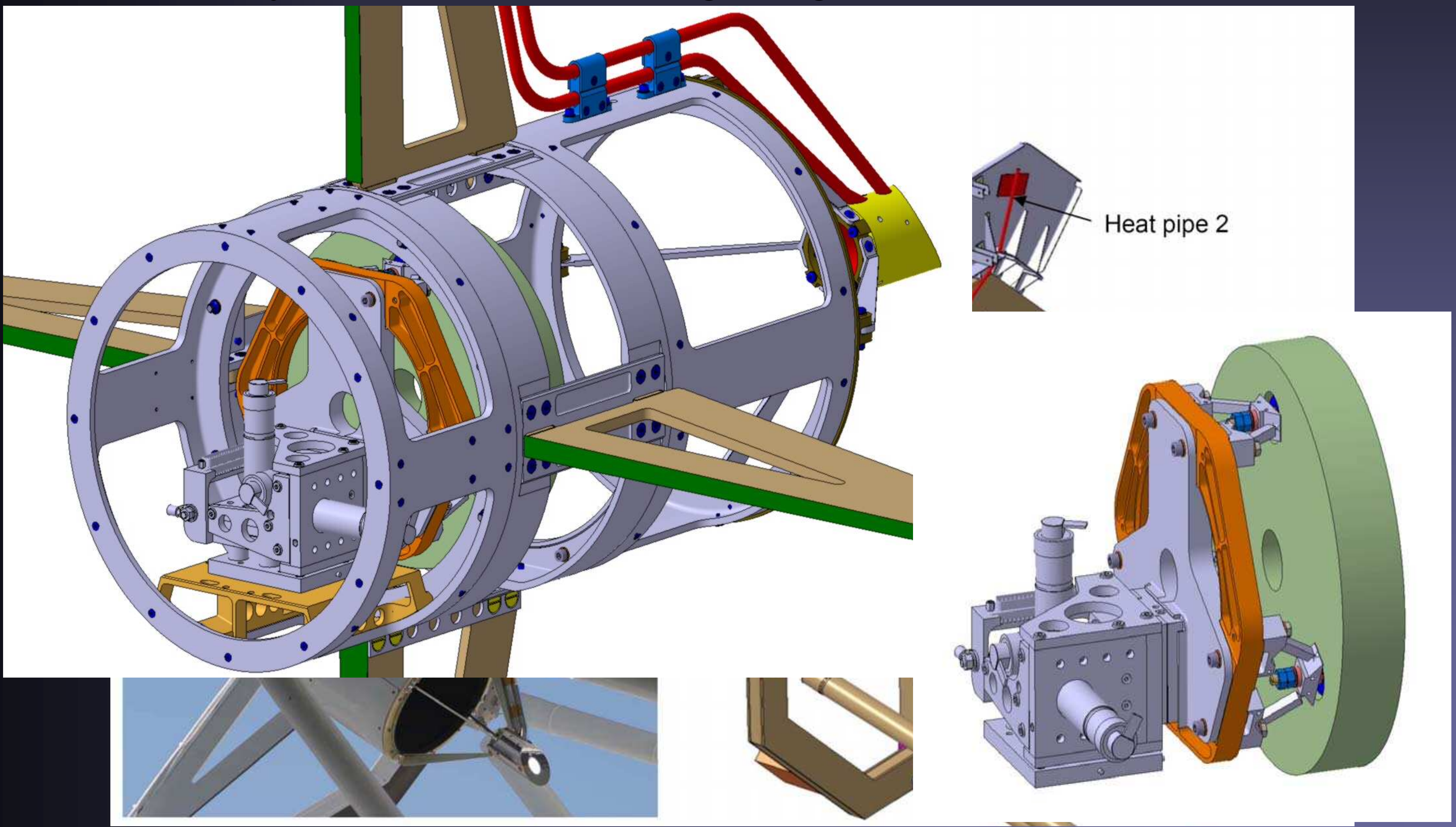
Telescope

- Carbon fiber based telescope structure (Kayser-Threde, Munich)
- Zerodur lightweighted primary mirror (SAGEM, France); 1 meter free aperture, diffraction limited in the visible



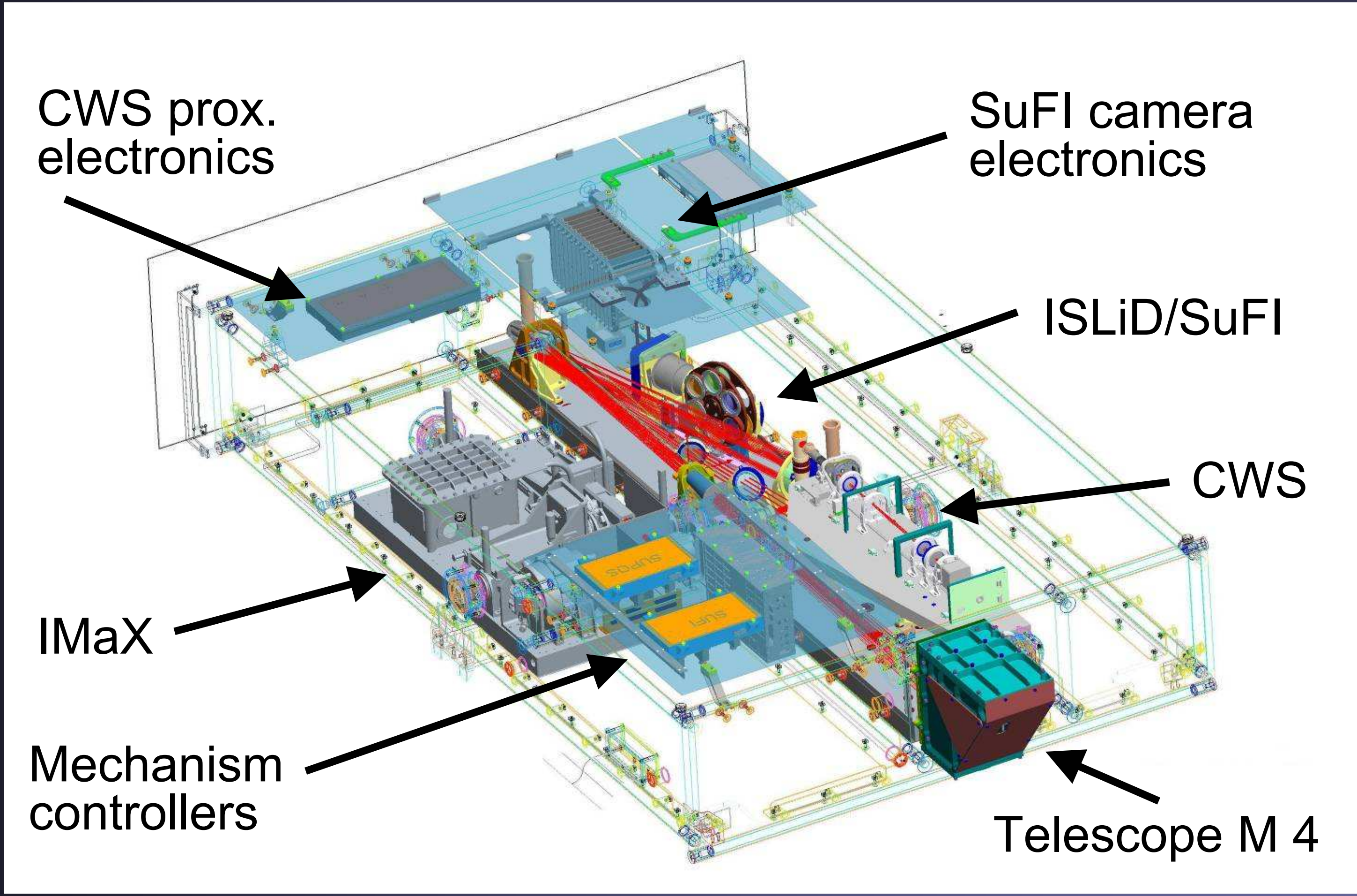
Telescope

- Heat rejection wedge @ prime focus with radiators + heat pipes
- Secondary mirror with active in-flight alignment



Postfocus Instrumentation

- Carbon-fiber based support structure
- Individual science (IMaX, SuFI) and support instruments (ISLiD, CWS)
- Proximity electronics (mech. controllers, power supplies etc.)



