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Future Synoptic Ground-based Network
–
Result of the SPRING
Feasibility Study

Markus Roth + Solarnet WP80 Team

Splinter Meeting on Synoptic Observations
Göttingen, October 16, 2017

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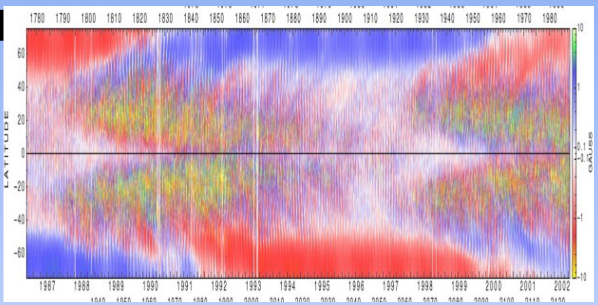
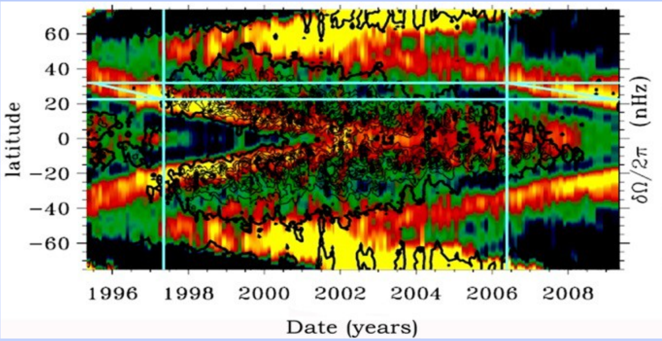
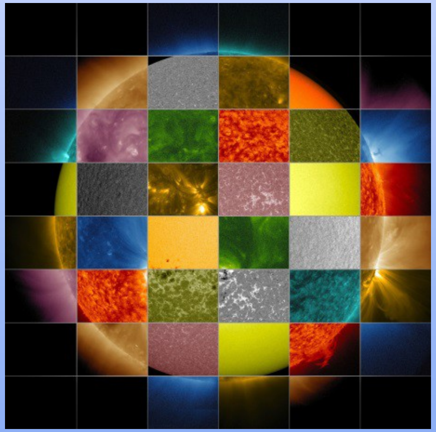


- **Long term monitoring of the solar magnetic fields**
  - to understand solar dynamo
  - evolution with solar cycle (polar and active region fields)
  - Active region evolution for space weather studies
  - surface flows via feature tracking



- **Long term monitoring of velocity fields**
  - subsurface flows via helioseismology
  - solar cycle variations and relationship to solar dynamo
  - Flows beneath emerging flux regions and active regions for space weather studies



- **Context imaging for next generation high-res telescopes such as DKIST and EST**
  - Large scale effects (flares, filament eruptions) of small scale events such as flux emergence
  - Technically the fulldisk image could support the pointing system

* **Hill, F. *et al. Space Weather, 11, 392, 2013***

* **Elsworth, Y . *et al., Space Sci. Rev., 2015*, *193,137***

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Future synoptic observations: Solar Physics Research Integrated Network Group (SPRING)

Objective: Development of instrumentation for large field-of-view observations of the Sun with a network of solar telescopes in support of observations with existing high-resolution solar telescopes (either isolated or in a coordinated way).

Technical Requirements / Future synoptic telescopes should provide

- Full-disk Doppler velocity images
- Full-disk vector magnetic field images
- Full-disk intensity images
- Measurements of quantities relevant for space weather

- Provide the above data products in a variety of wavelengths
- Provide the above data products at a high cadence (≤ 60 seconds)
- Provide the above data products at a spatial resolution of 1” (0.5” pixels)
- Provide the above data products at least 90% of the time
- Provide the above data products for at least 25 years
- Complement space missions

Participants:

KIS, IAC, INAF, MPS, QUB, AISAS, AIASCR, IGAM, UoB, NSO, HAO

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SPRING Activity – Three Working Phases

1. **Science requirement study**
   - describe the supporting data required by high-resolution observing programs
   - the scientific objectives to be achieved by high-quality synoptic observations
   - study of the relation with other existing ground-based solar observation networks

To be studied:

- List of small aperture telescopes and other ground-based solar observations networks available
- Develop a strawman document discussing the goals and preliminary support instrumental concepts
- **Write a Science Requirement Document (SRD) which shall be consistent, tangible and in accordance with other plans for the next 25 years (commissioning of large–aperture telescopes, space missions, etc.)**
  □ delivered with the 2nd report

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SPRING Activity – Three Working Phases

2. Feasibility study

2.1 Instrument design concepts

Definition of technical requirements for the instrument, based on scientific goals

Definition of alternatives of instruments concepts

To be studied:

- Adaptive optics or other image stabilizing/enhancement technology
- Observations in at least the following spectral lines: Ni I 6768, Fe I 6301/2, Na D, H-α, Ca K, Ca H, He10830,Fe I 6173 and Fe I 1.5 micron.
- High-speed image post-processing / High-speed real-time data access
  → **Fast determination of Dopplergrams**
- Location of telescopes for setting up a network mode → **BiSON/GONG experience**
- Possible instruments concepts:
  Filtergraph, Spectrograph and Interferometer, each one with different options

2.2 Operational concepts

Develop operational ideas (remote operations, data pipelining, delivery of real-time data to operating telescopes)

Develop high-speed image post-processing routines

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Science Requirements

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Working Groups

Group 1: Synoptic magnetic fields
- Sunspots (problems with cool atmospheres)
- Active regions
- Quiet Sun magnetism
- Synoptic Hanle Observations

Head: A. Pevtsov

Group 2: Solar seismology
- Waves (solar interior)
- MHD waves (magnetoseismology)
- Velocity field inside and on the Sun

Head: R. Jain

Group 3: Transient events
- Flow of energy through the solar atmosphere (3,2)
- Transient events (flares, prominences, CMEs)

Head: M. Sobotka

Group 4: Solar Awareness
- TSI / SSI
- Space Weather (4,3)
- Space Climate
- Sun-as-a-star

Head: I. Ermolli

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Workshops

ynoptic Network Workshop, 22. – 24.04.2013, Boulder, USA
st SPRING Meeting, 25. – 28.11.2013, Titisee, Germany
nd SPRING Meeting, 25. – 28.11.2015, Tatranska Lomnica, Slovakia
rd SPRING Meeting, 15.–17.05.2016, Boulder, USA

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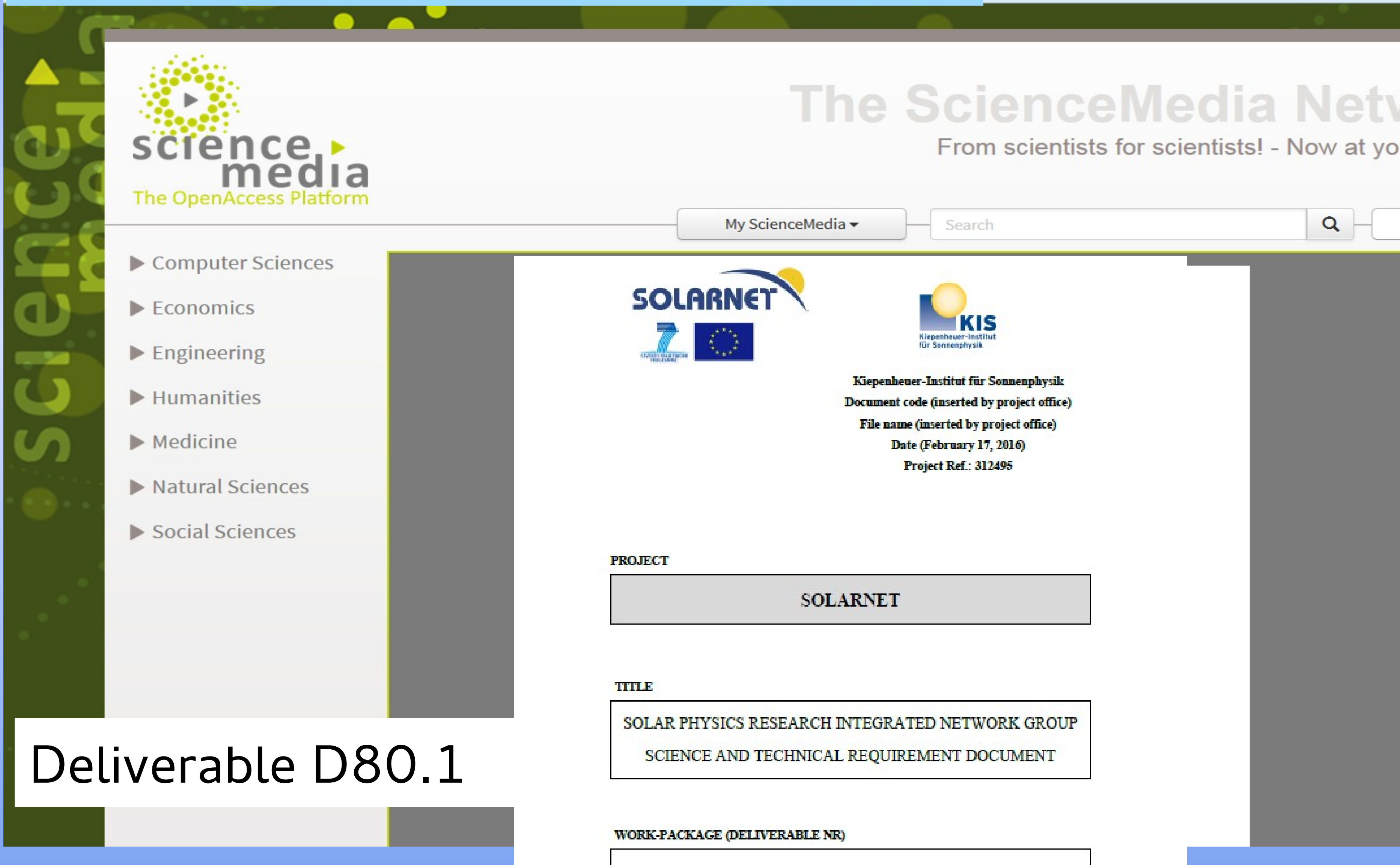
Science Requirement Document

http://www.science-media.org/cid/spring2016 -> papers



Deliverable D80.1

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Observational Requirements for SPRING

HIGHLIGHTS:

GOAL	Obs. Params	Cadence	Spectral/Spatial
Long–term behavior of solar magnetism	Accurate vector Magnetic Field measurements Senstivity Goal: B-los <1G, B-trans <50G	Few per day (long-term statistics only, not for short term evolution)	High spectral resolution (spectrograph), Fulldisk, seeing limited spatial resolution, Sensitive polarimetry.
Long–term behavior of solar internal flows	Accurate velocity field Measurements Sensitivity Goal: vel <10m/s	For photosphere: ~1 min, chromosphere ~30 sec	Moderate spectral resolution (filtergraph), fulldisk, seeing limited, Sensitive Doppler measurements
Space weather	High-cadence vector magnetic fields Sensitivity Goal: <10G for B-los, <150G for B-trans	Photo & Chromosphere: ~5-10 minute	Moderate spectral (filtergraph), fulldisk, seeing limited
High Resolution Contextual Imaging	High-resolution images of the sun in various wavelengths	Broad and Narrow band images at a cadence of 1 per minute	High spatial resolution (~1 arcsec; 4kx4k), fulldisk acquisition, Tip-tilt system for image stabilization **Image reconstruction only for desired FOV

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Feasibility Study

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Instruments Wishlist

- Vector Magnetograph
- Broad band imager
- Disk-integrated spectrograph (high spectral resolution)
- Multi-lambda-helioseismic-Doppler-imager-and-magnetic-field
- Irradiance device (resolved)

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Expected Improvements: Magnetometry

Multi-line high-resolution magnetic observations of the Sun

Several Advantages:

- 3-D magnetic topology of active region magnetic fields
- Improved coronal field extrapolations due to force-free behavior in upper layers of solar atmosphere.
- First ground based continuous vector magnetometry for near real time space weather predictions.
- Flare related changes in magnetic fields and electric currents in the chromosphere.
- Long-term magnetic field records with improved spatio-temporal resolution.

