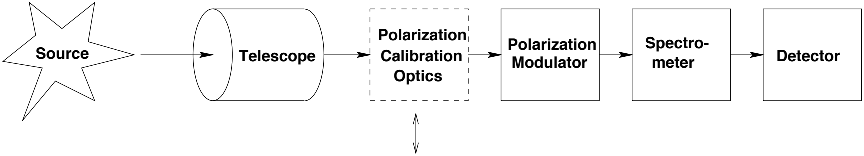
Lecture 10: Polarimeters

Outline

1. Temporal and Spatial Modulation
2. Rotating Waveplate Polarimeters
3. HARPS Polarimeter
4. Liquid Crystal Polarimeters
5. SOLIS VSM
6. Piezoacoustic Modulator Polarimeters
7. ZIMPOL
8. Spectral Modulation Polarimeter: SPEX

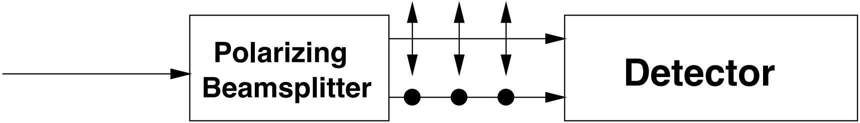
Temporal and Spatial Modulation

General Polarimeters



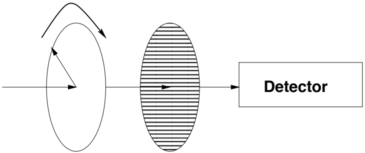
- polarimeters: optical elements (e.g. retarders, polarizers) that change polarization state of incoming light in controlled way
- detectors always measure only intensities
- intensity measurements combined to retrieve polarization state of incoming light
- polarimeters vary by polarization modulation scheme
- polarimeter should also include polarization calibration optics

Spatial Polarization Modulation



- polarizing beam-splitter polarimeter
- simple linear polarimeter: polarizing beam-splitter producing 2 beams corresponding to 2 orthogonal linear polarization states
- full linear polarization information from rotating assembly
- *spatial modulation*: simultaneous measurements of two (or more) Stokes parameters

Temporal Polarization Modulation



- rotating waveplate polarimeter
- rotating retarder, fixed linear polarizer
- measured intensity as function of retardance δ, position angle θ

$$I' = \frac{1}{2}\left(I + \frac{Q}{2}\left((1+\cos\delta) + (1-\cos\delta)\cos 4\theta\right) + \frac{U}{2}(1-\cos\delta)\sin 4\theta - V\sin\delta\sin 2\theta\right)$$

- only terms in θ lead to modulated signal
- equal modulation amplitudes in Q, U, and V for δ=127°
- *temporal modulation*: sequential measurements of $I\pm$ one or more Stokes parameters

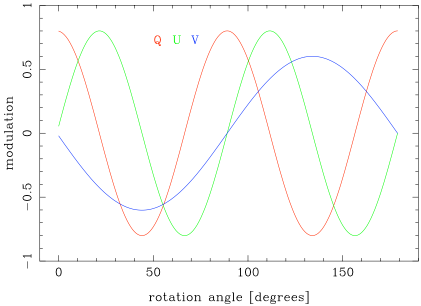
Comparison of Temporal and Spatial Modulation Schemes

Modulation	Advantages	Disadvantages
temporal	negligible effects of flat field and optical aberrations	influence of seeing if modulation is slow
	potentially high polarimetric sensitivity	limited read-out rate of array detectors
spatial	off-the-shelf array detectors	requires up to four times larger sensor
	high photon collection efficiency	influence of flat field
	allows post-facto reconstruction	influence of differential aberrations

schemes rather complementary ⇒ modern, sensitive polarimeters use both to combine advantages and minimize disadvantages

Rotating Waveplate Polarimeters

Fundamentals



$$I' = \frac{1}{2}\left(I + \frac{Q}{2}\left((1+\cos\delta) + (1-\cos\delta)\cos 4\theta\right) + \frac{U}{2}(1-\cos\delta)\sin 4\theta - V\sin\delta\sin 2\theta\right)$$

- Q, U modulated at twice the frequency of V
- phase shift in modulation between Q and U is 90°⇒ measurements at 8 angles to determine all 4 Stokes parameters

Double-Ratio Technique

- combination of spatial and temporal modulation
- data reduction minimizes effects of many artifacts
- rotatable quarter-wave plate, polarizing beam-splitter
- consider case of circularly polarized light
- quarter-wave plate switches between +45° or -45° to polarizing beam-splitter
- both beams recorded simultaneously
- four measurements are combined to obtain estimate of Stokes V/I ratio largely free of effects from seeing and gain variations between different detector areas
- excellent if polarization signal is small
- frequently used in stellar polarimetry
- can be applied to any polarized Stokes parameter
- works very well for solar applications where the spectrum in the first and the second exposures are different

Double-Ratio Technique (continued)

- measured intensities in two beams in first exposure

$$S_1^l = g_l \alpha_1 (I_1 + V_1), \quad S_1^r = g_r \alpha_1 (I_1 - V_1)$$

  - subscript 1: first exposure
  - subscripts l, r: left, right beams
  - S: measured signal
  - g: gain in particular beam
  - α: transmission of atmosphere, instrument
- second exposure

$$S_2^l = g_l \alpha_2 (I_2 - V_2), \quad S_2^r = g_r \alpha_2 (I_2 + V_2)$$

- incoming I and V in second exposure may be completely different from first exposure
- also includes beam-wobble induced by rotation of wave plate

Double-Ratio Technique (continued)

- combination of 4 measured intensities removes effect of transmission changes and differential gain variations of different detector areas

$$\frac{1}{4}\left(\frac{S_1^l}{S_2^l}\frac{S_2^r}{S_1^r}-1\right)=\frac{1}{2}\frac{I_2V_1+I_1V_2}{I_1I_2-I_2V_1-I_1V_2+V_1V_2}$$

- if $V \ll I$

$$\frac{1}{2}\left(\frac{V_1}{I_1}+\frac{V_2}{I_2}\right)$$

- obtain average V/I signal of two exposures
- no spurious polarization signals are introduced

HARPS Polarimeter

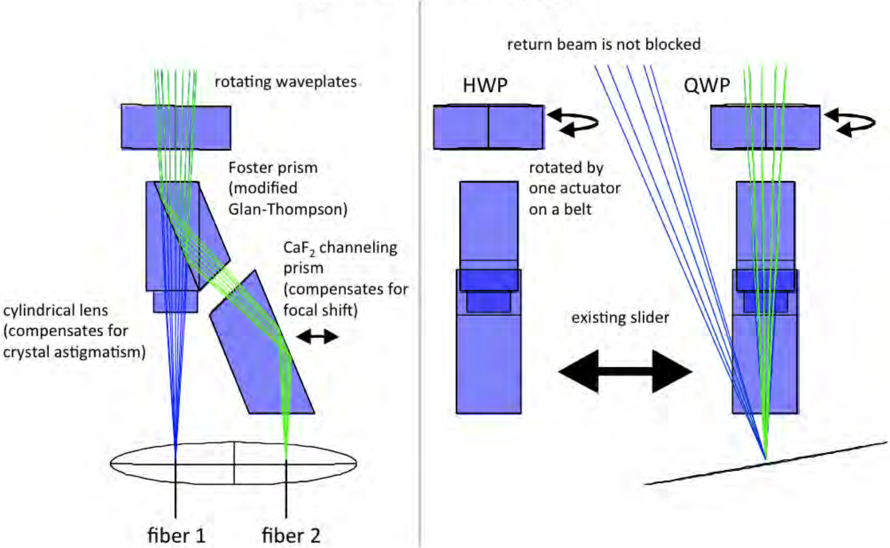
Introduction

- HARPS: Most successful exoplanet finder
- measure magnetic fields of planet-hosting stars
- only publicly accessible high-resolution spectropolarimeter in the southern hemisphere