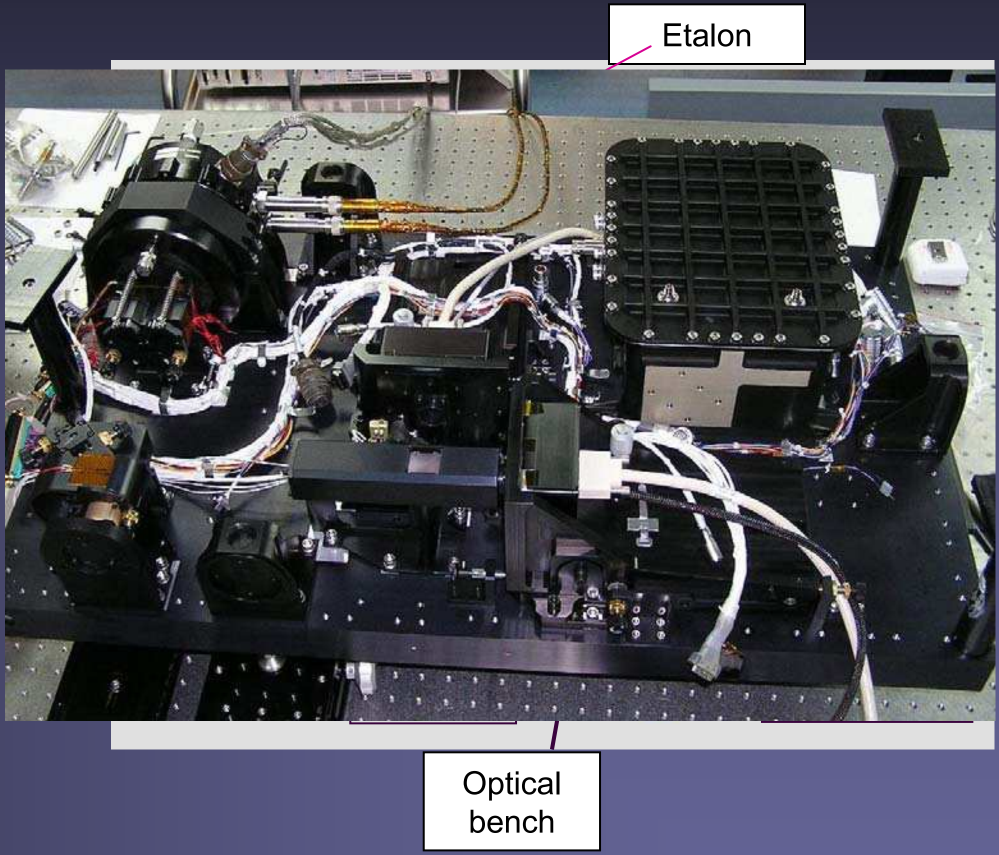
Postfocus Instrumentation

- Sensitive to particle and molecular contamination (UV!)
- Stringent requirements on mechanical and temperature stability

- Foam based thermal insulation for structural elements
- Surface treatments according to results of detailed thermal mathematical models, e.g.
  - White paint (Aeroglaze A276)
  - VDA Mylar as second surface mirrors
  - Silver Teflon
- Wind shield for tropopause transit

IMaX: Imaging Magnetograph Experiment

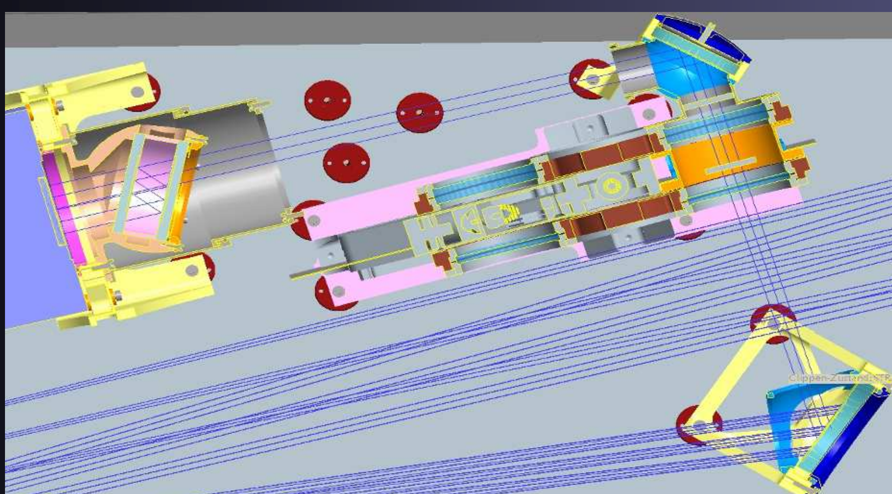
- 2D maps of magnetic vector & LOS velocity
- Full Stokes vector images every 30s; (I,V) every 5s
- FoV: 50” x 50”
- 525.02 nm, Fe I, g=3
- Spectral resolution: 85 mÅ
- Fabry-Perot etalons, liquid crystal modulators
- 2 CCDs for phase diversity & improved polarimetry

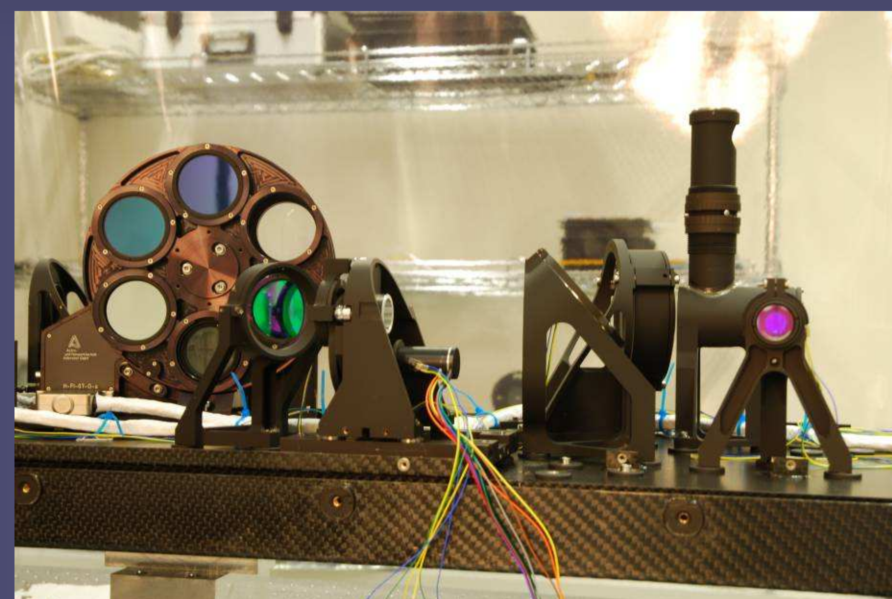


Designed and built by Spanish IMaX consortium

SuFI: Sunrise Filter Imager

- Medium band imager with λ bands (< 1nm wide) :
  - 397 nm (Ca II K, 1 Å wide)
  - 388 nm (CN band)
  - 313 nm (OH band)
  - 300 nm pseudo continuum
  - 214 nm pseudo continuum
- FOV: 40x15” with 2048x2048 CCD
- Phase diversity for image reconstr.
- ~ 125 m effective focal length
- 1s cadence at fixed λ
- 2s cadence for diff. λ

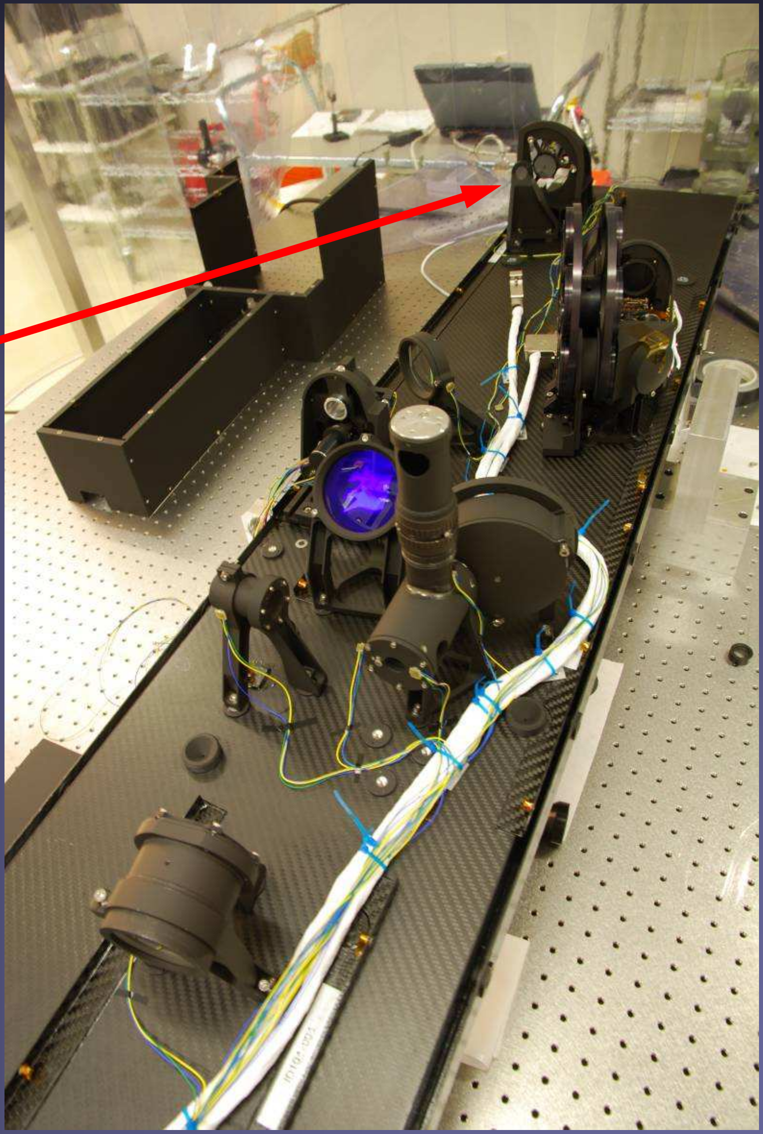




Designed and built by MPS

ISLiD: Image Stabilization and Light Distribution

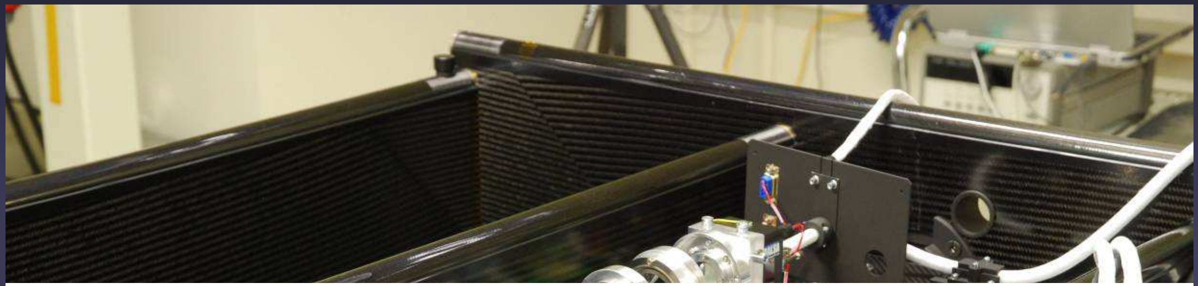
- Complex panchromatic reimager
- Distributes incoming radiation to science instruments
- Fast tip/tilt mirror in pupil image part of CWS system for image stabilization (KIS)