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Expected Improvements: Helioseismology

Multi-line high-resolution Doppler observations of the Sun

Several Advantages:

- Improved accuracy and precision of helioseismic mapping, in vicinity of active regions (Hill 2009).
- Reduction in systematic errors (i.e., improved accuracy) (Baldner & Schou 2012)
- Also, multi-height observations are useful for seismic mapping of solar atmosphere (Wisniewska et al. 2016, Finsterle et al. 2014, Nagashima et al. 2009).
- Transportation of convective energy through solar atmosphere (Jefferies et al 2006).

..... more details in the review by Elsworth et al., 2015, Space Sci. Review, 193, 137

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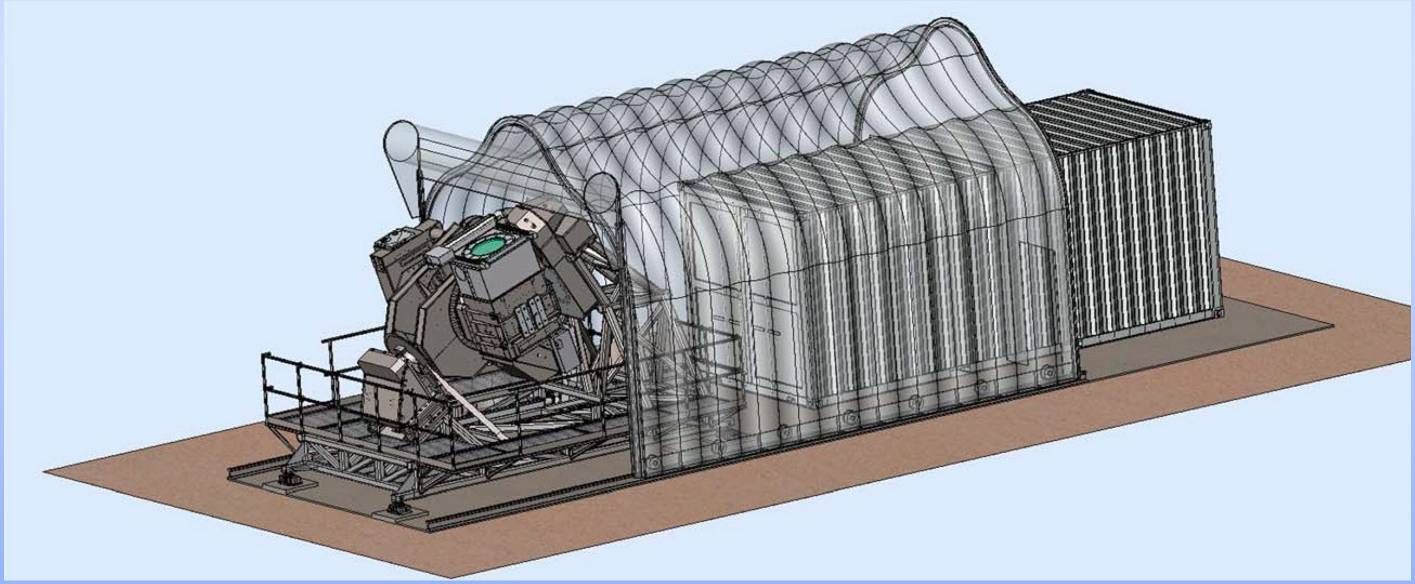
Technical Requirements for SPRING

HIGHLIGHTS

KEY IDEA SIMPLICITY

 SINGLE instrument can not do the job, even if it can, its complexity would lead to higher costs and low MTBF (mean time between failures).

 MULTIPLE instruments on a single platform is the way to go.



Automated equatorial mount hosting multiple independent instruments with retractable dome and container for computers.

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Technical Requirements for SPRING

HIGHLIGHTS

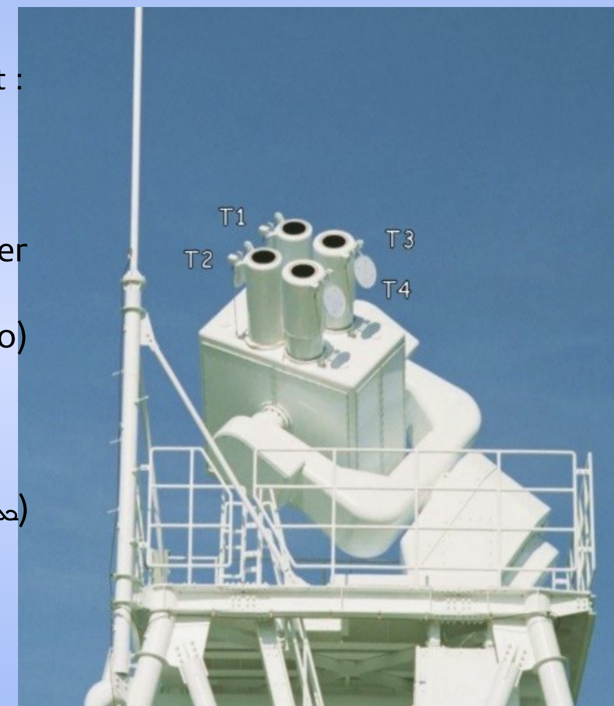
SOLIS

Representative Examples for the concept :

1. SOLIS NSO
   - -Spectro-Polarimeter
   - -Fulldisk Patrol Telescope
   - -Integrated Sunlight spectrometer

2. SMART (Hida Obsrvatory, Kyoto)
   - -Fulldisk H-alpha Imager
   - -Fulldisk vector Magnetograph
   - -High-resolution Magnetograph
   - -High-resolution Flare patrol (Hα)

3. SFT Mitaka, Japan
   - -H-alpha fulldisk
   - -Whitelight fulldisk
   - -Infrared spectropolarimeter
   - -G-band imager



SMART

SFT

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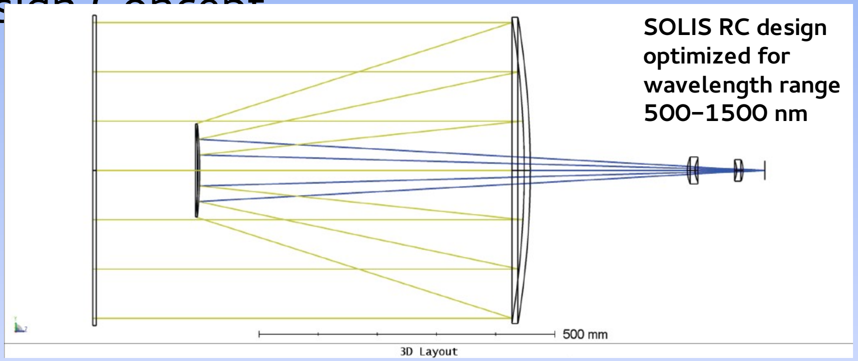
Science Goal: Long-term behavior of solar magnetism

Front-end Design Concept



SNR Req: Accurate spectropolarimetry of the solar magnetic fields typically requires SNR in Stokes measurements

- $Q,U,V/I_{cont}$

~ 1000 for photospheric fields, and

~10000 for chromospheric magnetic fields

Other requirements:

- Spatial sampling: 1 arcsec/pix (2arcsec res.; 2kx2k)
- Spectral Res.: 200,000
- Temporal: every 2-3 hours /Fulldisk
- Spectral lines: in photospheric and chromospheric spectral lines (525.0, 617.3, 630.2, 589.6, 854.2, 1083.0 nm, and 1.5 micron)

Front-end telescope design:

- D=50 cm; Polarization free; Helium filled
- Ritchey-Chretien Design with secondary as tip-tilt
- Wavelength range: 500-1500 nm
- Diffraction limited over full field
- Cooled secondary

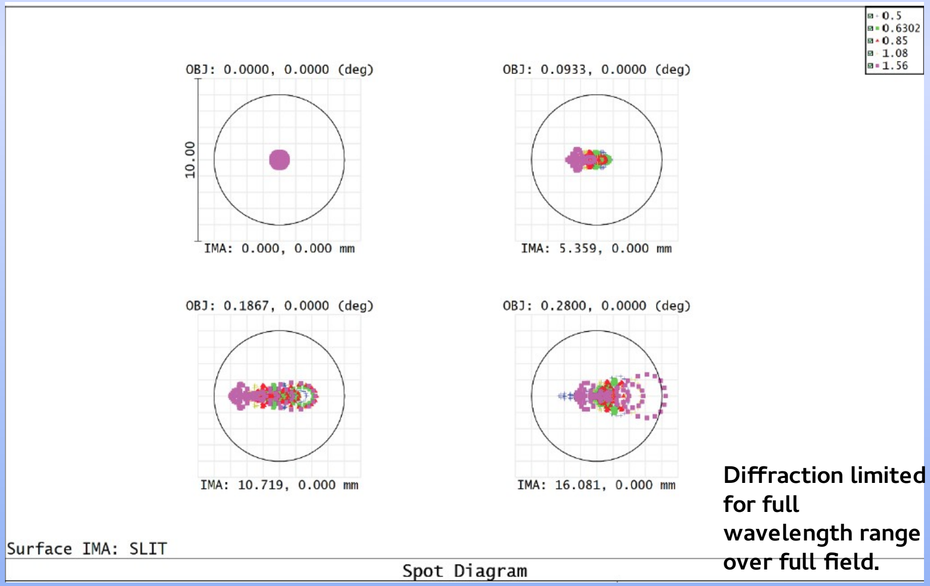


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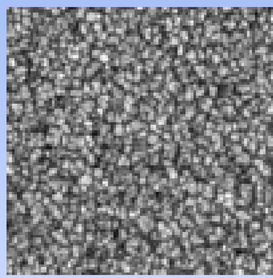
Image Stabilization

Image motion: Effect on image subtraction



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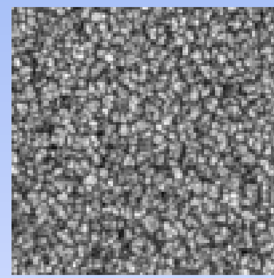