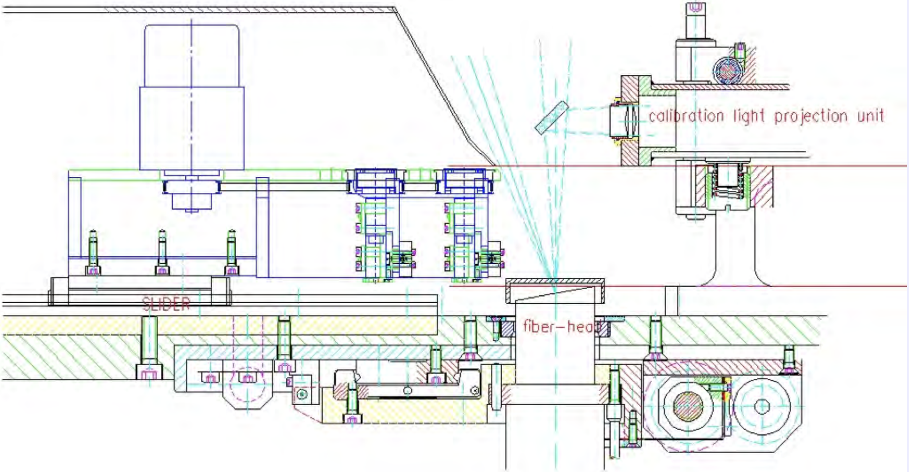
Requirements

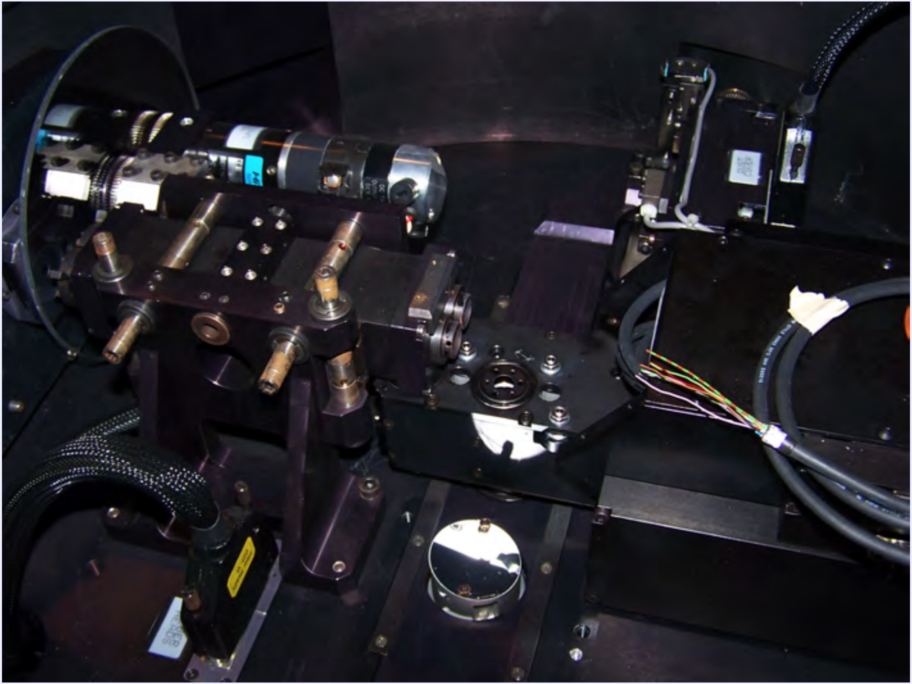
- Use slider and volume of Iodine cell
- Do not compromise performance and operations of HARPS
- Full Stokes
- Polarimetric sensitivity 10^{-4} for one night on a bright star
- 380-690 nm
- Minimal instrumental polarization
- Minimal (polarized) fringes

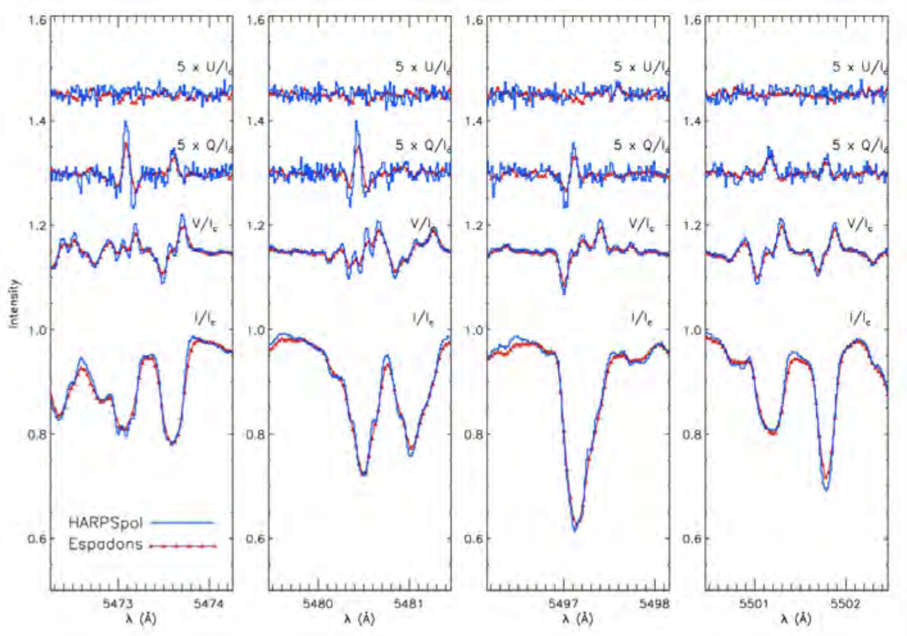
optical design



mechanical design






1.6
1.4
1.2
1.0
0.8
0.6
Intensity
5 x U/I_c
5 x Q/I_c
V/I_c
I/I_c
HARPSpol
Espadons
5473
5474
5480
5481
5497
5498
5501
5502
λ (Å)