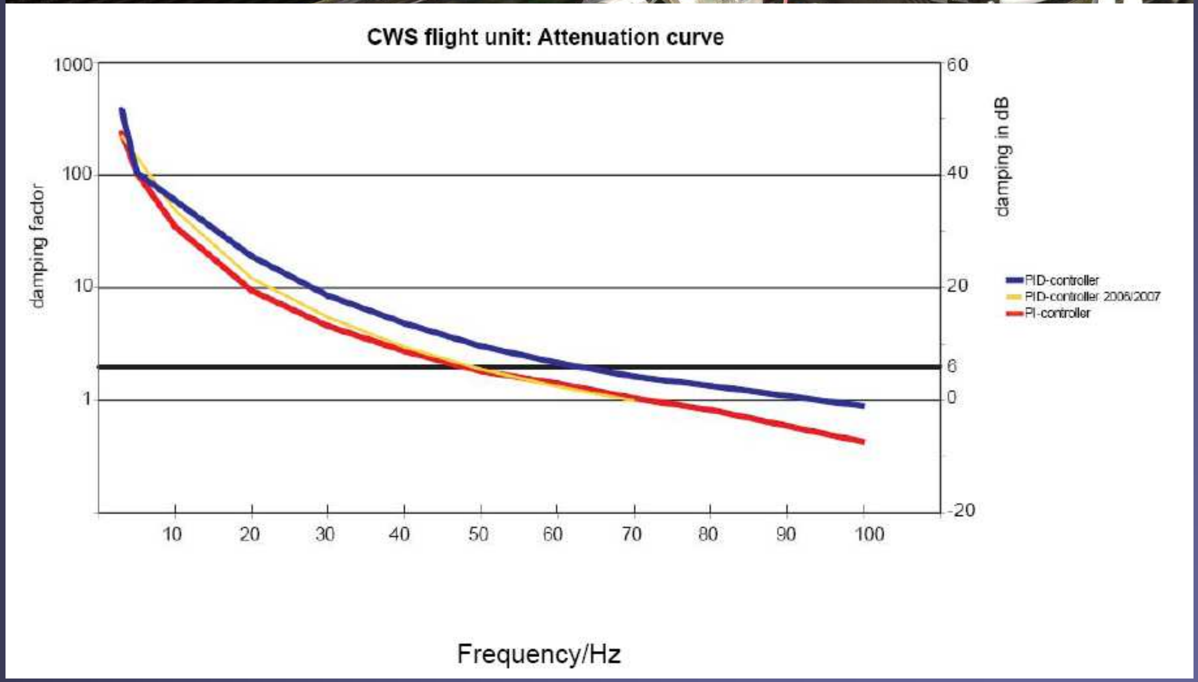


Designed and built by MPS

CWS: Correlation Tracker and Wavefront Sensor

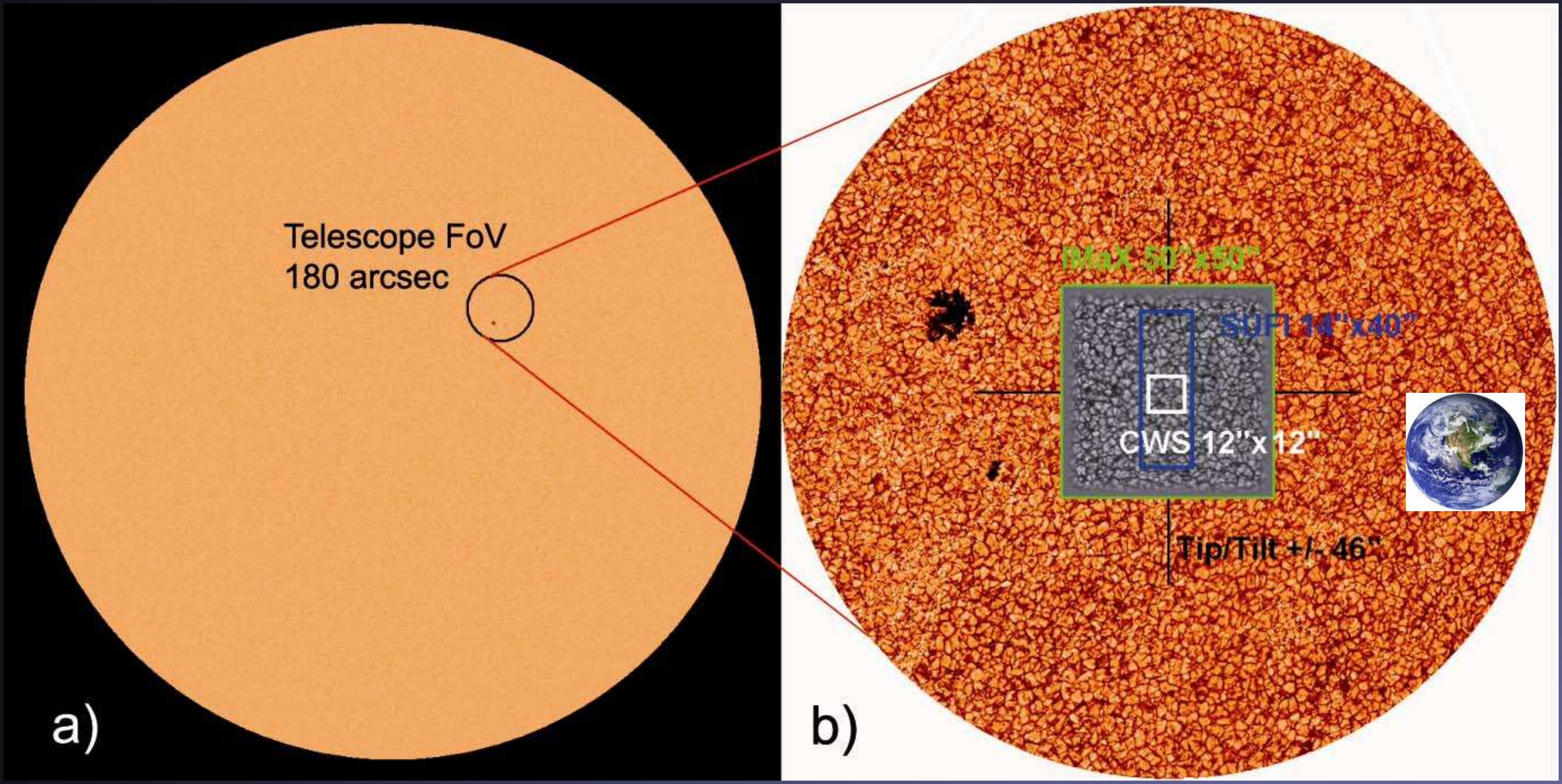
- Shack-Hartmann Sensor with 6 sub-apertures on lenslet array
- Provides focus and coma correction by telescope M2 inflight alignment
- High speed detection of correlated image motion, drives tip-/tilt mirror for image stabilization