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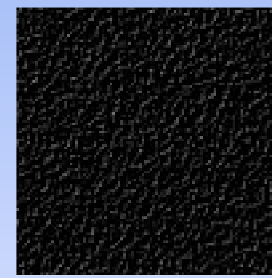
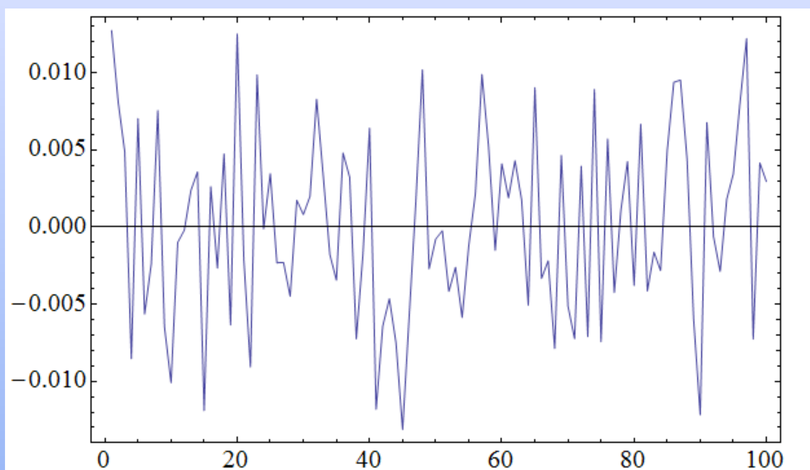
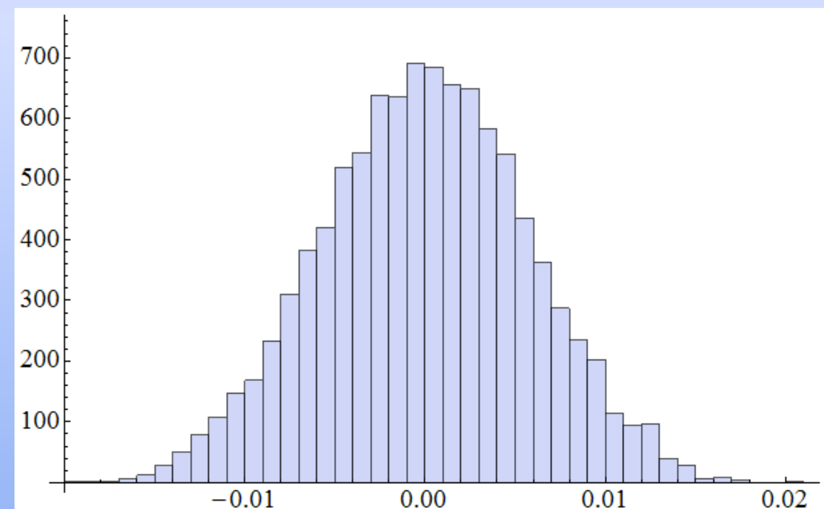


Example: shift by 0.1 pixel □ 10^{-2} noise





□ Image stabilization needed, dual beam polarimetry desirable

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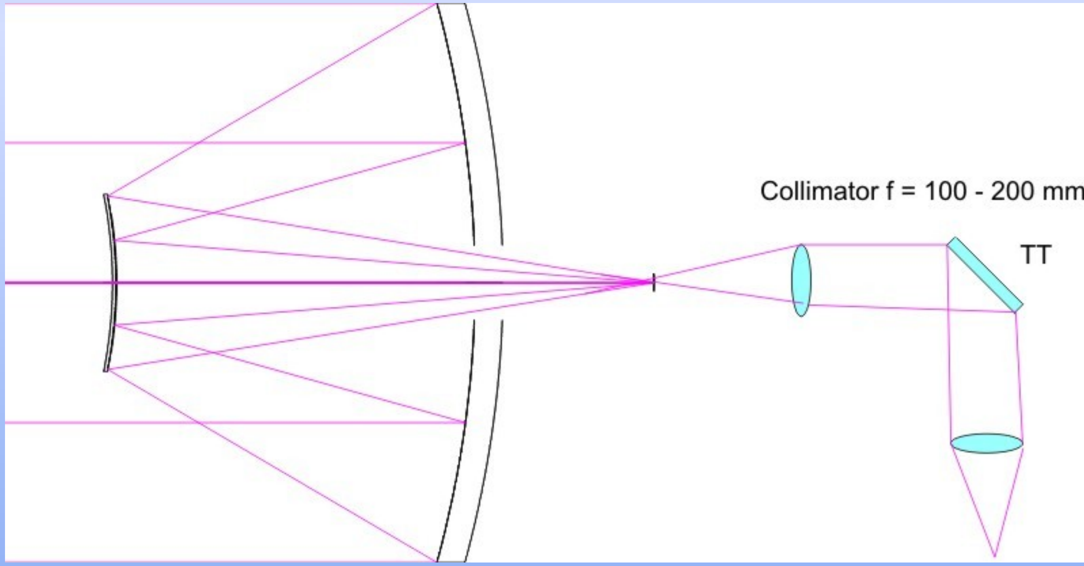
Image Stabilization?

- Main cause probably instrumental:
  - spatial dimensions: 1m □ 1 arcsec = 5 µm at the mirror edge
- Clearly: Full-AO not possible
  Suggested concepts:
  - low-order AO
  - Tip-tilt mirror



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Science Goal: Long-term behavior of solar magnetism

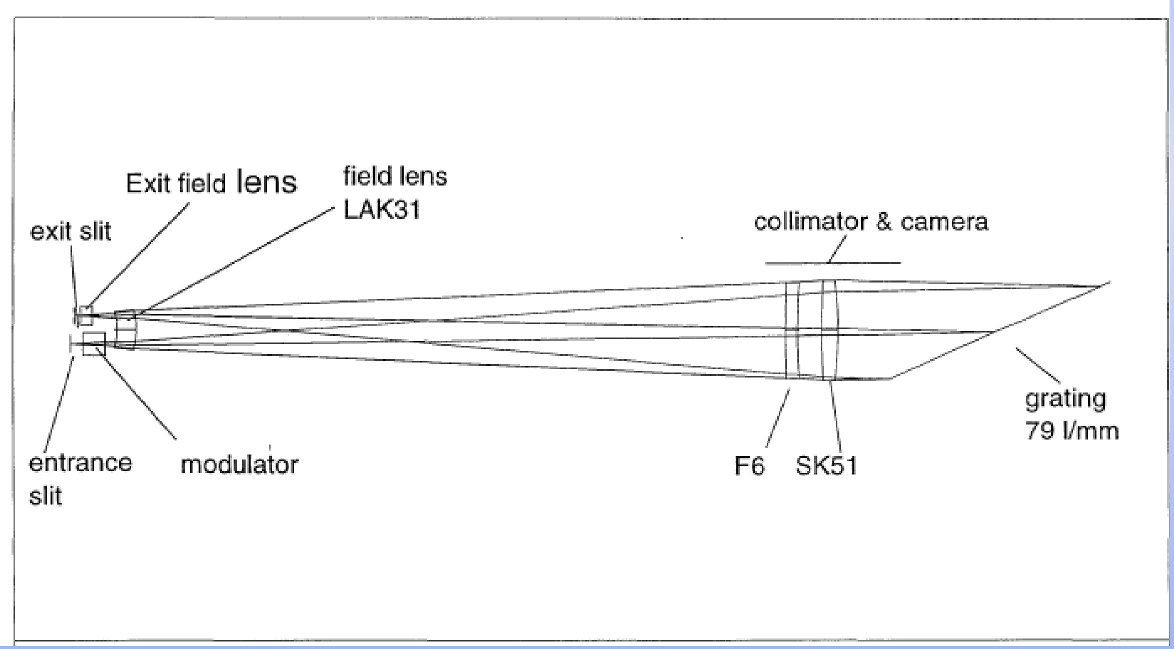
Back-end Design Concept

Spectrograph Requirements:

- Littrow configuration
- Echelle Grating 408x204 mm, 79 l/mm, Blaze angle: 63.5 deg.
- Spectral Res.: 200,000
- Focal length : 1100 mm
- Wavelength band: 525-1565 nm

Modulator Requirements:

- Ferroelectric liquid crystals for fast modulation
- Fast CCD/CMOS camera
- Calibration optics before prime focus
- Dual beam analyser (Polarizing beam splitter, dual camera)
- Beam exchange for higher SNR



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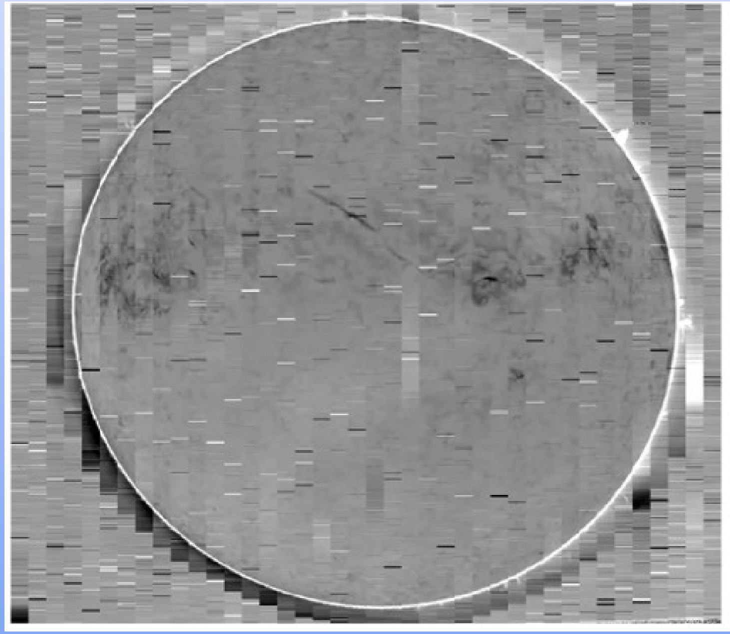
Spectrograph (Feasibility)

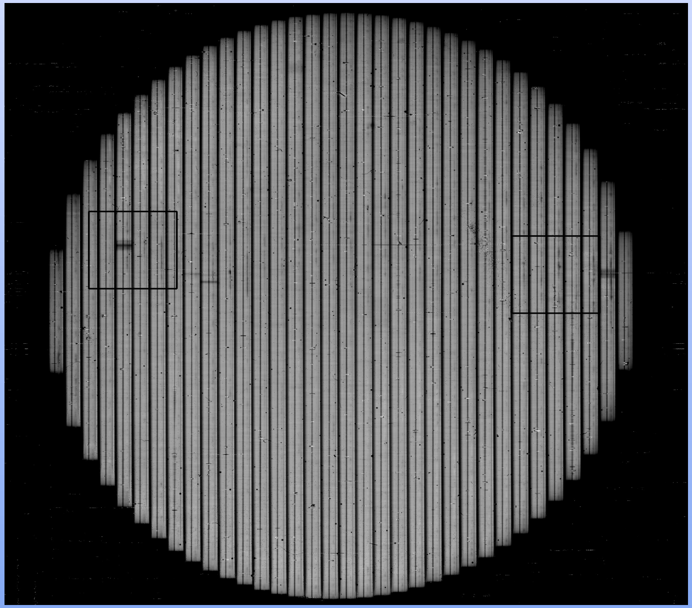
- **Slit spectropolarimeter:** e.g. SOLIS/VSM
  - Cadence is ~20 minute for full disk vector magnetogram with single slit.
  - Multiple-slit design can be implemented for improved cadence

Haosheng Lin from IFA, Hawaii carried out multi-slit demo. Observations with NSO DST for Stokes-I in He 10830, achieving cadence of 1 minute with 35 slits.