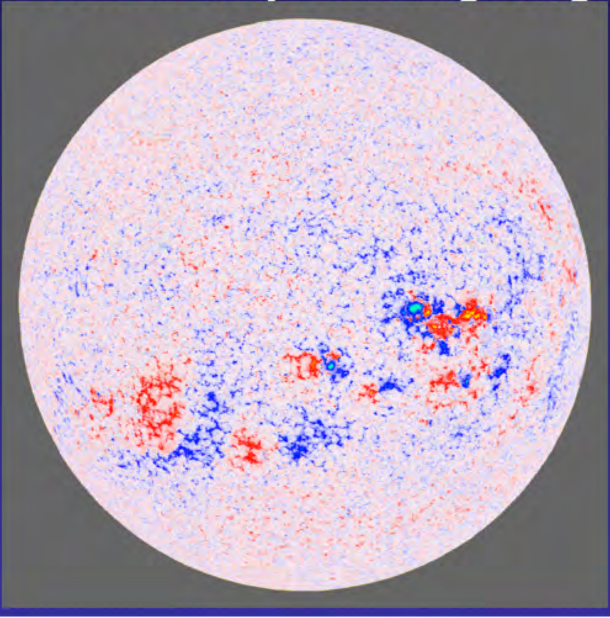
Liquid Crystal Polarimeters

Introduction

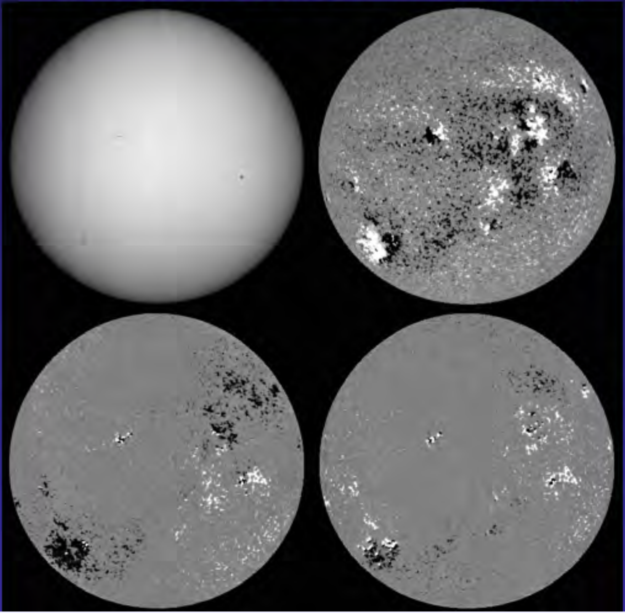
- no moving parts
- nematic liquid crystals
  - change retardance with applied electric field
  - relatively slow (<50 Hz)
  - electrically tunable for different wavelengths
- ferro-electric liquid crystals
  - flip fast axis orientation with applied electric field (2 states only)
  - fast (<10 kHz)
  - fixed retardation and optimum wavelength
- often combinations of variable liquid crystal retarders and fixed retarders

SOLIS Vector-Spectromagnetograph (VSM)

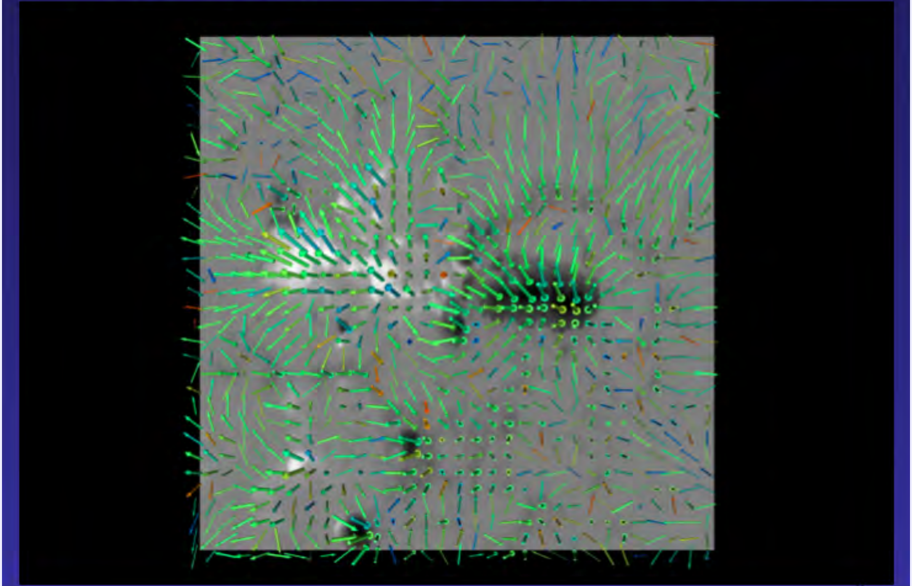
Full-Disk Photospheric Magnetogram

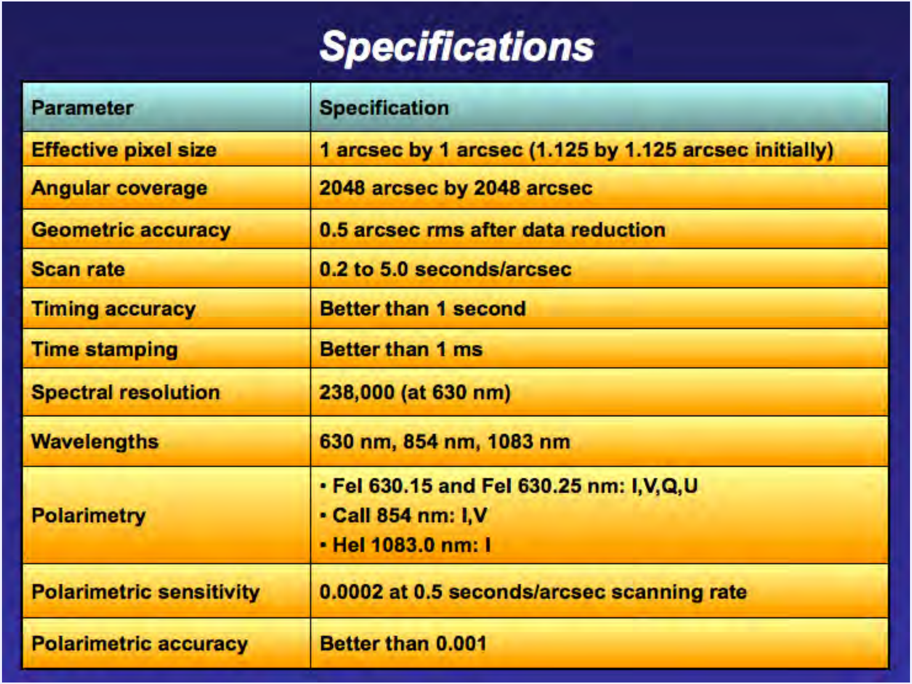


Full-Disk Vector-Polarimetry



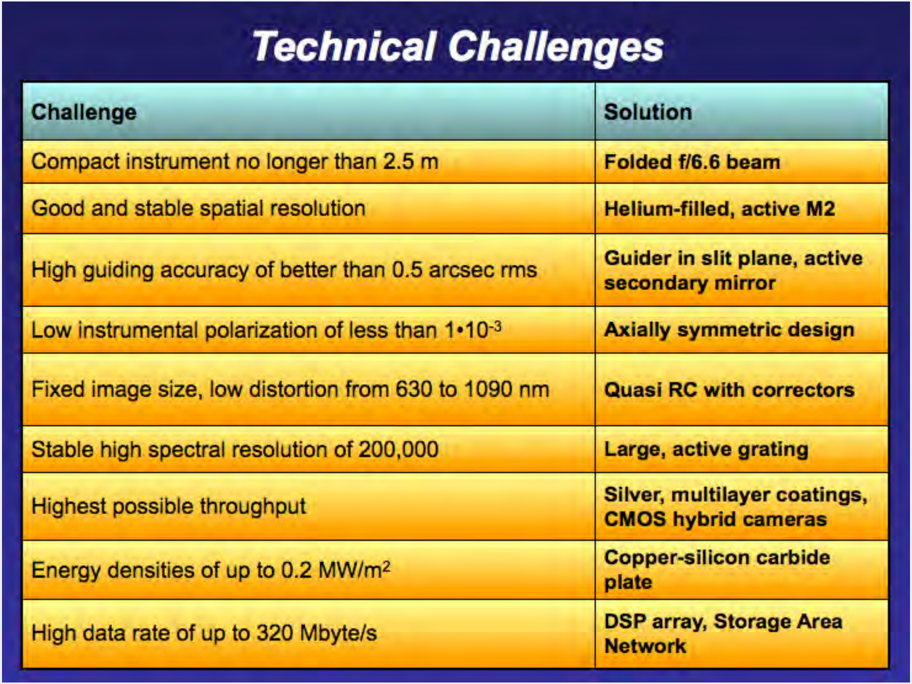
Field Vector, Filling Factor, and Helicity