Designed and built by KIS

Telescope and Instrument Fields-of-View

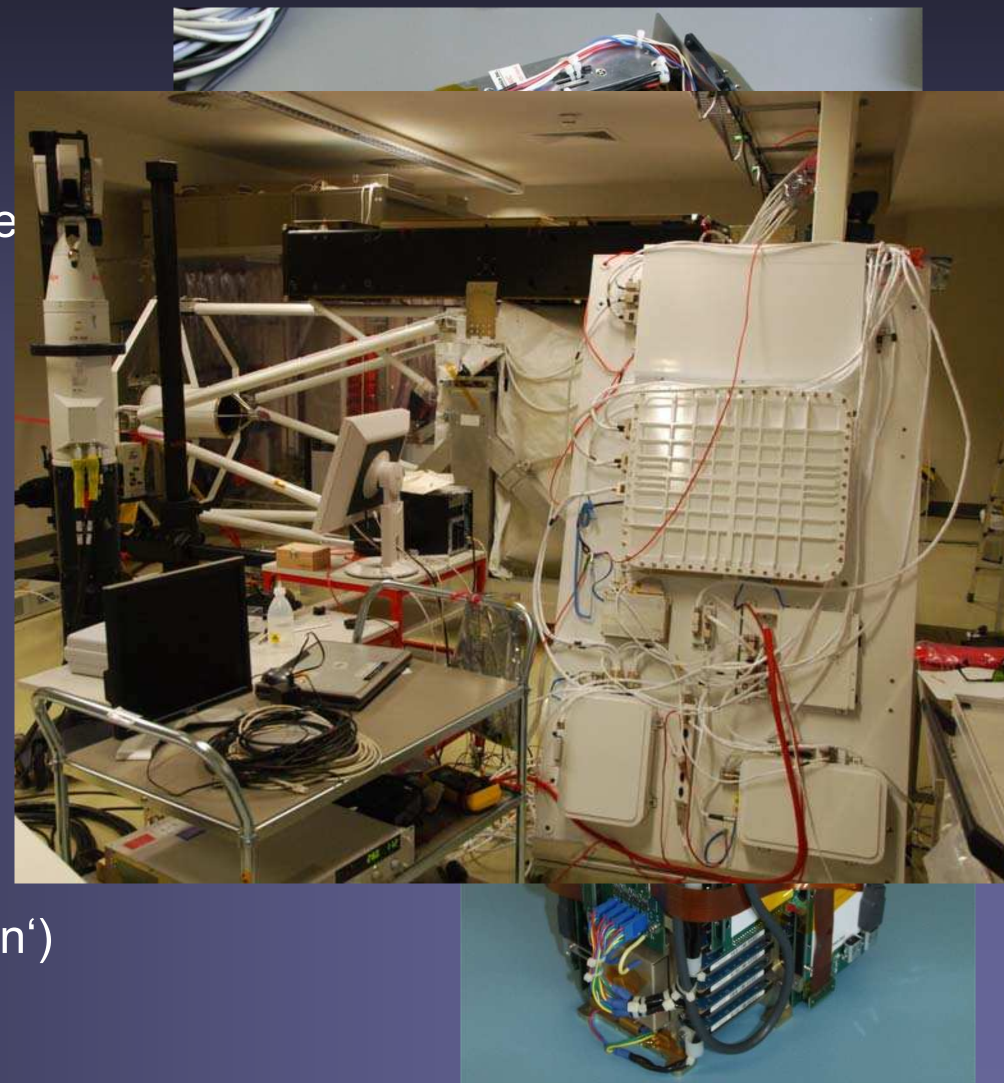


a) Full solar disk with circular telescope FoV

b) science instruments FoV and free range of image stabilization

SUNRISE Electronics

- Instrument Control System
  - Main on-board control computer
  ICU
  - 2 Data storage units (2x 2.4TByte
  science data are stored on-board)
  - 2 Power distribution units
  - Harness
- PFI Instrument electronics
- Pointing system computer
- Power system (solar panels)
- Communication systems
  (‚line-of-sight‘ and ‚over-the-horizon‘)
  →on gondola



SUNRISE Challenges

Technological challenges like in a space project

but

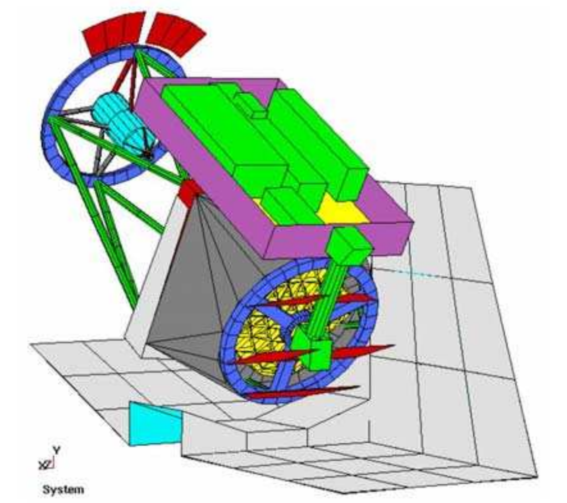
Funding comparable to ground based instruments

- Collaboration of groups with different background, ground based experimenters meet space engineers
- International team, exciting, but also challenging ;-)
- Technical:
  - COTS products, most parts need qualification, modification or encapsulation in pressure vessels
  - No EM or QM on most of the units
  - Thermal, structural, optical issues

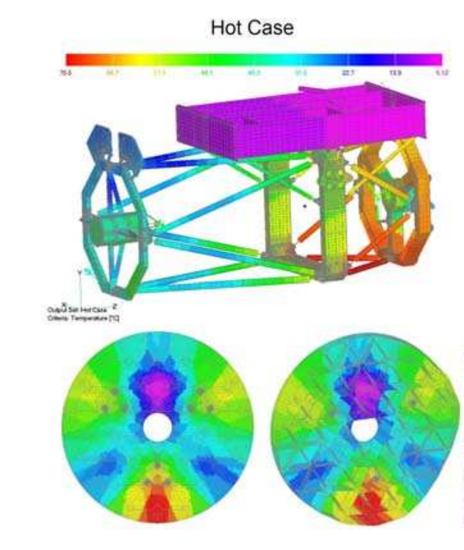
Technological challenge 1: Thermal

- At 3 hPa no convective energy transport
- System is mainly radiatively controlled
- Surface treatments (paints, tapes, foils etc.) are important to control solar absorption (α) and infrared emission (ε)
- Variable energy input (Sun, Albedo) and high power dissipating commercial electronics requires detailed thermal modelling
- Tropopause transit gives temperatures below -60°C
- „Off nominal" conditions need special consideration, i.e. pointing loss or off-pointing