Reconstructed Line Core Image



Sample 35-Slit Full Disk Spectral Image



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Science Goal: Long-term behavior of solar internal flows
Front-end Design Concept

For Doppler measurements in different spectral lines:
One only needs moderate sized aperture

Most of photospheric lines:
Sensitivity of 10 m/s can be reached with an aperture size of 20 cm
Chromospheric lines one needs to integrate more photons.

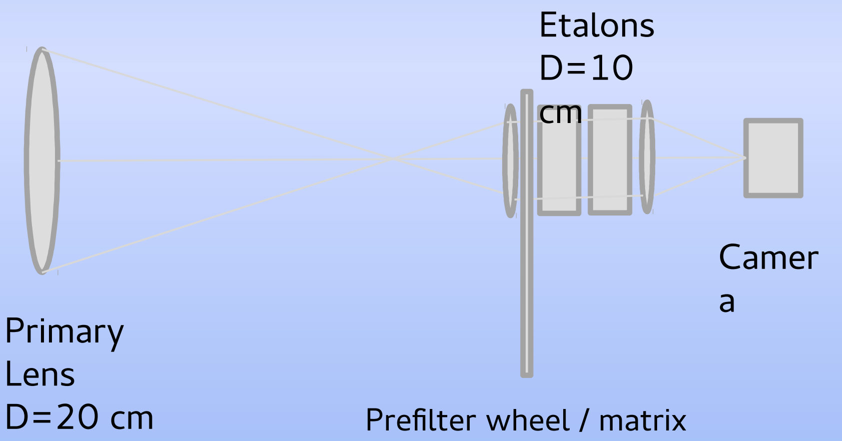
Temporal cadence requirement:
dictates that a tunable filter with high throughput, such as Fabry-Perot interferometer, must be used.

To achieve the requirements of
- multiple lines
- velocity sensitivity
- SNR
- and the fact that different cameras and etalons will be needed for infrared measurements

We split the instruments into two

Identical setups, one for visible (500–750nm) and another for infrared (800–1500nm)

Optical Setup:
Achromatic Doublet
D=20-25 cm
f/D=10
Relay optics: Achromatic wide field



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Science Goal: Long–term behavior of solar internal flows
Back–end Design Concept

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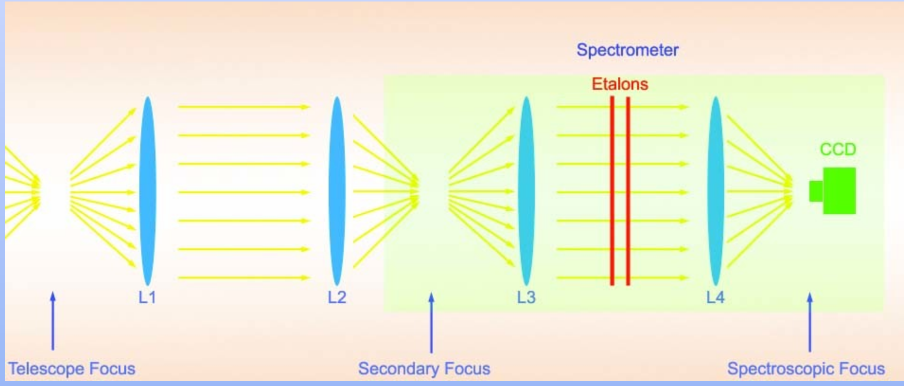
We split the instruments into two
Identical setups, one for visible (500–750nm) and another for infrared (800–1500nm)

Optical Setup:

Collimated Mount
Dual Fabry-Perot interferometers
Fast Pre-filter changing mechanism
Etalon air gap, piezo tuned
Servo stabilized for parallelism

HELRIDE concept tested for fulldisk Dopplergrams



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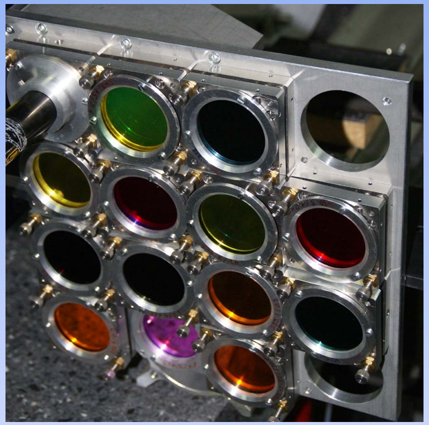
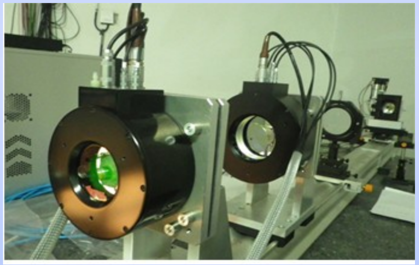
Filtergraph Concept (Feasibility)





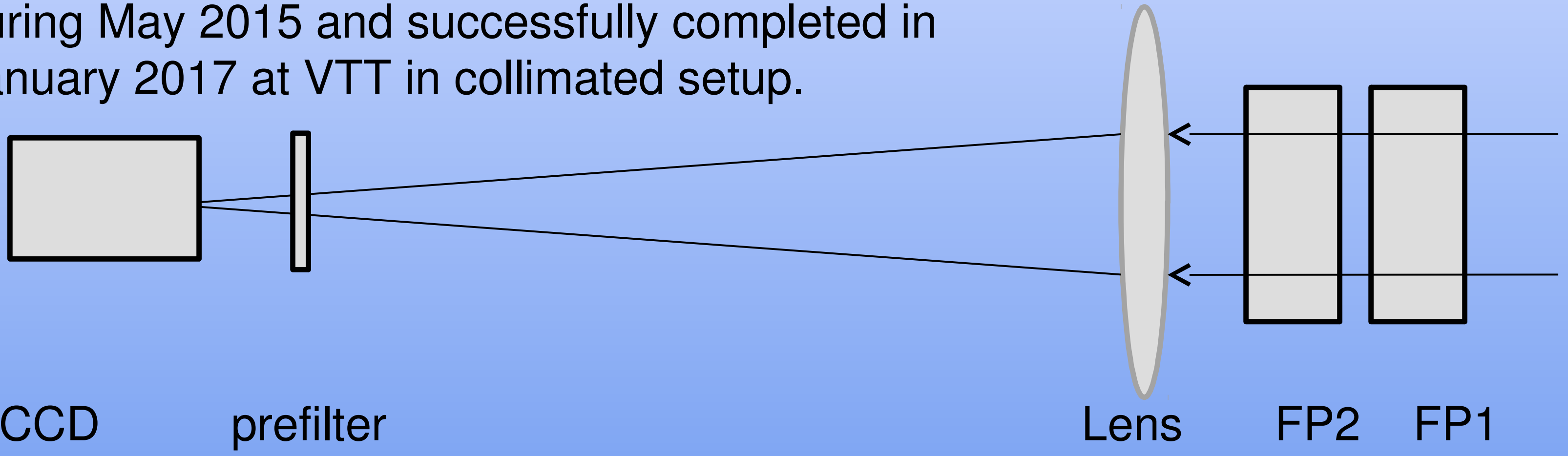
Demonstration Instrument at Vacuum Tower Telescope

HELioseismic Large Region Interferometric DEvice (HELLRIDE, Staiger 2011)

Dual Etalon system designed for multi-line observations over 100 arcsec FoV

The fast prefilter positioning system is used for minimizing the dead-time between subsequent spectral scans.

HELLRIDE was tested for feasibility of fulldisk measurements during May 2015 and successfully completed in January 2017 at VTT in collimated setup.



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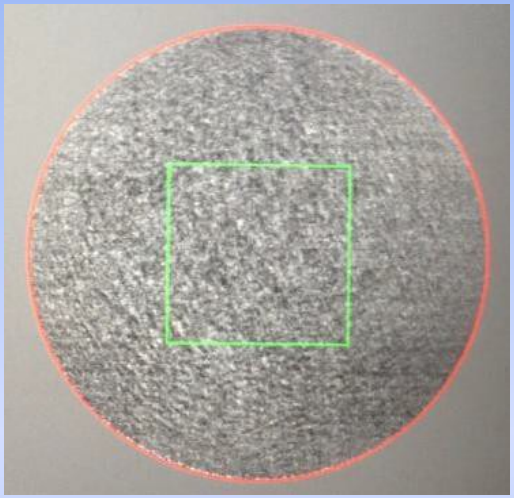
Filtergraph (Feasibility)



- HELLRIDE observations of fulldisk with Fe 6302 line
- Long time series possible: instrument stable enough.

For operations:

- Diffuser + lens system to obtain flat-fields
- Online spectral drift monitoring system: using Laser
- Simultaneous white-light camera for image restoration.
- Polychromatic Polarimeter: to obtain LOS/vector magnetic and velocity maps in various lines

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Data Processing

- **Requirement: Deliver data in real–time**

Observational data taken with HELLRIDE in 2015-2017

- **Possibilities:**
  - Doppler velocities
  - Line-of-sight magnetic field
  - Intensity

- Longer processing
  - Full-stokes inversions

Data obtained during these test campaigns will be made publicly available to community

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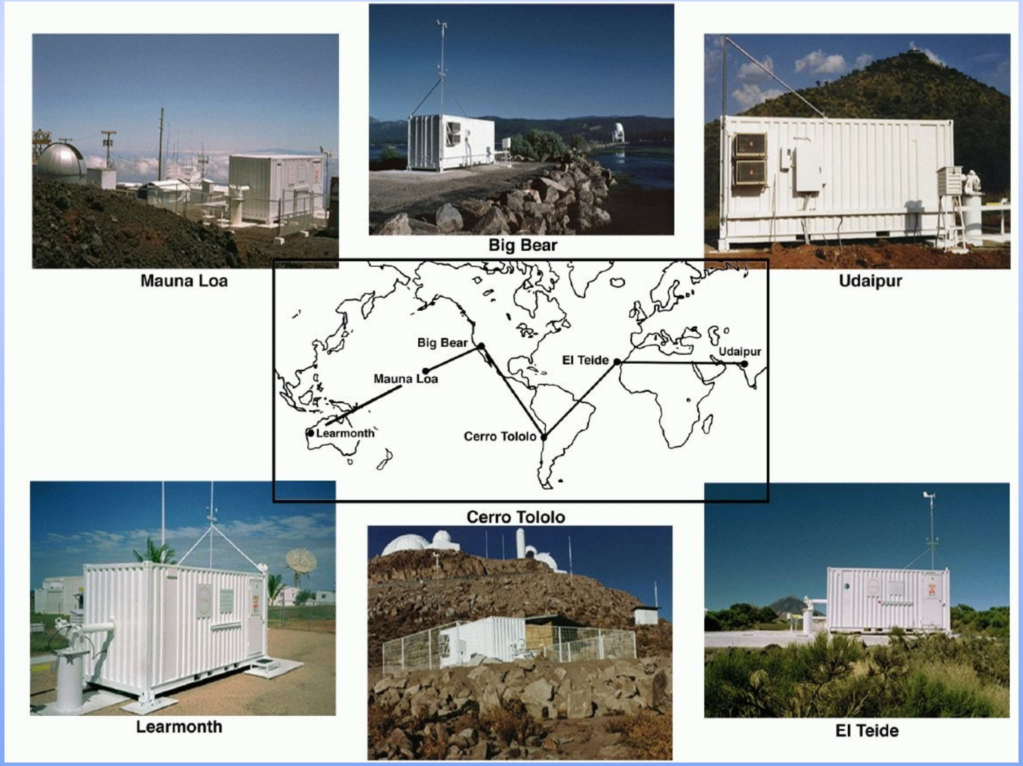
Location of the Telescopes