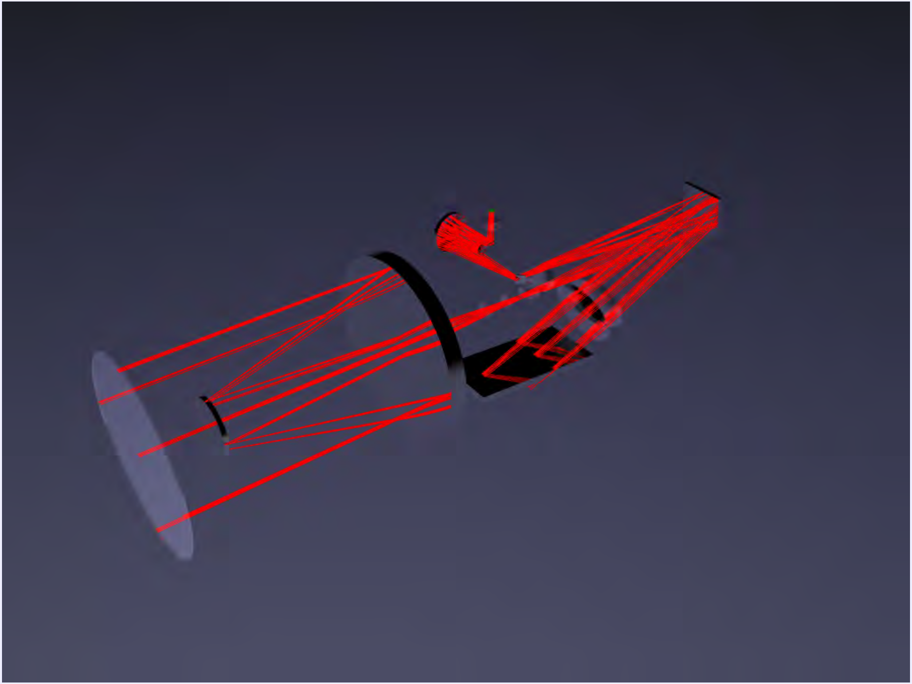
Specifications

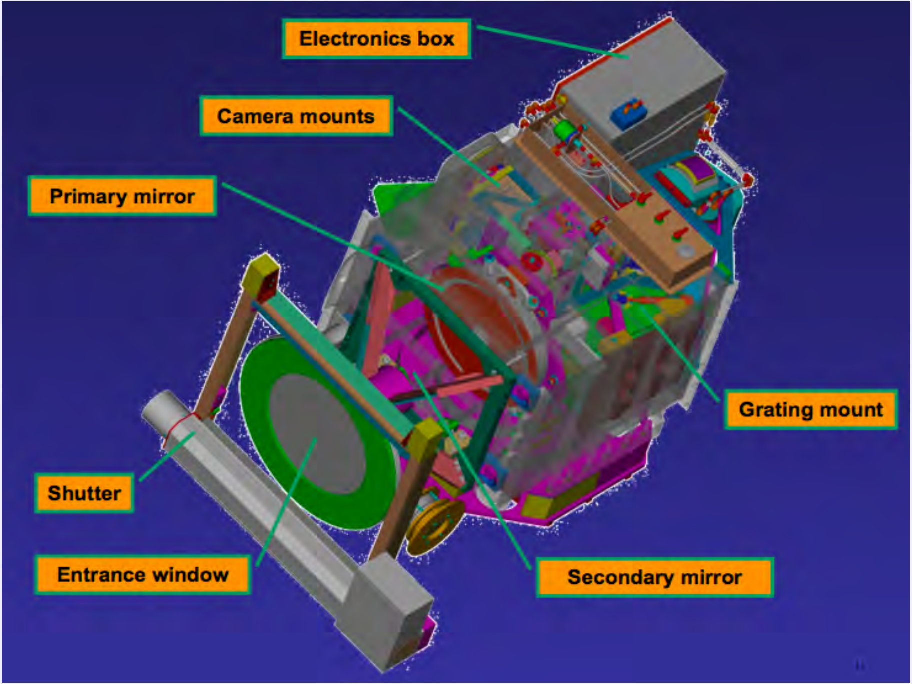
Parameter	Specification
Effective pixel size	1 arcsec by 1 arcsec (1.125 by 1.125 arcsec initially)
Angular coverage	2048 arcsec by 2048 arcsec
Geometric accuracy	0.5 arcsec rms after data reduction
Scan rate	0.2 to 5.0 seconds/arcsec
Timing accuracy	Better than 1 second
Time stamping	Better than 1 ms
Spectral resolution	238,000 (at 630 nm)
Wavelengths	630 nm, 854 nm, 1083 nm
Polarimetry	• FeI 630.15 and FeI 630.25 nm: I,V,Q,U • CaII 854 nm: I,V • HeI 1083.0 nm: I
Polarimetric sensitivity	0.0002 at 0.5 seconds/arcsec scanning rate
Polarimetric accuracy	Better than 0.001

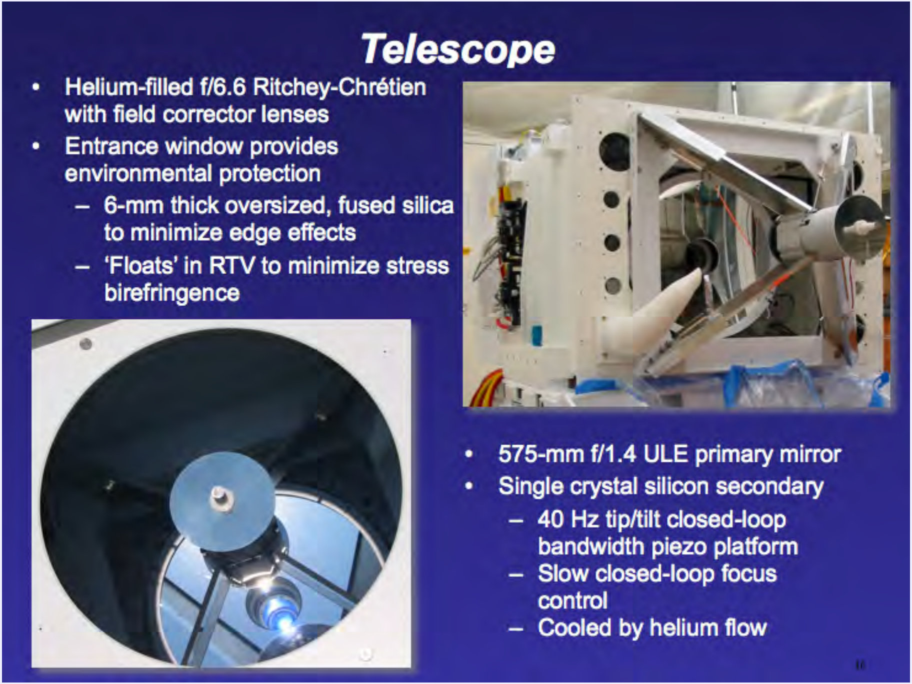


Technical Challenges

Challenge	Solution
Compact instrument no longer than 2.5 m	**Folded f/6.6 beam**
Good and stable spatial resolution	**Helium-filled, active M2**
High guiding accuracy of better than 0.5 arcsec rms	**Guider in slit plane, active secondary mirror**
Low instrumental polarization of less than $1 \cdot 10^{-3}$	**Axially symmetric design**
Fixed image size, low distortion from 630 to 1090 nm	**Quasi RC with correctors**
Stable high spectral resolution of 200,000	**Large, active grating**
Highest possible throughput	**Silver, multilayer coatings, CMOS hybrid cameras**
Energy densities of up to 0.2 MW/m^2	**Copper-silicon carbide plate**
High data rate of up to 320 Mbyte/s	**DSP array, Storage Area Network**