SUNRISE GMM: Rear View with Solar Panels



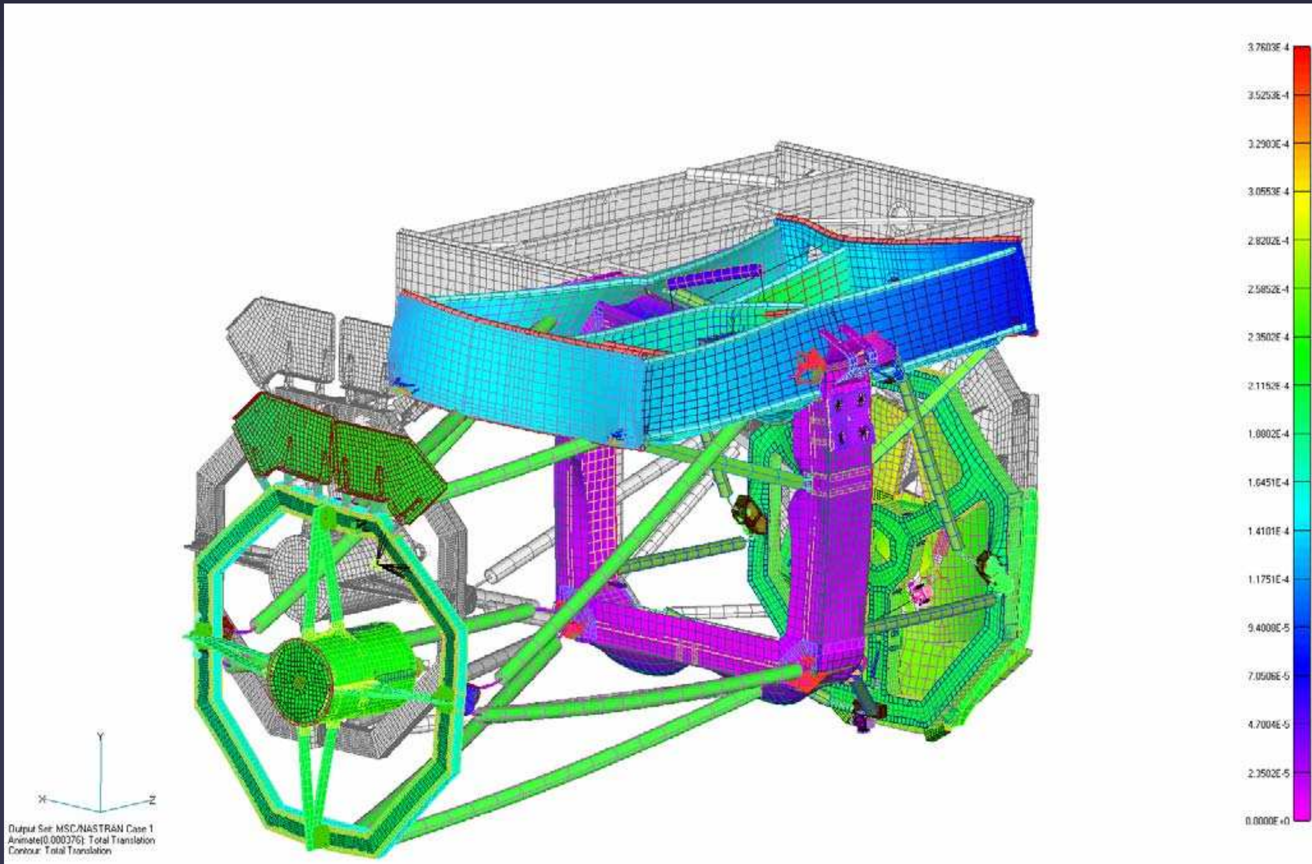
SUNRISE GMM: View into Gondola Cage



Technological challenge 2: Mechanical

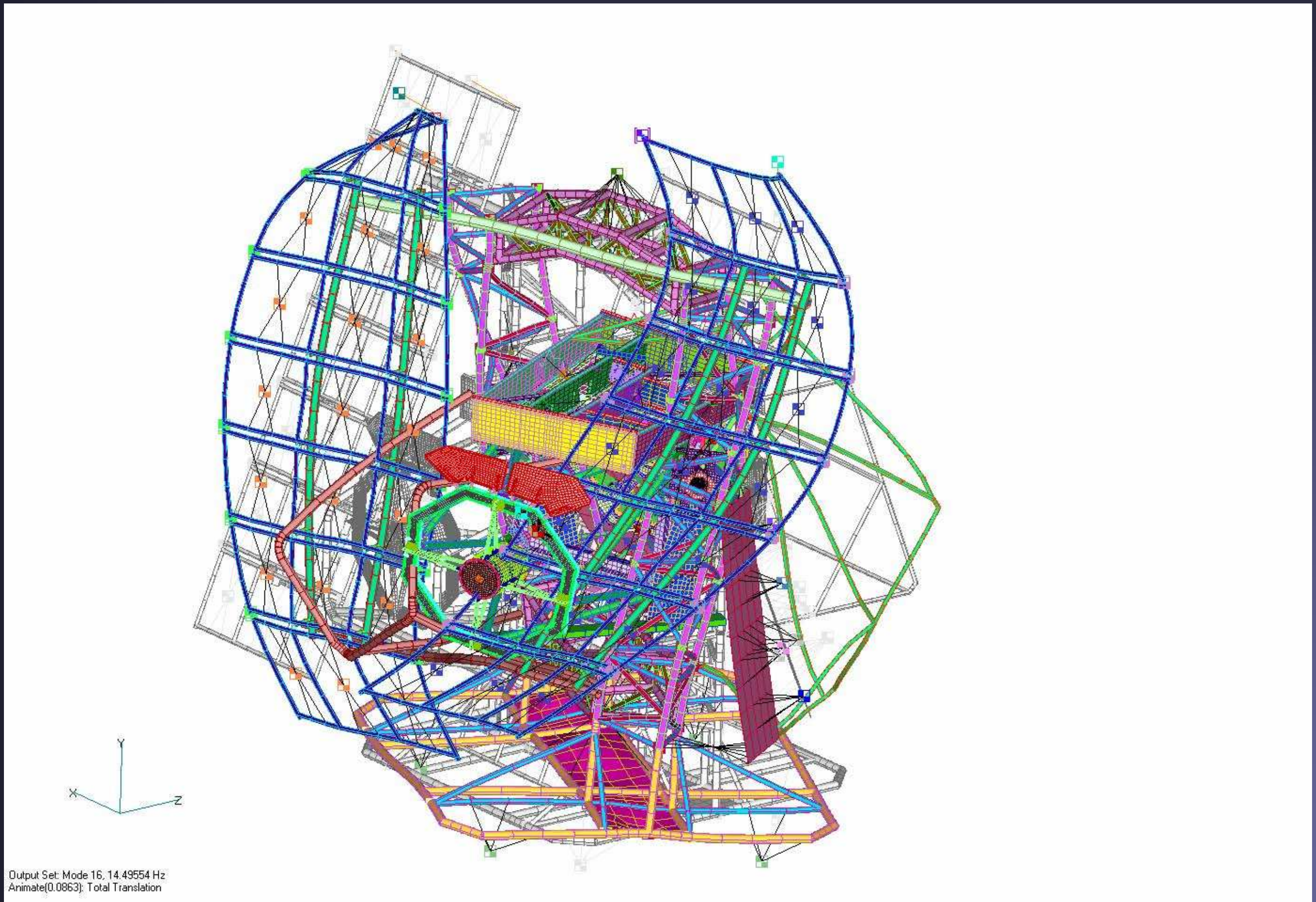
- Telescope in Alt-Az mount: varying gravity vector!
- Instruments piggy-back on telescope
- Demanding requirements on pointing stability

- Detailed structural analyses and high structural stiffness



Structural Deformations under 1g Load

Technological challenge 2: Mechanical

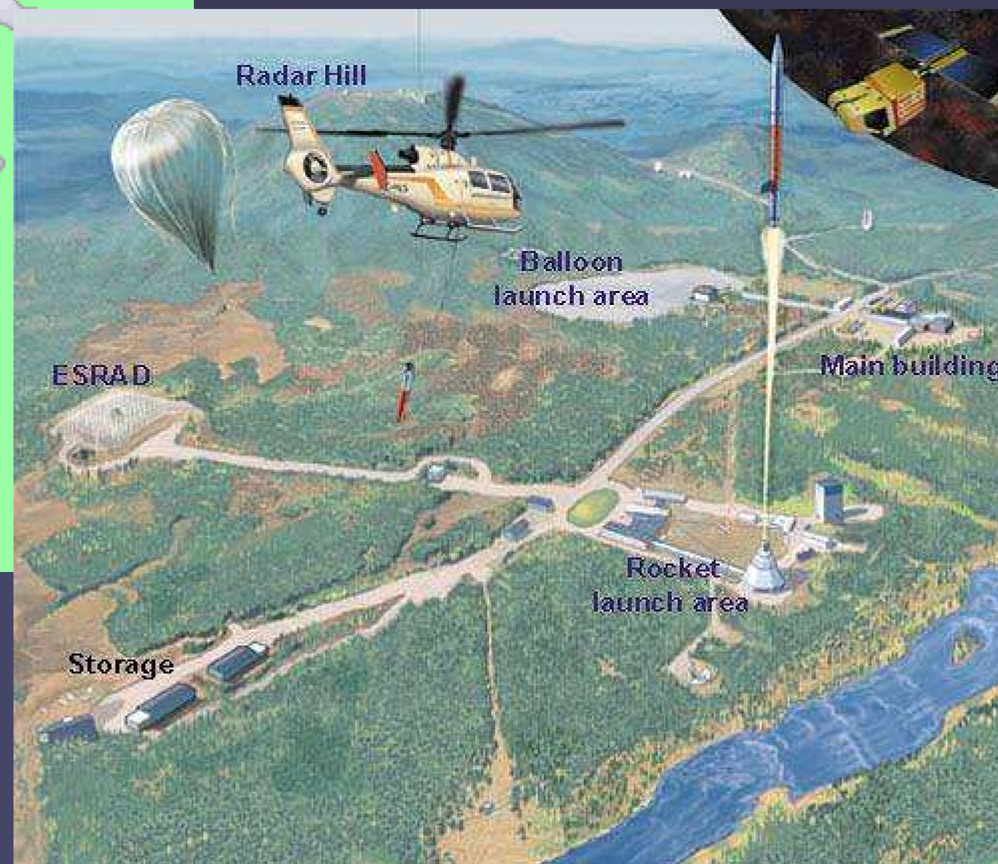


Eigenfrequency assessment, decoupling important for pointing control loops

Technological challenge 3: Optical

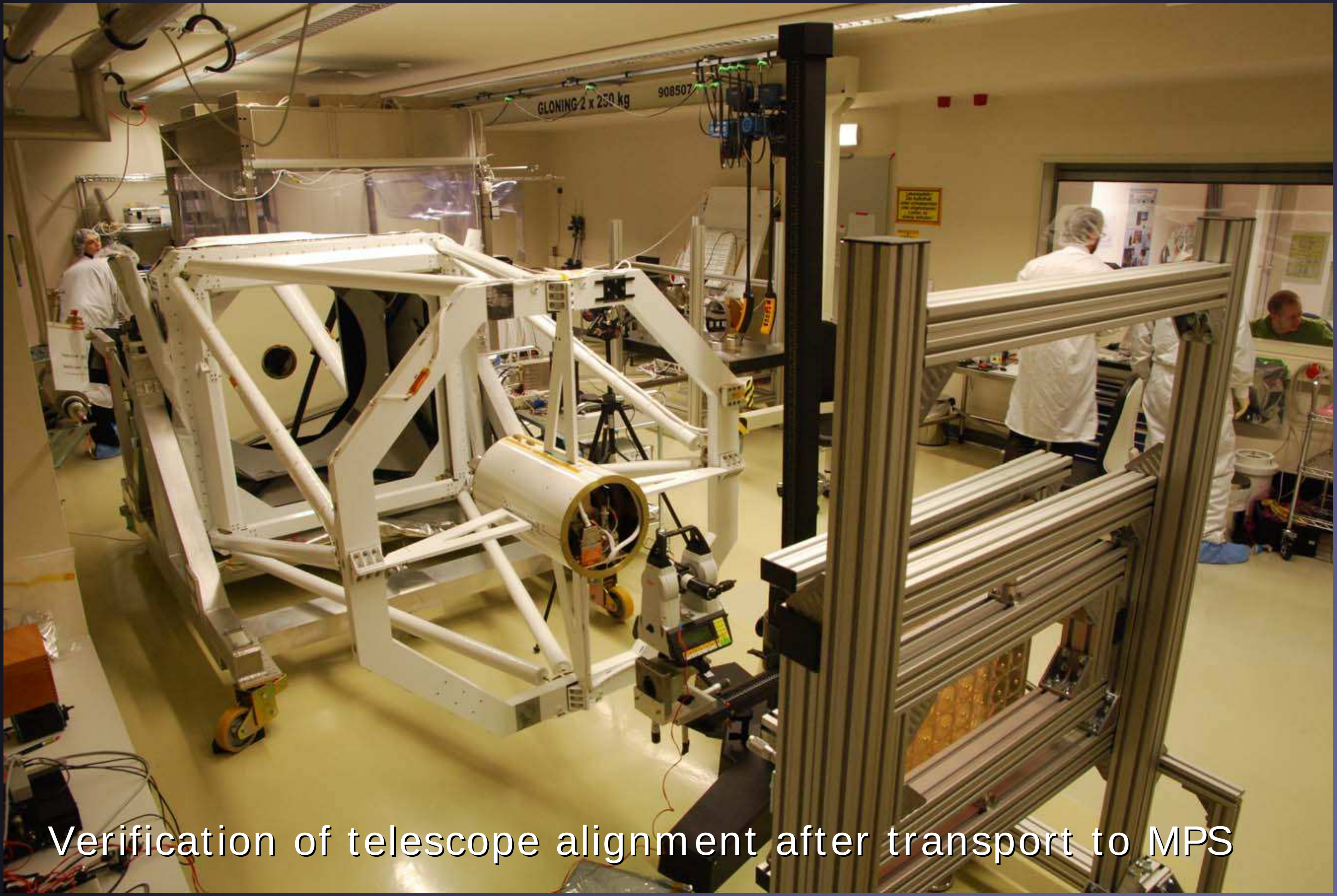
- Lightweighted 1 meter primary mirror with diffraction limited performance is a challenge of its own, long lead item (2.5 y)
- UV optics asks for contamination control (particles and molecular)
- Polarization optics requires careful design of coatings, mechanical mounts (bi-refringence) and temperature stability
- Telescope in-flight alignment stable to 1 µm (actively controlled)
- High spectral resolution requires calibration with real sunlight
  On-ground system tests after assembly/integration