- SPRING to replace GONG / Upgrade of GONG
  - NSO is willing to offer the six GONG sites
  - Contact to all site hosts established



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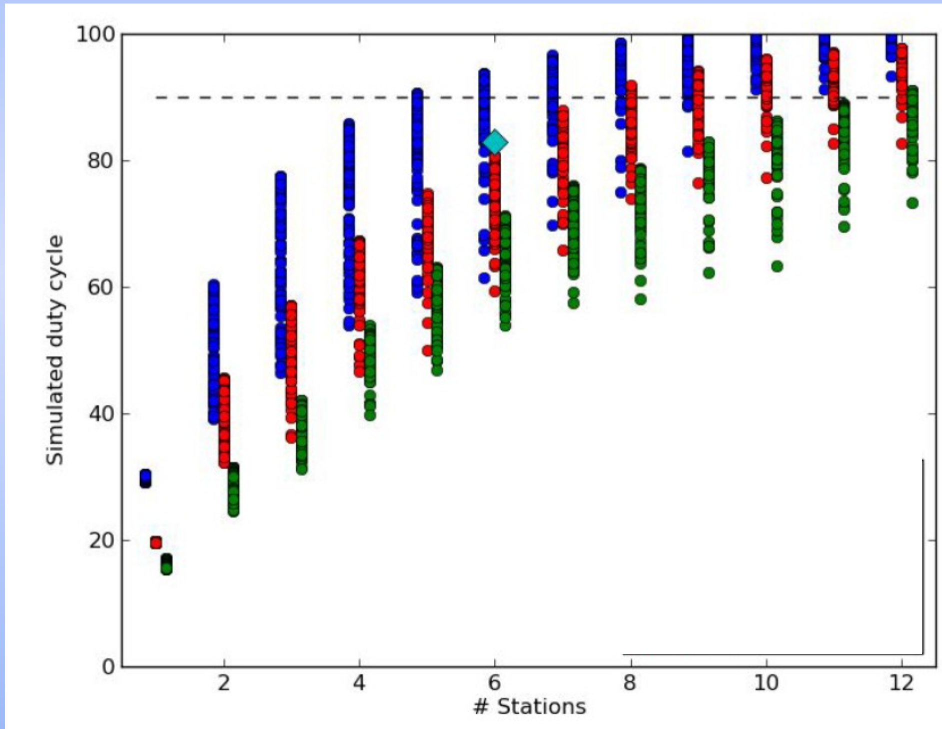
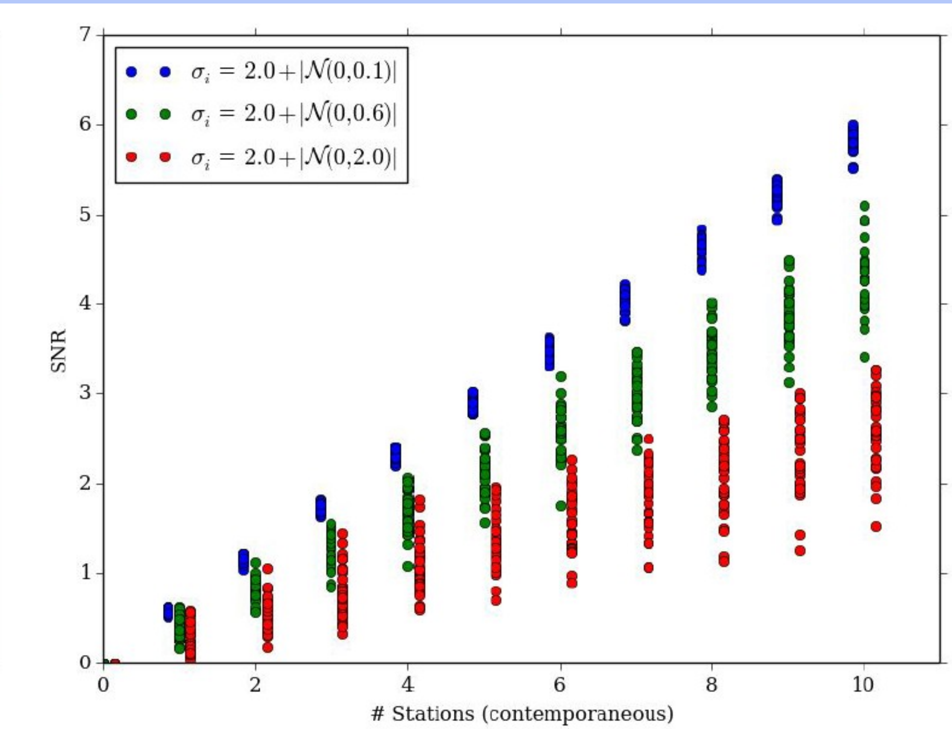
Expected Duty Cycle & SNR depending on the size of the network





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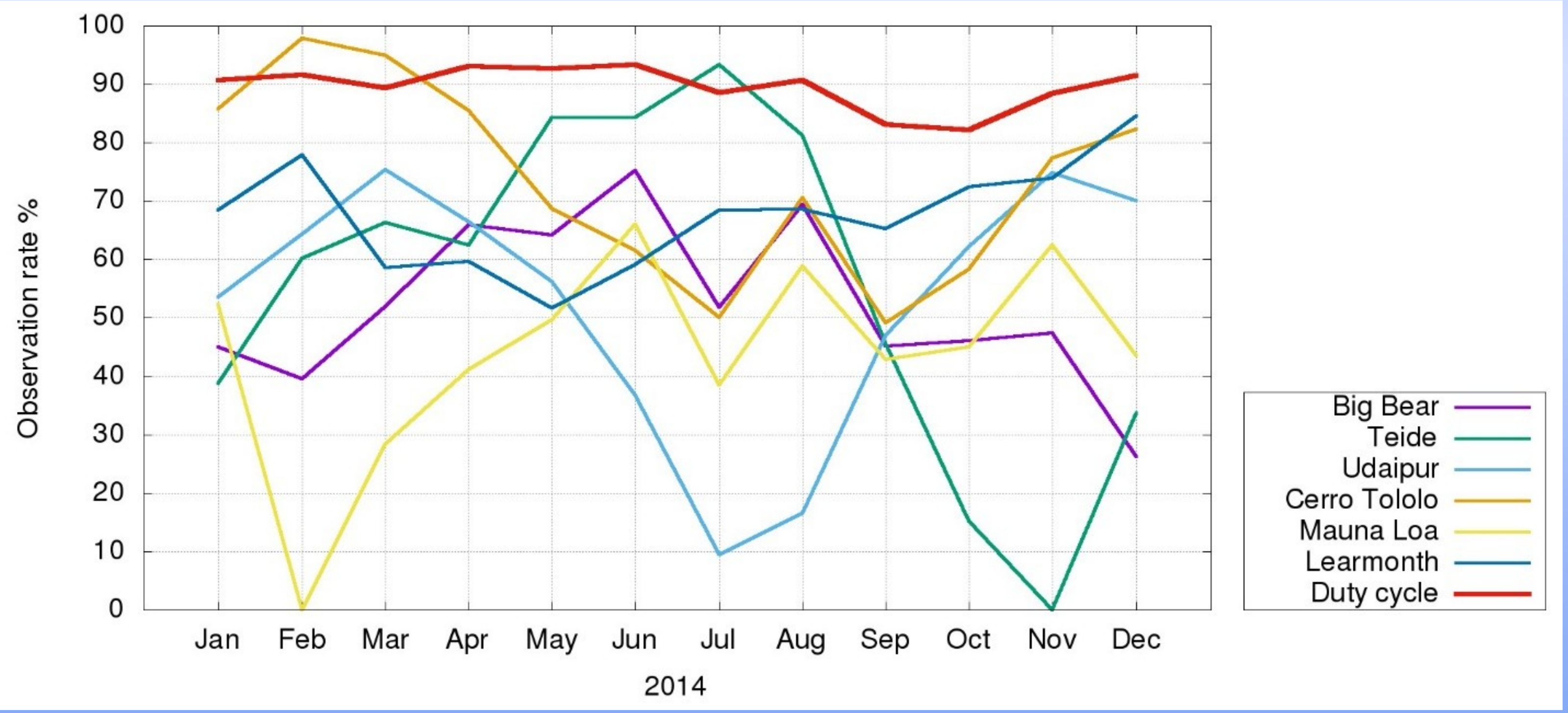
Duty Cycle at the GONG Sites

Duty cycle (red) and percentage of possible observing time for the six GONG sites in the year 2013.

- Duty cycle around 90% throughout the year – even when only five sites are active
- Individual observation rates depend on weather conditions at each site
- High duty cycle essential for successful compliance with the science requirements
- Adding more sites will increase duty cycle only marginally see BISON study



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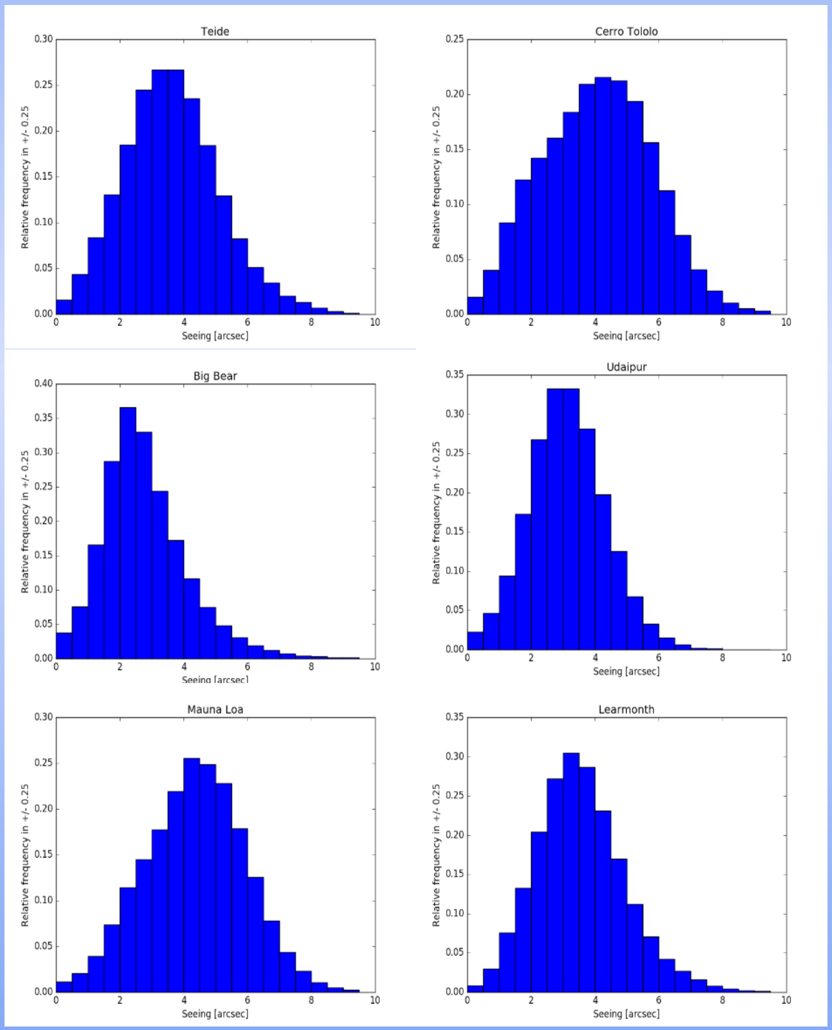
Seeing Conditions at the GONG Sites

Distribution of the seeing at the six GONG sites in the year 2014.