Electronics box
Camera mounts
Primary mirror
Shutter
Entrance window
Secondary mirror
Grating mount

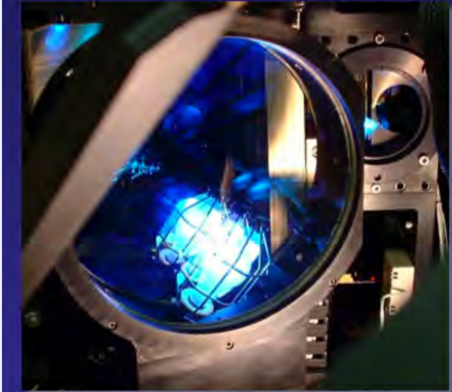


Telescope

- Helium-filled f/6.6 Ritchey-Chrétien with field corrector lenses
- Entrance window provides environmental protection
  - 6-mm thick oversized, fused silica to minimize edge effects
  - 'Floats' in RTV to minimize stress birefringence

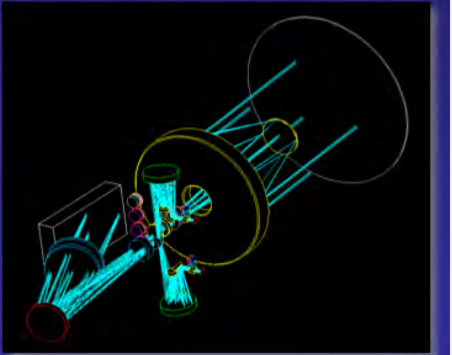
- 575-mm f/1.4 ULE primary mirror
- Single crystal silicon secondary
  - 40 Hz tip/tilt closed-loop bandwidth piezo platform
  - Slow closed-loop focus control
  - Cooled by helium flow

Folded Littrow Spectrograph



Grating

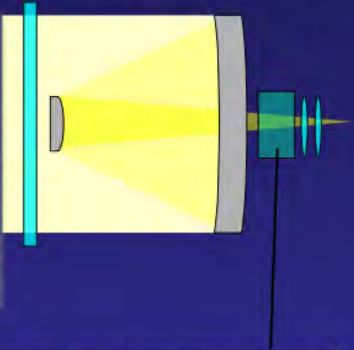
- 79 lines/mm on 204 mm by 408 mm fused silica blank
- Almost no instrumental polarization
- Rotates for different wavelengths
- Active adjustment in 2 axes to compensate for flexure



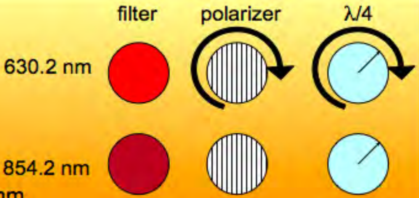
Littrow lens

- Air-spaced doublet
- Athermal design
- Moves to adjust for different wavelengths
- Dual Offner reimaging optics

Polarization Calibration



- 'Polarization-free' optics before polarization calibration
- Polarization calibration occurs as early as possible
- interference filters to limit solar flux
- rotating polarizers and retarders at 630 nm, fixed at 854 nm



Polarization Modulation

- Ferroelectric liquid crystal (FLC) variable retarders (all $\lambda/2$ at 630 nm)
- Fixed $\lambda/4$ (at 630 nm) and $\lambda/6$ (at 854 nm) polymer retarders
- All true zero-order retarders to cope with fast f/6.6 beam
- Full vector modulation similar to Gandorfer and Rabin schemes
- Exact position angles optimized based on measured FLC properties
- After modulation, both polarization states pass the same low-polarization optics
- Solar-B spectropolarimeter and Diffraction-Limited Spectro-Polarimeter (DLSP) at Dunn Solar Telescope are based on VSM concept

filter FLC1 $\lambda/4$ FLC2 $\lambda/4$ polarizer

output signal

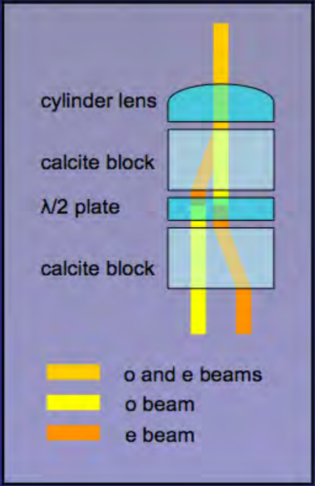
I-0.85Q+0.15U-0.5V

I+0.85Q-0.15U-0.5V

I-0.15Q+0.85U+0.5V

I+0.15Q-0.85U+0.5V

Polarization Analysis



- Modified Savart plate
- Crystal astigmatism is a major issue for an f/6.6 beam, corrected by cylinder lens
- Provides high quality polarizing beam-splitting for fast beam and large field of view
- Different beamsplitters for 630.2 nm and 854.2 nm
  - Calcite splitting is wavelength dependent
  - Can use simple mica retarder

Separation of Polarization Modulation and Polarizer

- FLC and retarders located behind spectrograph entrance slit
- polarizing beamsplitters located in front of cameras
- spectrograph and associated optics built to minimize instrumental polarization between modulators and polarizing beam splitters
- advantages of VSM approach: no moving parts for polarization analysis, switching of polarization states can occur rapidly, and both polarization states are detected simultaneously after having passed through the same optics

Piezo-Elastic Modulators (PEMs)

- stress-induced birefringence, also sometimes called piezo-optical or photo-elastic effect
- block of a few cm in side length of common BK7 glass can be stressed enough by hand such as to introduce a quarter-wave retardation
- stress-induced birefringence is proportional to stress σ
- retardation (in waves)

$$\delta = \frac{1}{\lambda} K d \sigma$$

K stress optical constant
d thickness of variable retarder
λ wavelength

- construct variable retarder by compressing optical glass
- requires considerable mechanical power to modulate

Mechanical Resonance

- mechanically resonant oscillation reduces power requirement to one over the mechanical Q (10^3-10^4 for most glasses)
- slab of length L excited at fundamental mode ⇒ standing acoustic wave with wavelength $2L$, frequency ω

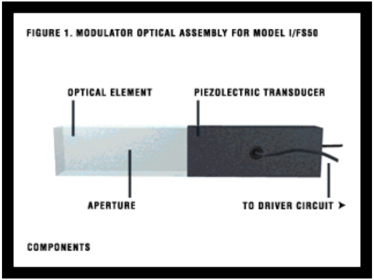
$$\omega = \frac{c_s}{2L}$$

- c_s: sound speed in optical material
- 57-mm-long fused silica slab ⇒ resonance frequency is 50 kHz.
- resulting stress, retardance as function of position x and time t
- stress-induced birefringence $\delta(x,t)$ given by

$$\delta(x,t) = A \sin \omega t \sin(\frac{\pi x}{L})$$

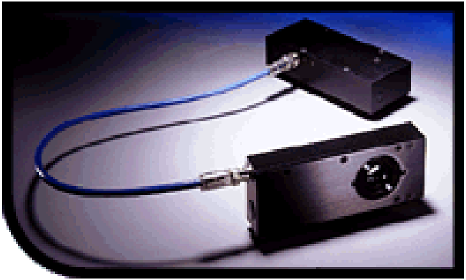
A amplitude of oscillation
x from 0 to L