Mission Preparations Spring 2009



Destination:
ESRANGE 68°N, 21°E
close to Kiruna
(Northern Sweden)

SUNRISE Telescope Characterization @MPS



Precision Alignment and Functional Testing

Instrumentation mounted on telescope

Packing and Shipment of SUNRISE

The telescope being stowed in a dedicated sea-container

Packing and Shipment of SUNRISE

Crane lifting of telescope container

Packing and Shipment of SUNRISE

Several tons of equipment leave the institute on March 27, 2009

Shipment of Telescope+Instrumentation

A few ‚meters‘ to ESRANGE, after 2400 km driving...

ESRANGE: the „cathedral˝

Unloading the telescope

April 1: Instrument check-out and integration starts

April 18: Integration of telescope/instrumentation into gondola

May 15: Telescope first light

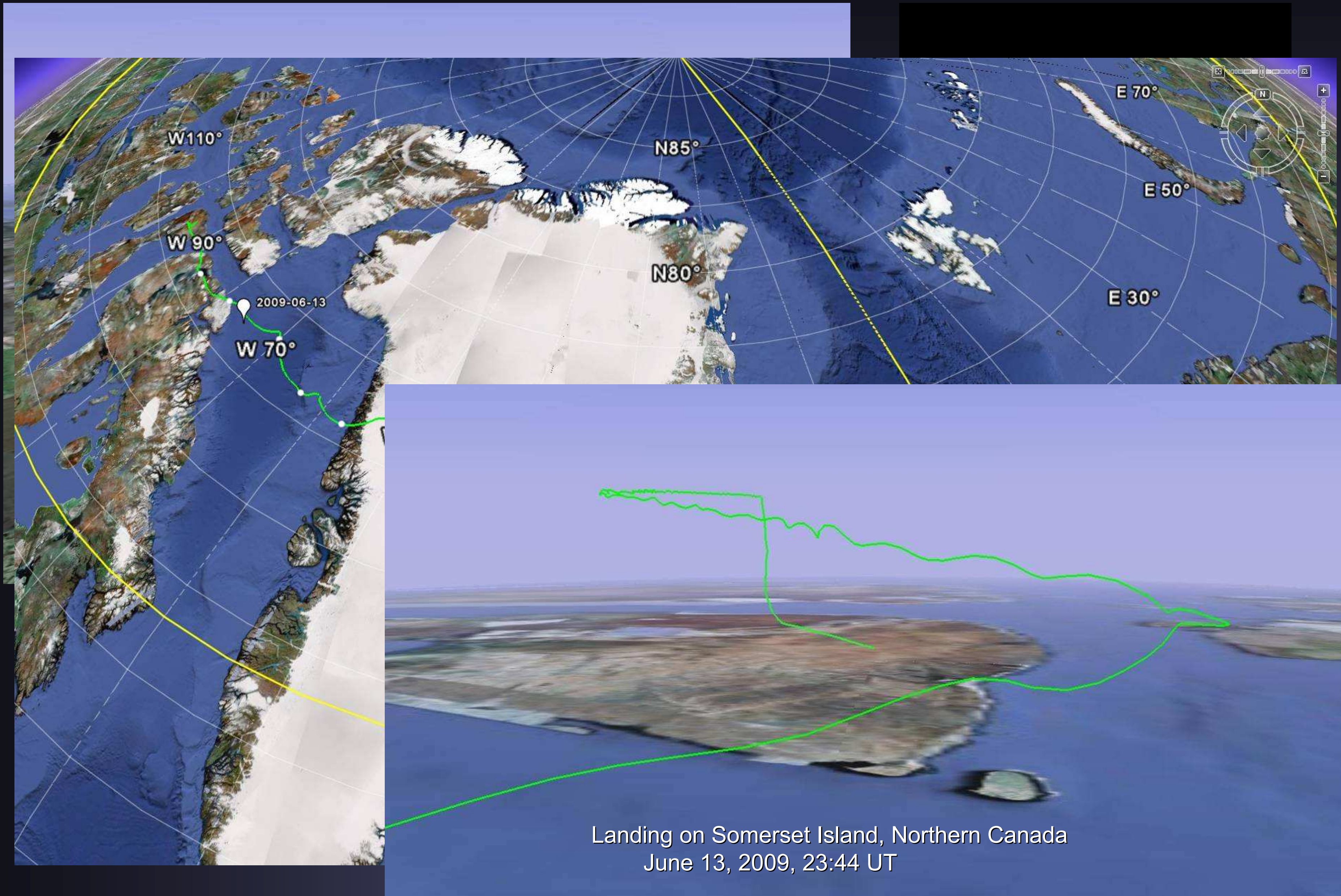
3 Days of Solar pointing …

Compatibility Test May 30, 2009

Launch on June 8, 08:27 LT

Launch in Esrange, Sweden

8th June 2009



SUNRISE trajectory, ~134 hours (~6d) at 34-37 km float altitude

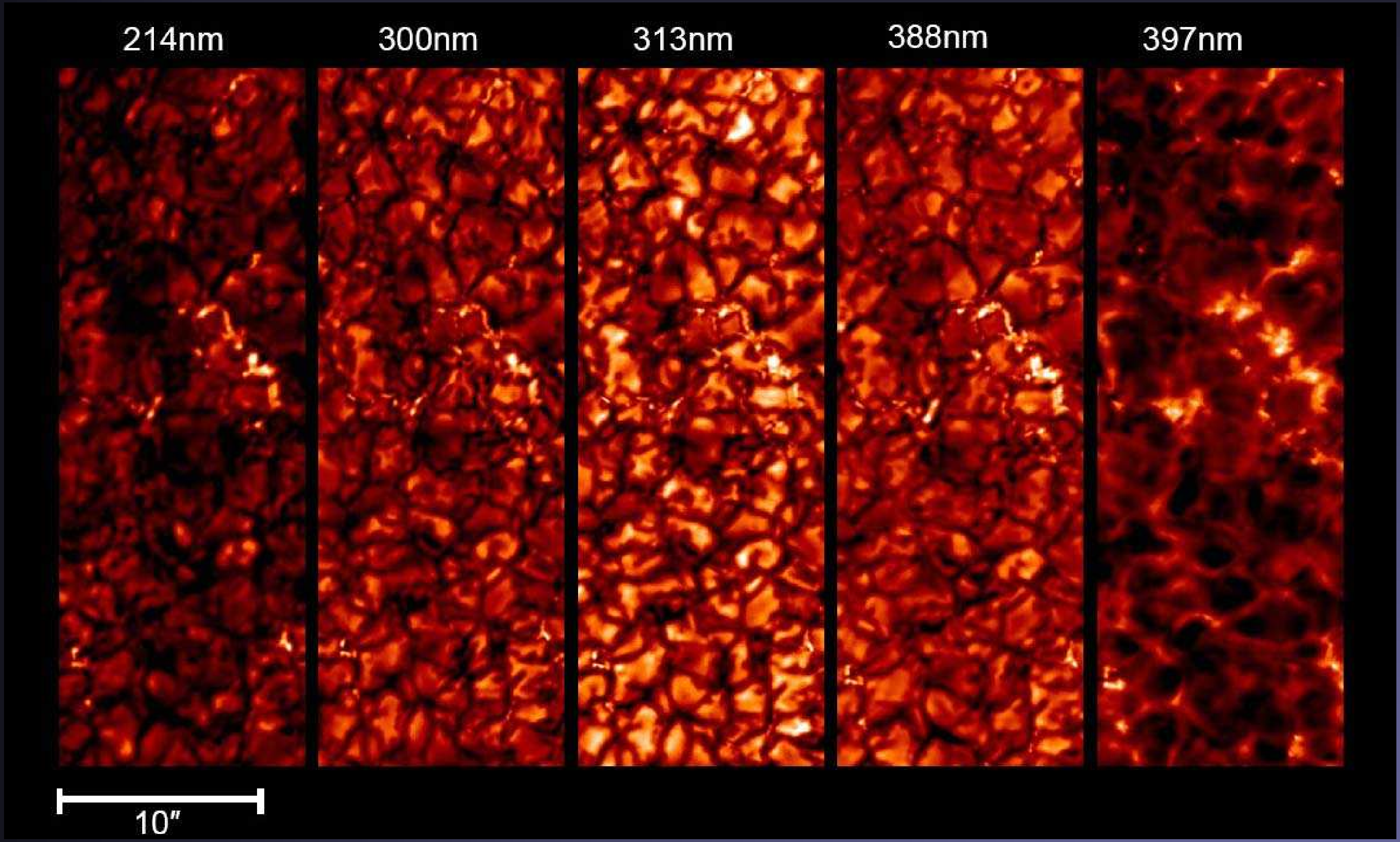
Recovery from Somerset Island
via Resolute Bay and Yellowknife June 17-23, 2009