- Science goals require seeing around 1 arcsec
- GONG sites typically between 1 and 10 arcsec with significant differences between the sites
- Strong dependence of the seeing with the time of day respectively the altitude of the Sun
- Heating of the ground increases seeing at GONG telescopes which are located well within the turbulent ground layer (<10 m)

SPRING telescopes need to be put above the turbulent ground layer

Site	Average seeing in 2013 in arc sec	Average seeing in 2014 in arc sec
Teide	3.8 ± 1.7	3.6 ± 1.5
Cerro Tololo	4.2 ± 1.6	4.1 ± 1.6
Big Bear	2.7 ± 1.6	2.8 ± 1.4
Mauna Loa	4.4 ± 1.6	4.4 ± 1.6
Learmonth	3.6 ± 1.4	3.6 ± 1.4
Udaipur	3.2 ± 1.2	3.1 ± 1.2

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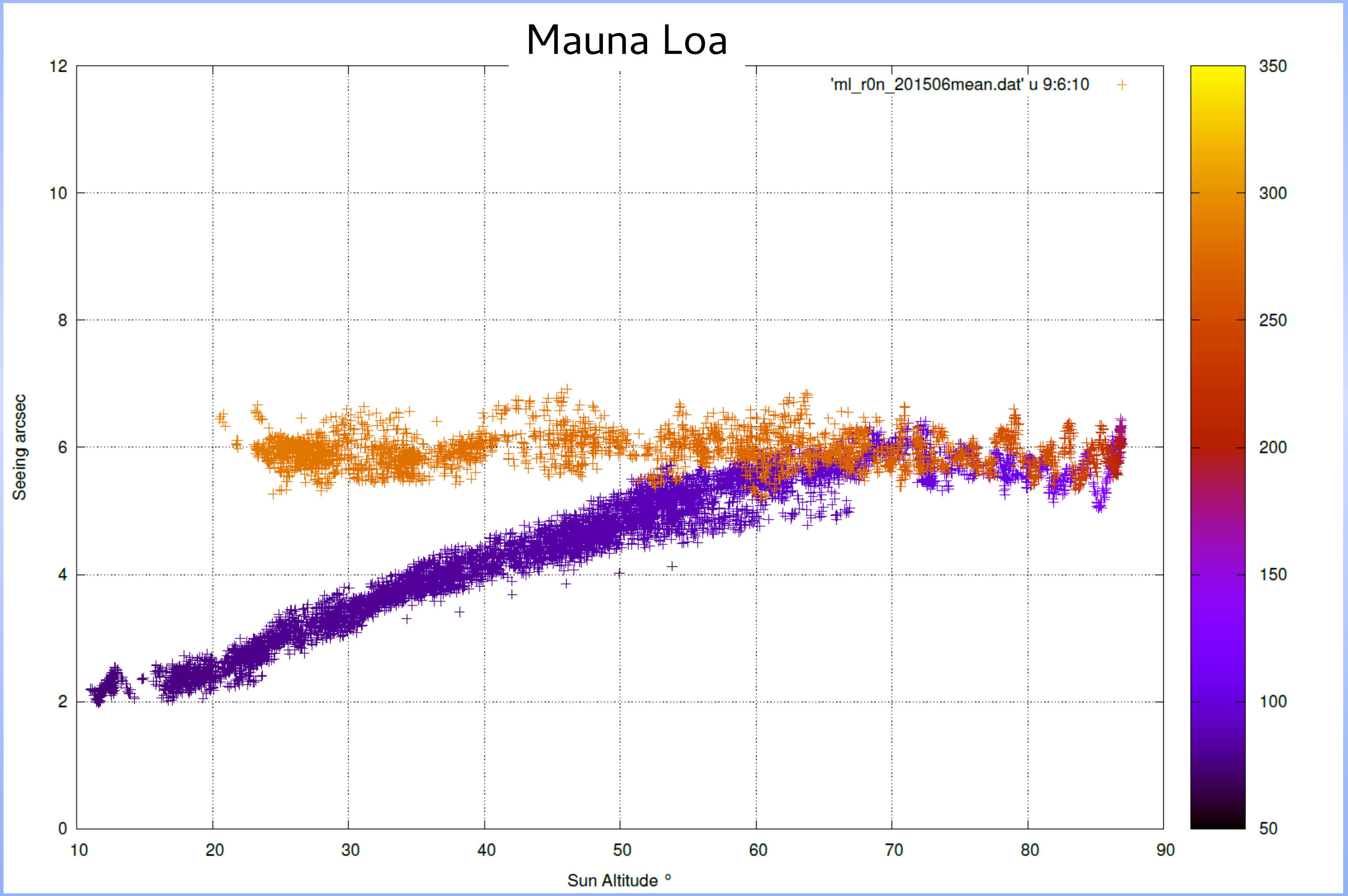
Seeing quality at the GONG sites



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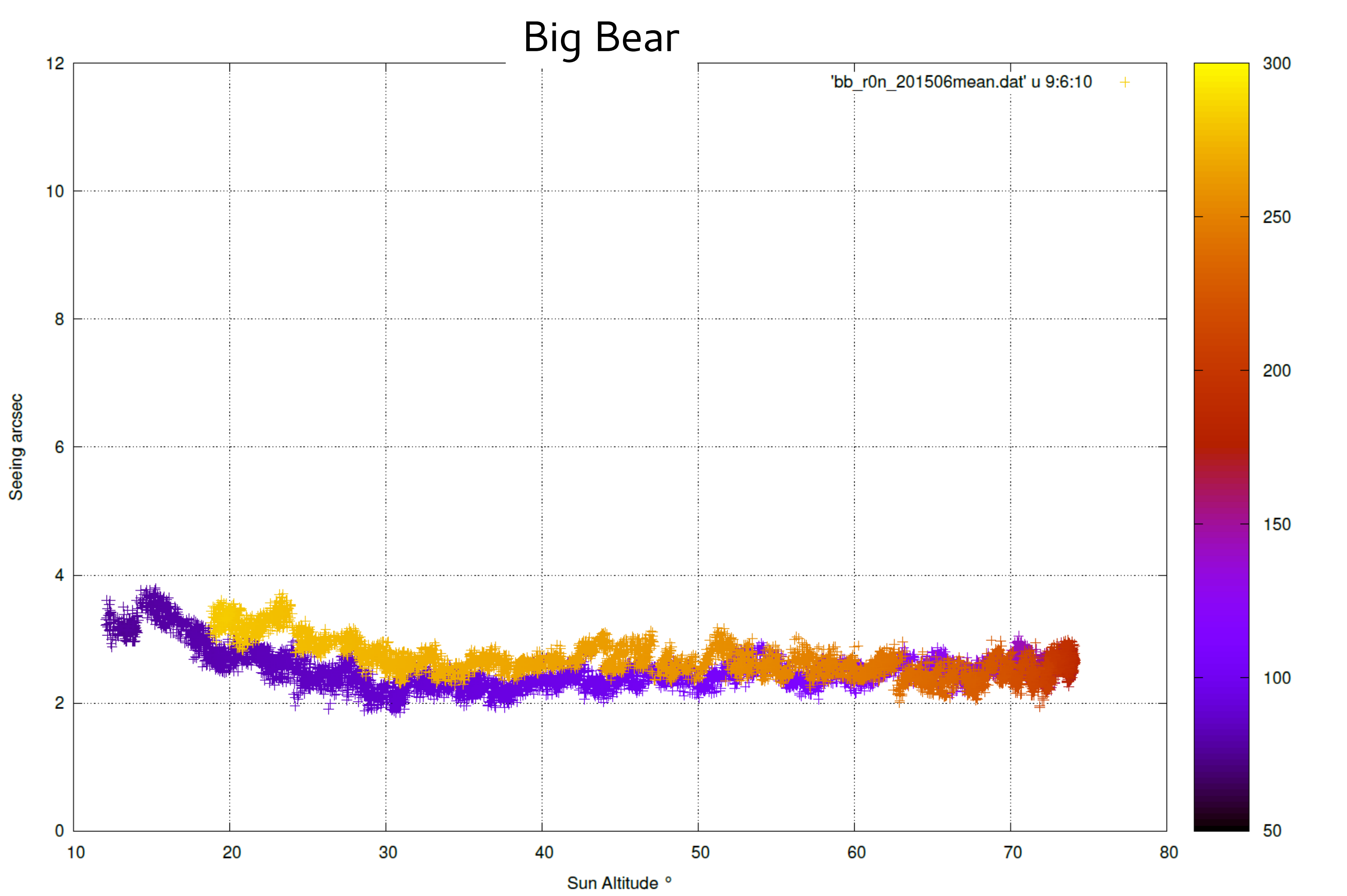