PEM Driver



- to make slab oscillate, quartz crystal with electrodes on its surfaces is forced to oscillate by externally applied electrical field via piezo effect
- quartz slab mechanically coupled to modulator slab
- electrical field driven at mechanical resonance frequency
- oscillation amplitude A regulated with electronic feedback circuit

PEM Power



- oscillation dampened by friction losses within modulator material
- energy loss inversely proportional to mechanical Q
- Q very large $\Rightarrow$ little energy loss in modulator small (0.1 to 1 W)
- material with high Q (fused silica, $Q \approx 10^4$) desirable
- typical glass has $Q \sim 10^3$
- required drive power does not depend on length of slab

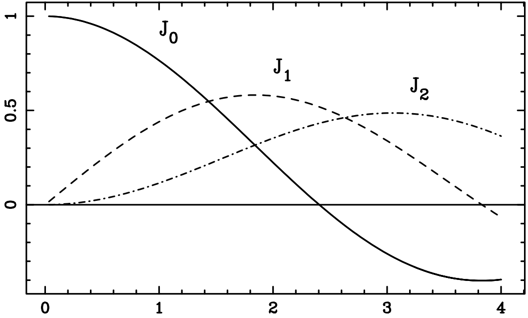
PEM Birefringence

- stress-induced birefringence

$$\delta(x,t) = A \sin \omega t \sin(\frac{\pi x}{L})$$

- combine $\sin(\frac{\pi x}{L})$, amplitude A into spatially varying amplitude $A(x)$
- birefringence becomes $\delta(x,t) = A(x) \sin(\omega t)$
- A small $\Rightarrow$ PEM is true zero-order retarder
- PEM Mueller matrix corresponds to retarder with time-dependent retardation
- retarder Mueller matrix contains elements with $\sin \delta(x,t)$ and $\cos \delta(x,t)$
- expand $\sin(\sin(\cdot))$ and $\cos(\sin(\cdot))$ in terms of Bessel functions

Bessel Functions



- Mueller matrix elements become

$$\begin{aligned}\sin\delta(\mathrm{x},\mathrm{t}) &= 2J_1(A(x))\sin\omega t+\cdots\ ,\\ \cos\delta(x,t) &= J_0(A(x))+2J_2(A(x))\cos 2\omega t+\cdots\ ,\end{aligned}$$

- $J_{0,1,2}$: Bessel functions of order 0,1 and 2

PEM Advantages and Disadvantages

Advantages:

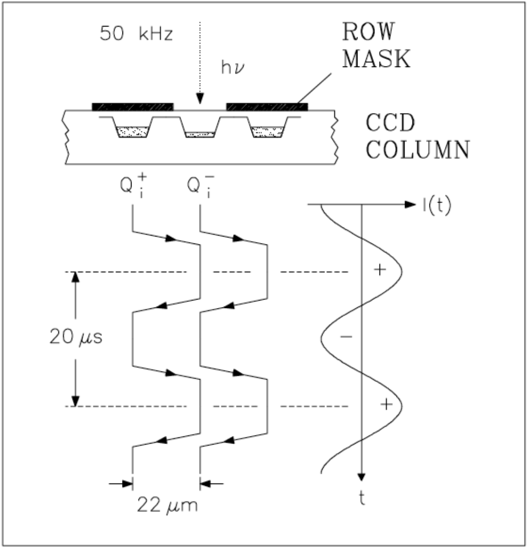
- PEMs are stable in operation
- show no degrading at high intensity levels and/or UV irradiation
- have good optical properties
- large spatial and angular aperture
- require only low voltages at moderate driving powers (< 1 W)

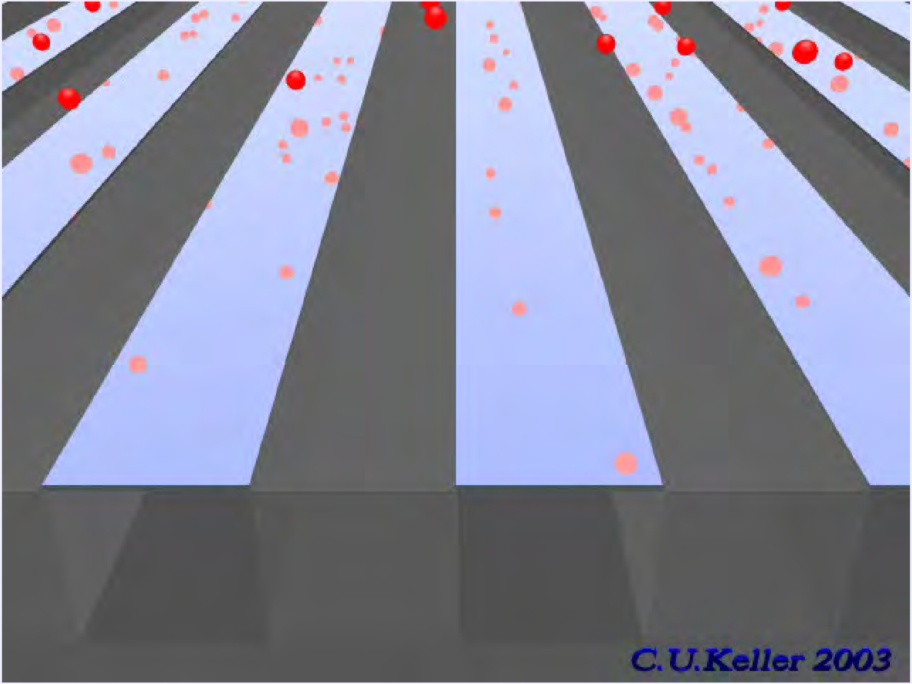
Disadvantages:

- sinusoidal modulation (as compared to more efficient square-wave modulation possible with liquid crystals)
- very high modulation frequency (20 to 50 kHz), which requires specialized array detectors (ZIMPOL)

Zurich Imaging Polarimeters (ZIMPOL)

CCD Array as Fast Demodulator



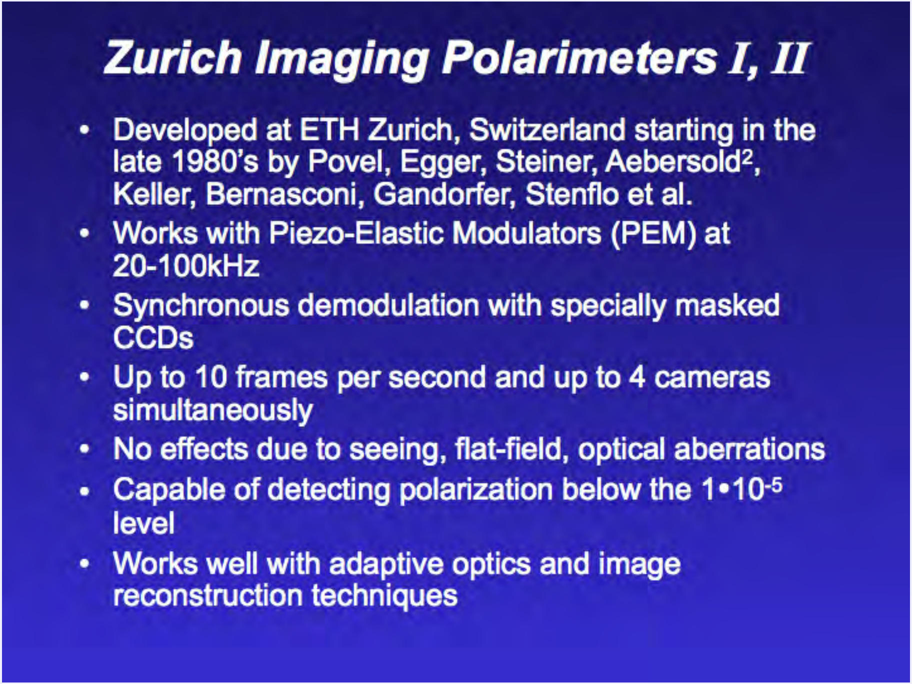

C.U.Keller 2003

CCD Array as Fast Demodulator

- ZIMPOL I polarization modulator consists of 2 PEMS and a polarizer (single beam)
- modulation according to