First Results

- Telescope and instrumentation worked flawlessly
- More than 1.8 TByte science data, IMaX ~480.000 img, SuFI ~150.000 img
- About 33 hours of observation at various pos. on the Solar disk, incl. limb
- Several continous time series of more than 30 min length
- Achieved spatial resolution: ~0.1 arcsec, ~100 km @ solar surface

- 12 science papers submitted to *Astrophysical Journal*,
  4 instrument papers submitted to *Solar Physics*
- SuFI images show RMS intensity contrast of granulation in the UV of up to 30 %, consistent with numerical simulations
- Bright points in the UV at 312 nm, 300 nm and 214 nm reveal very high intensities, up to a factor 5 above the mean brightness at 214 nm
- High-resolution time sequences of vector magnetic field maps reveal very dynamic small-scale fields
- First ever spatial resolution of the magnetic and brightness structure of small-scale intense magnetic flux concentrations

SUFI Images



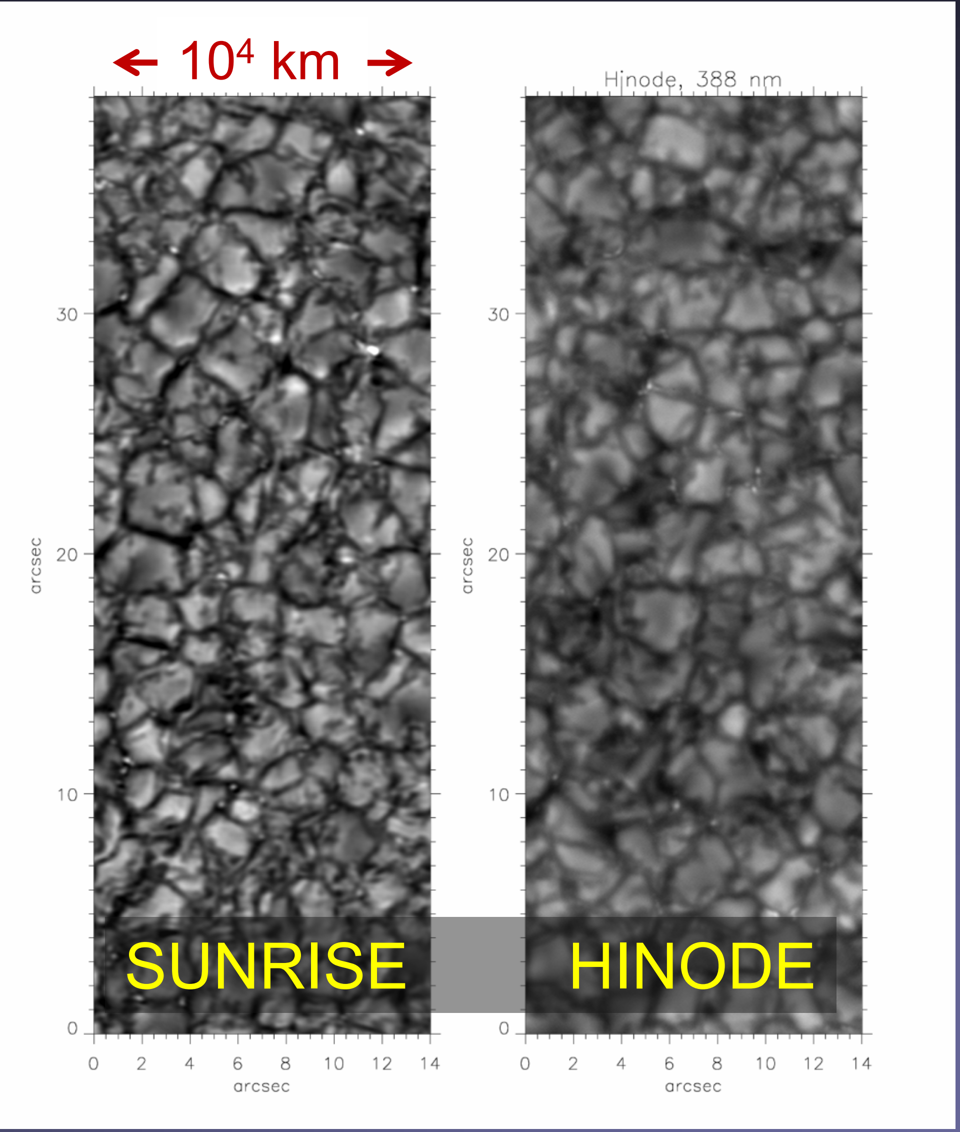
Comparison SUNRISE with HINODE Data

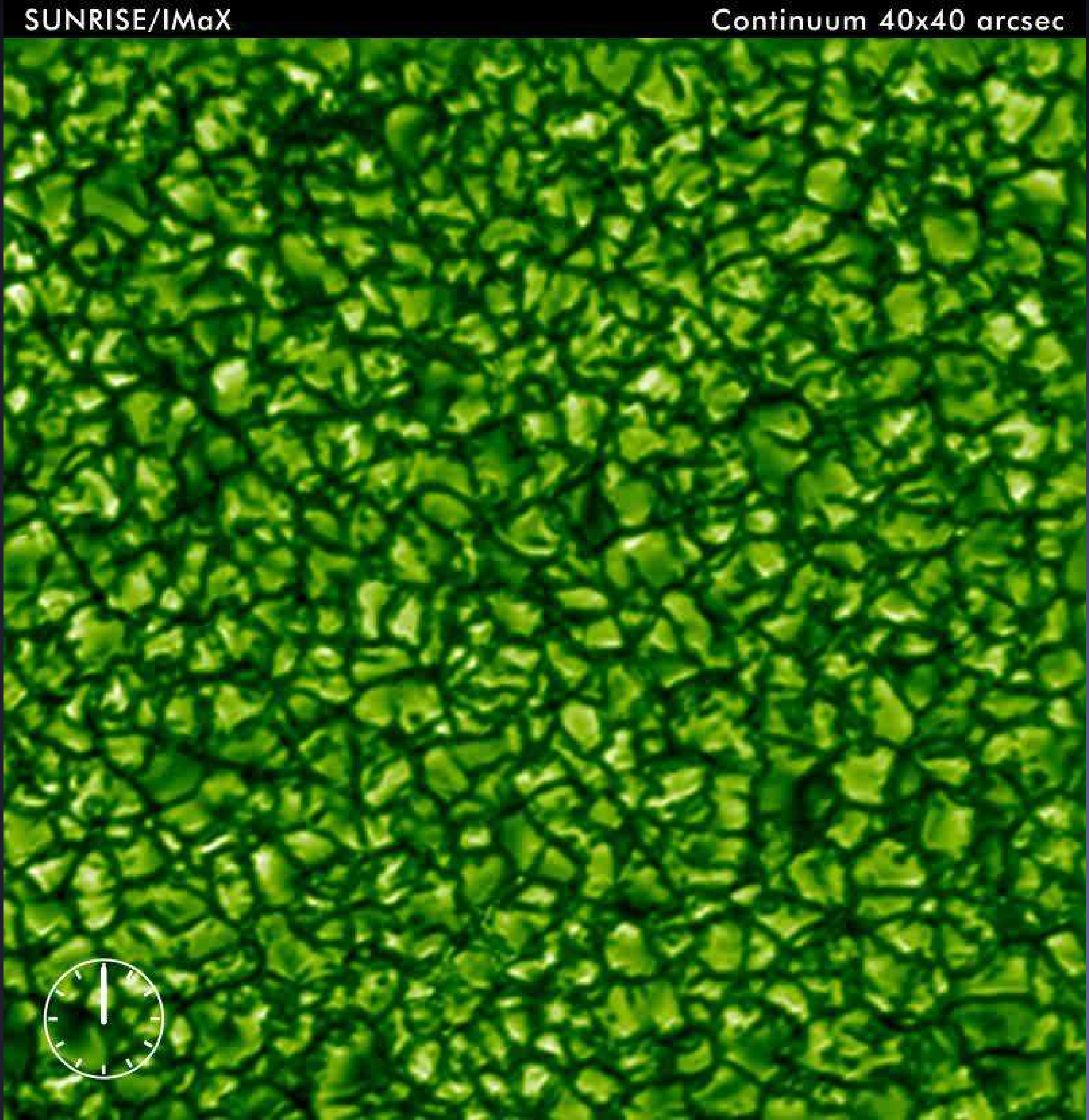
SUNRISE: SUFI 388 nm
(filter width 0.8 nm)