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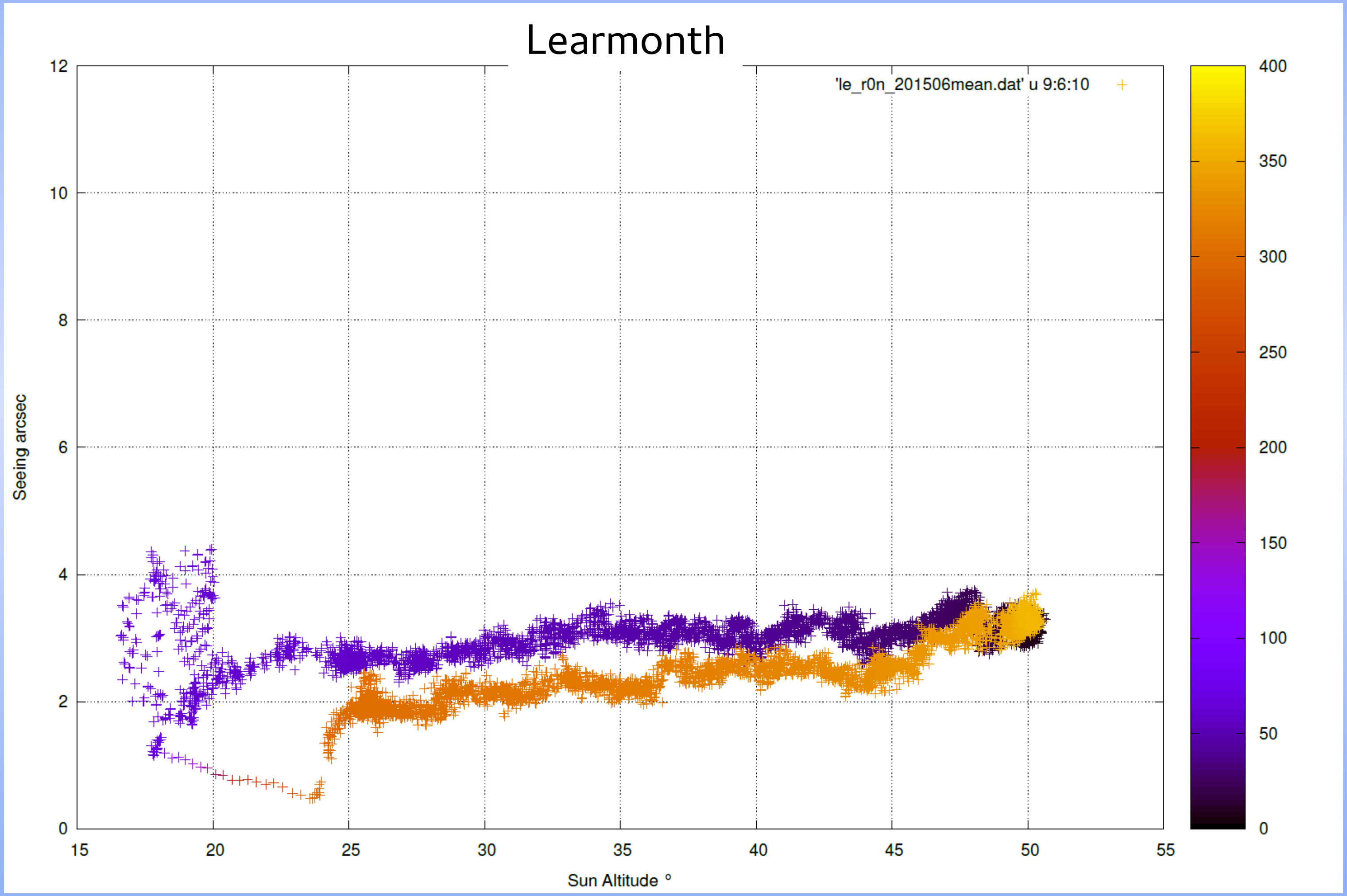

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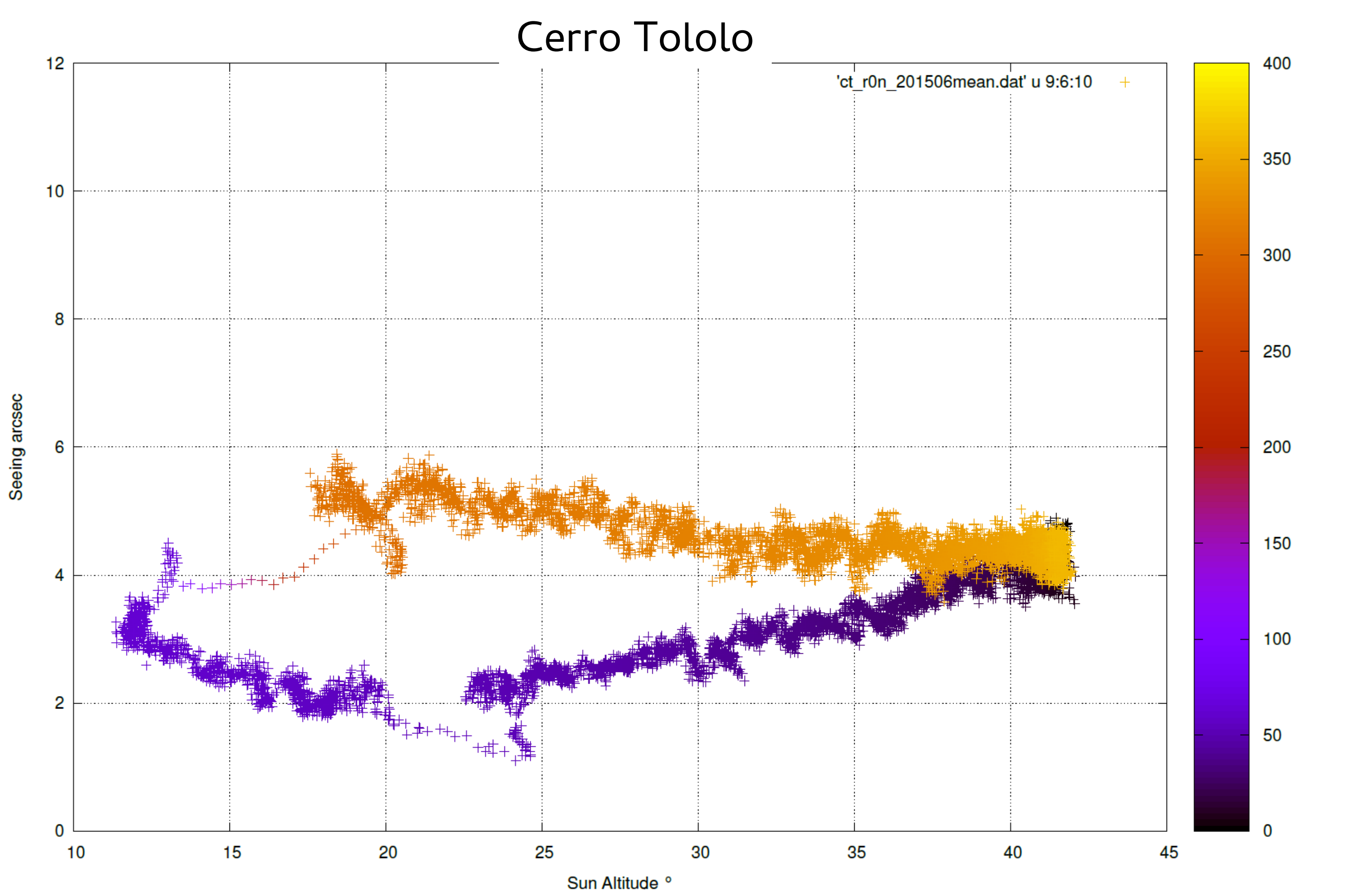

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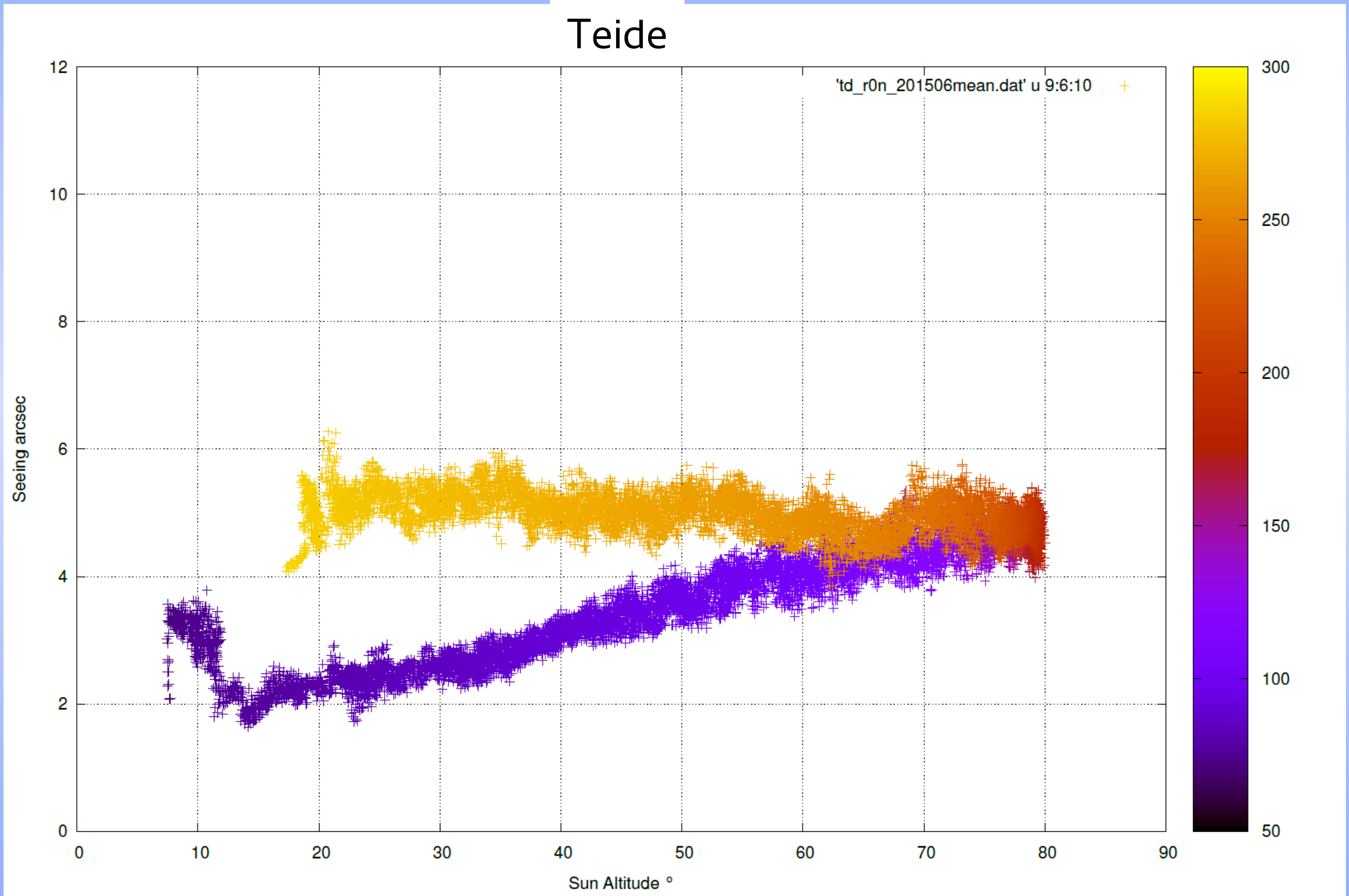
Seeing quality at the GONG sites