$$I'(t) = \frac{1}{2}\left(I + Q\sqrt{2}J_2(A)\cos(2\Omega_1 t) + U\sqrt{2}J_2(A)\cos(2\Omega_2 t) + V\sqrt{2}J_1(A)\sin(\Omega_1 t)\right)$$

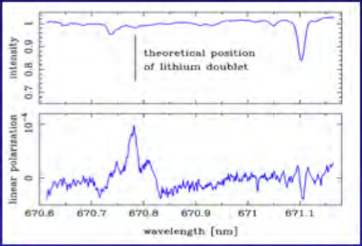
- frequencies of PEMs given by Ω_1, Ω_2
- amplitudes of both PEMs, A, chosen such that $J_0(A) = 0$
- for vector polarimetry: 3 synchronous demodulators, each sensitive to one of $2\Omega_1$, $2\Omega_2$, Ω_1
- development of demodulating CCD by Povel and coworkers about 20 years ago
- fractional polarization free of flat-field effects
- no seeing effects due to high modulation frequency

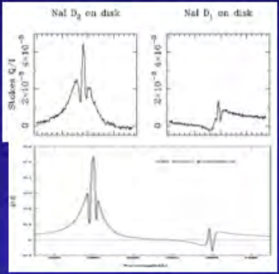


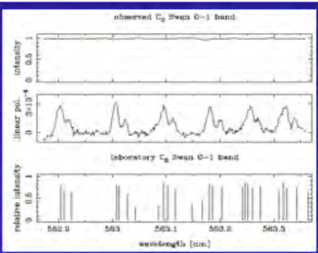
Zurich Imaging Polarimeters I, II

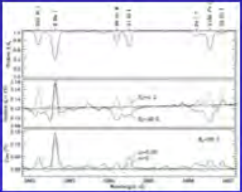
- Developed at ETH Zurich, Switzerland starting in the late 1980's by Povel, Egger, Steiner, Aebersold^2, Keller, Bernasconi, Gandorfer, Stenflo et al.
- Works with Piezo-Elastic Modulators (PEM) at 20-100kHz
- Synchronous demodulation with specially masked CCDs
- Up to 10 frames per second and up to 4 cameras simultaneously
- No effects due to seeing, flat-field, optical aberrations
- Capable of detecting polarization below the $1 \cdot 10^{-5}$ level
- Works well with adaptive optics and image reconstruction techniques

Scattering Polarization

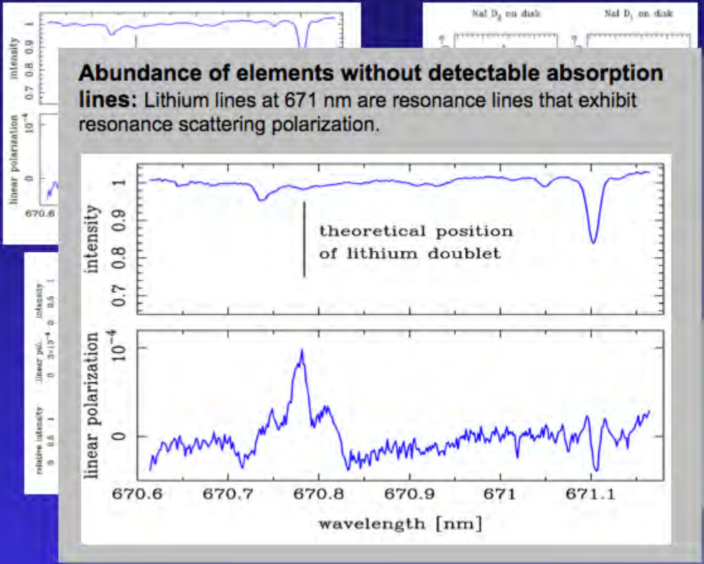








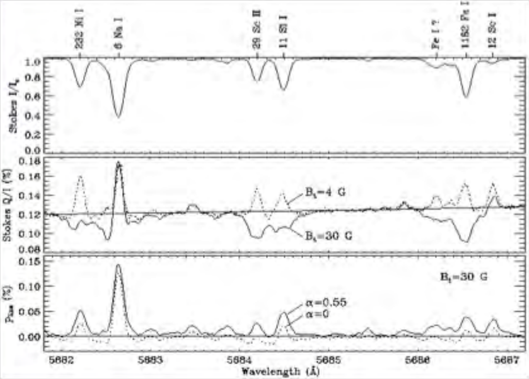
Scattering Polarization



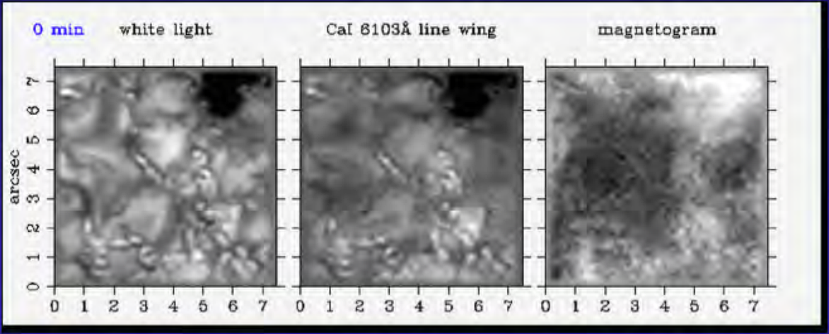
Abundance of elements without detectable absorption lines: Lithium lines at 671 nm are resonance lines that exhibit resonance scattering polarization.