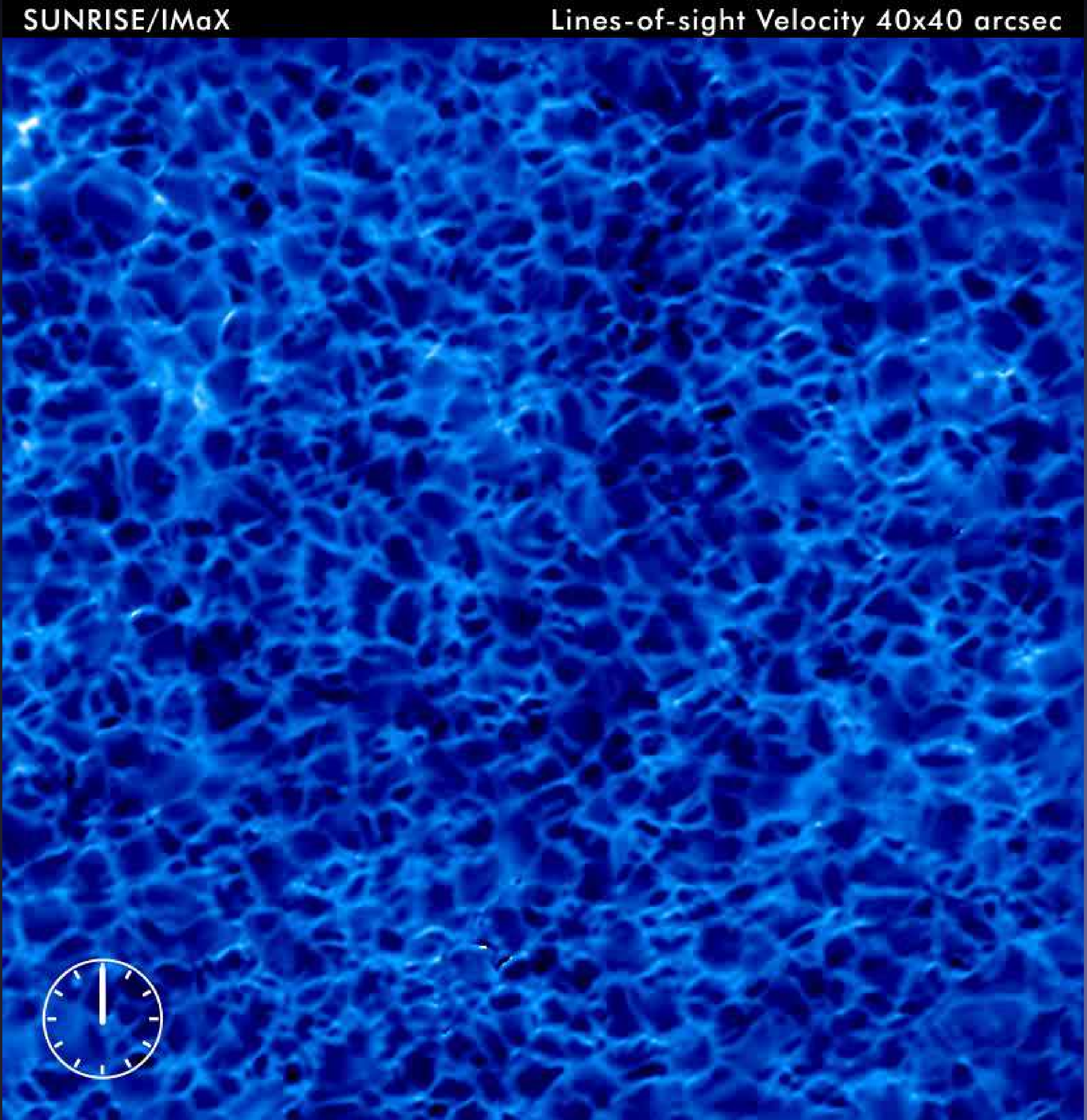
HINODE: BFI 388 nm
(filter width 0.7 nm)

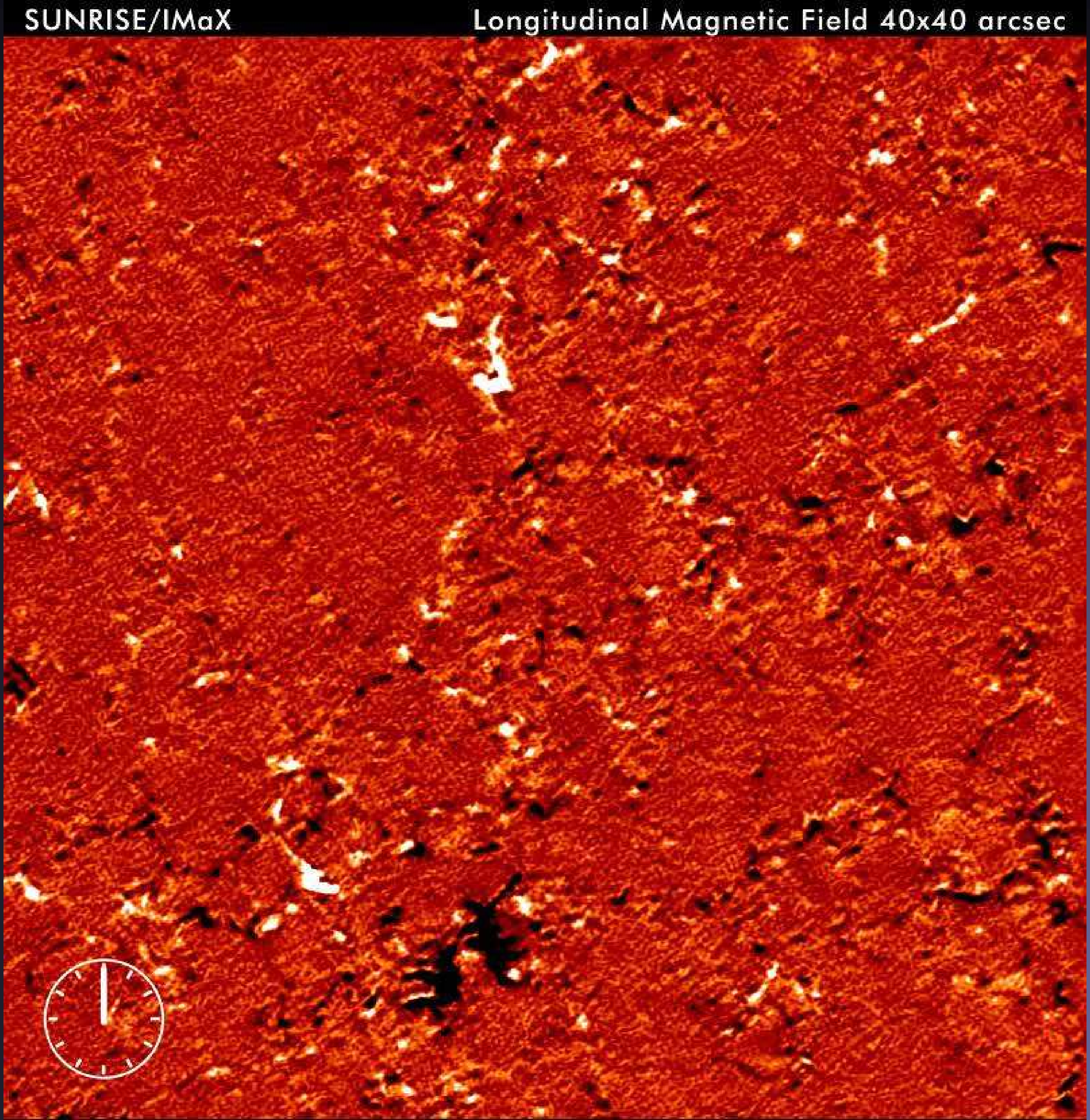
Same grey scale

Note that the two images were not taken simultaneously (different granules), but both refer to quiet Sun at $\mu = 1$




SUNRISE/IMaX
Continuum 40x40 arcsec


SUNRISE/IMaX
Lines-of-sight Velocity 40x40 arcsec


SUNRISE/IMaX
Longitudinal Magnetic Field 40x40 arcsec

Outlook

- Data will be available to science community very soon (open access)
- Data analysis is ongoing, next round of publications submitted in near future

- We plan for a second flight, target 2012 (higher solar activity)
- Improvements shall be implemented for
  - ‘over-the-horizon’ telemetry and
  - stability of telescope pointing

Thank you for your attention