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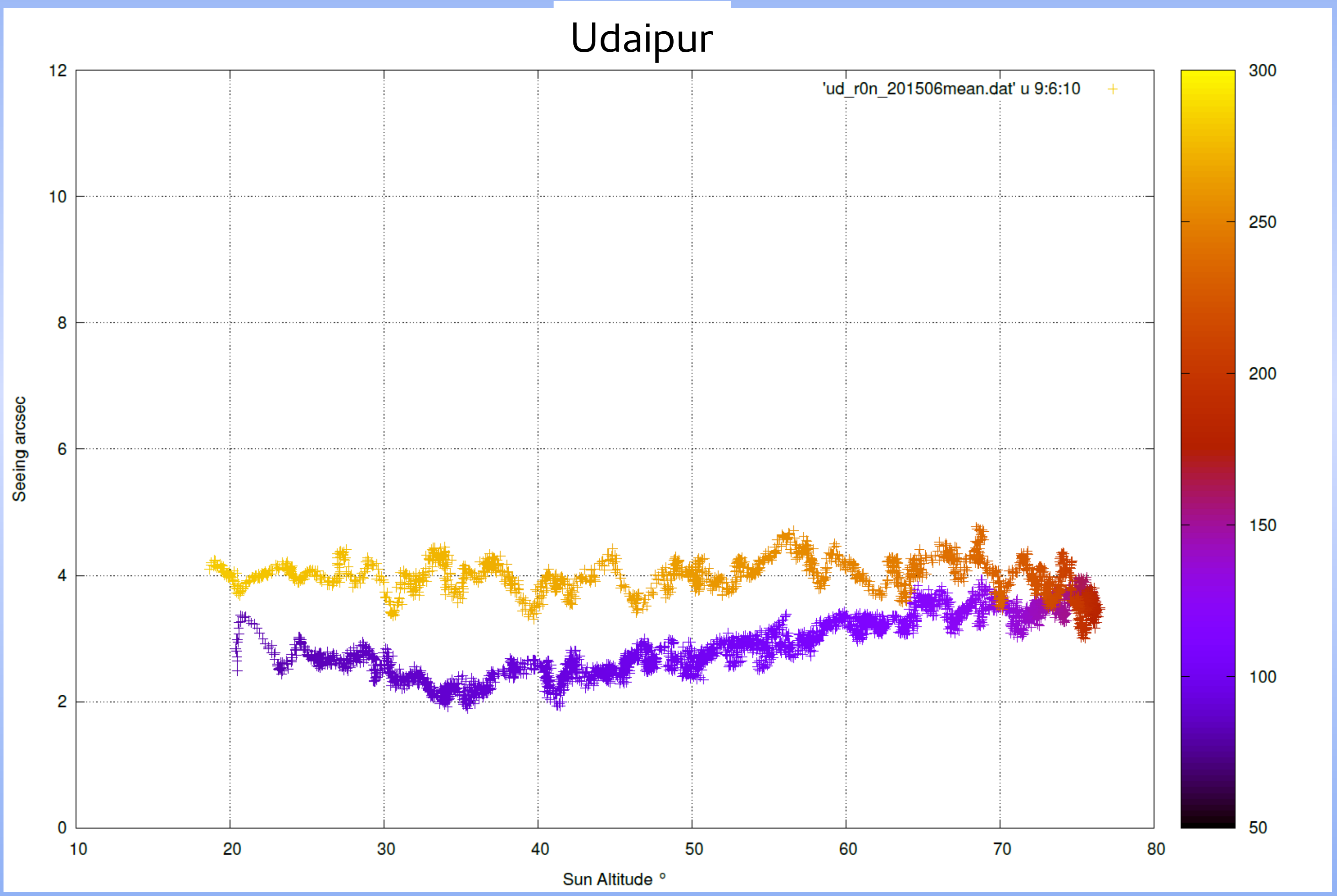
Seeing quality at the GONG sites



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- At all sites seeing is between 2 – 8 arcseconds
  - Depending on day-time and season

- Consequences for SPRING
  - GONG is on the ground, i.e. no tower
  - SPRING has to be on a tower
  - Integration times need to be short
  - Higher temporal cadences

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- Operational Study
  - Cloud detection by Ondrejov

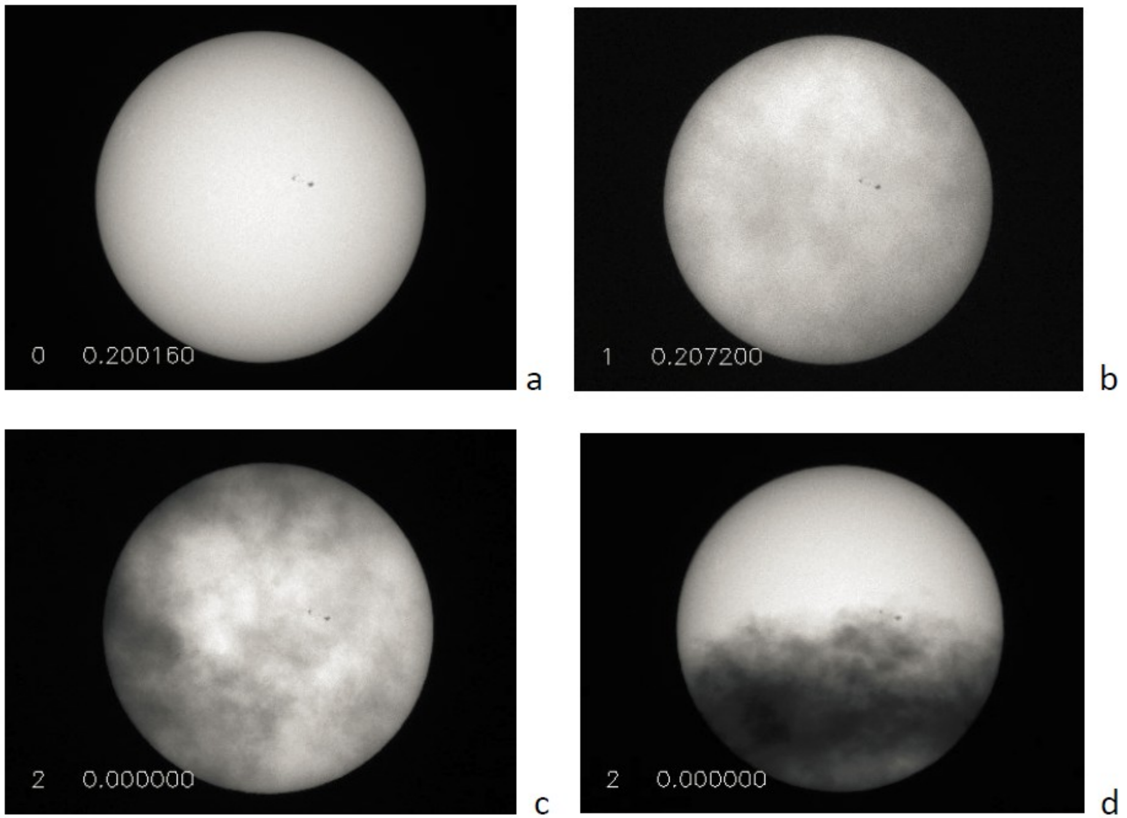

Fig. 1 – Examples of the cloud effects: a - clean Sun; b - weak clouds; c, d - strong clouds.

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Expected Data Rates at SPRING Sites 1/2

Science Requirements

- Sun has to be observed in full-disk mode
- Spatial resolution of 1 arc second
- Temporal cadence of 10 s in photospheric velocity and intensity as well as in the line-of-sight magnetic field and the full-vector magnetic field
- Five spectral lines at 20 wavelength-bins per line.
- For a full-disk image of the Sun, a resolution of 1 arc sec can be achieved with a 2048 x 2048 pixel² CCD

Specifications of the expected observations

- 2k x 2k camera, 16 bits
- Five spectral lines
- 20 wavelength bins per spectral line
- Cadence: 10 sec
- Full Stokes vector (= 4 components)

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Expected Data Rates at SPRING Sites 2/2

Estimation of the expected data rate:

- Size of one image uncompressed: 2048^2 x (16/ 8) = 8388608 Bytes = 8 MB
- Number of images per cycle (=10 sec): 5 x 20 x 4 = 400
- Data rate per cycle: 8 MB x 400 = 3 200 MB = 3.1 GB
- Expected data rate: **18.7 GB/minute**
- After data compression (e.g. with gzip): ~**10 GB per minute** or ~**7 TB per day** (assuming 12 hours of data)

- For a mean value of 65% duty-cycle per site ? **4.5 TB** of compressed raw data per day and per site.
- Connection with 1 GB/s can transfer a maximum of ~10 TB per day to a Data Centre, where further data processing can be carried out.
- Storage buffer for 10 weeks need about 500 TB of storage at each of the six observing sites.

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Cost Estimates for Six Network Sites

Instrument	Cost (M€)	Nsites	total (M€)	
MMS	1,0	3	3,0	
Chromag	2,0	6	12,0	includes input optics
F-P	2,0	6	12,0	
PSPT	1,5	3	4,5	includes telescope
IR Detectors	0,5	6	3,0	
			22,5	Includes only one of Chromag/F-P
Pointing, etc.				
Mount	0,5	6	3,0	
30cm telescope	0,5	6	3,0	
50cm telescope	2,0	6	12,0	
1m telescope	8,0	3	24,0	
Tip-tilt	0,5	6	3,0	
			33,0	For 1m telescope

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Summary

- WP80 SPRING is completed
- Suggested concepts:
  - Mulit-platform carrying several instruments
  - Large telescope (>0.5m) for magnetic fields
  - Smaller telescope (~0.2m) for Doppler velocities

- Instruments
  - Fabry-Perot solution with filter-matrix
  - Multiplexed slit spectrograph
- Data rates high
  - But not impossible to handle

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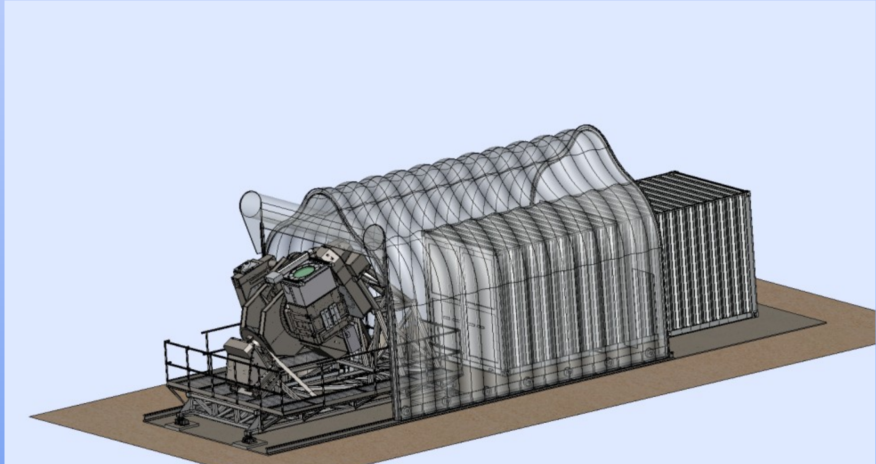
SPRING Future Plans

- International effort needed to build SPRING
  - European-US jointly led activity
  - Worldwide interest in the concept

- Further steps in Solarnet 2:
  - Detailed design-study
  - Proto-typing of post-focus instruments
  - Proposal submission in March 2018



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Kiepenheuer-Institut für Sonnenphysik

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Thank you Joe!

Joachim Staiger
*18. 9. 1950
+28. 2. 2017 (on mission for SPRING)