Scattering Polarization

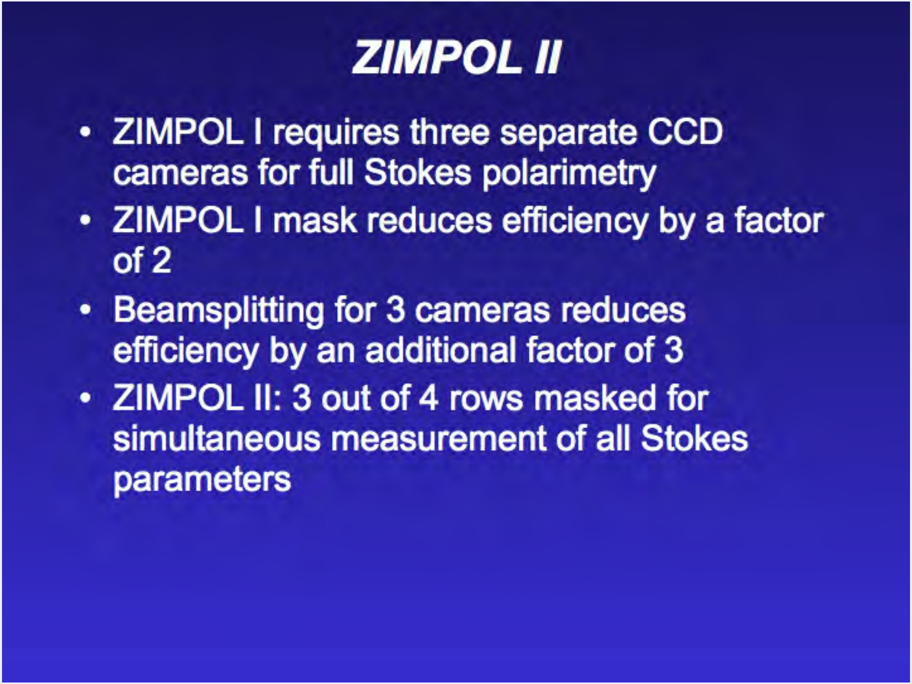
Turbulent background field revealed by Hanle effect:
The differential variation of scattering polarization in various lines can be explained by a spatially varying, turbulent background field.



Polarimetry and Adaptive Optics

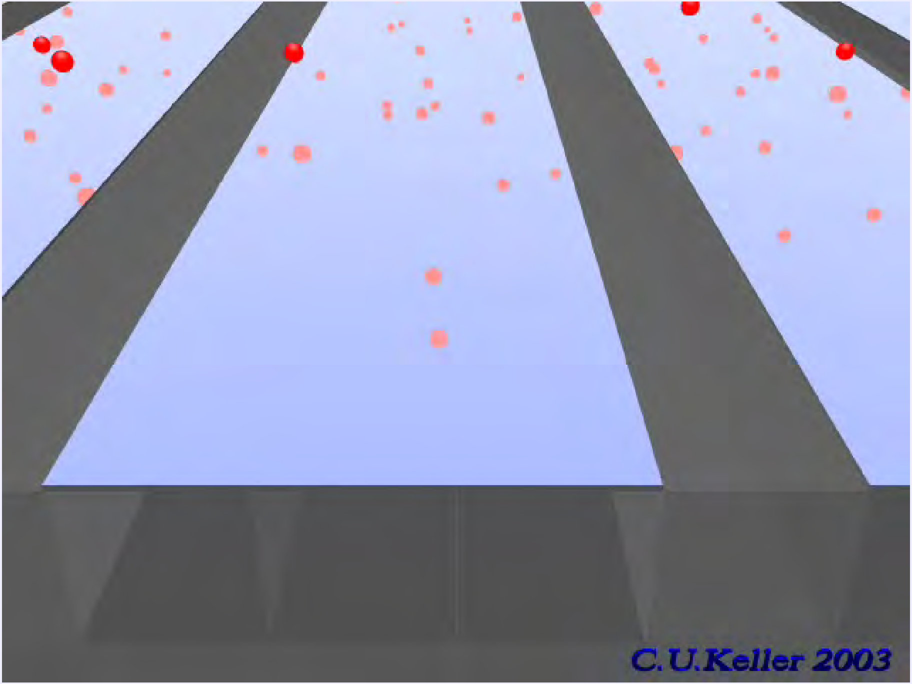


Phase-diverse speckle imaging uses in-focus and out-of-focus image sequences to completely remove the aberrations due to the Earth's atmosphere and the telescope over a field of view that is much larger than the isoplanatic patch.
With R.Paxman, J.Seldin, D.Carrara, T. Rimmele

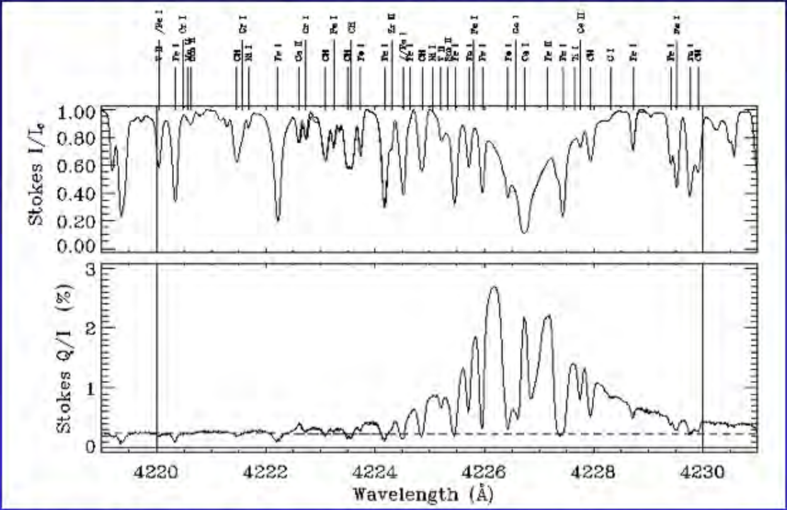


ZIMPOL II

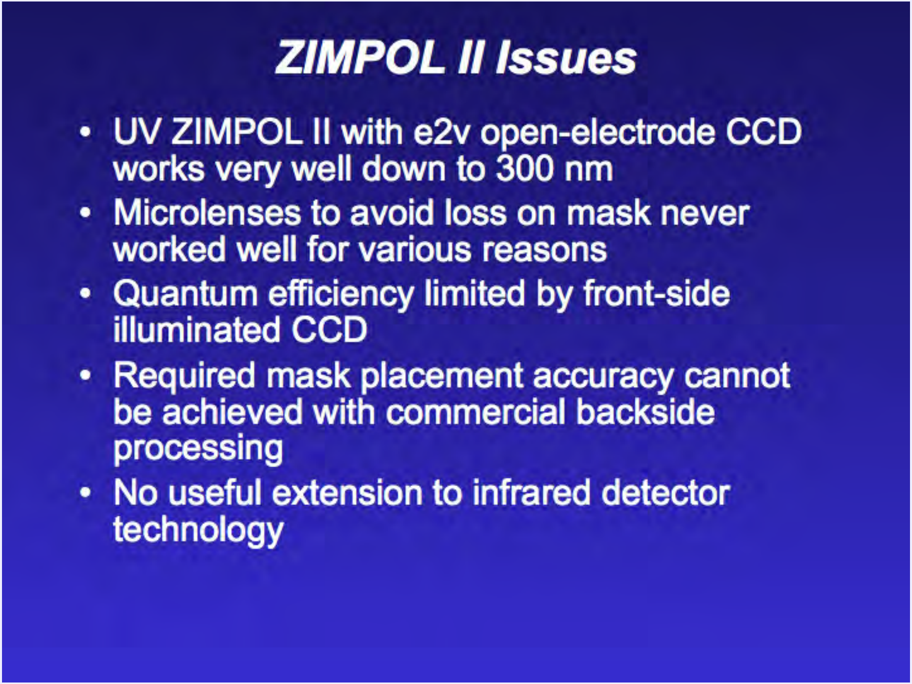
- ZIMPOL I requires three separate CCD cameras for full Stokes polarimetry
- ZIMPOL I mask reduces efficiency by a factor of 2
- Beamsplitting for 3 cameras reduces efficiency by an additional factor of 3
- ZIMPOL II: 3 out of 4 rows masked for simultaneous measurement of all Stokes parameters


C.U.Keller 2003

Scattering Polarization Atlas

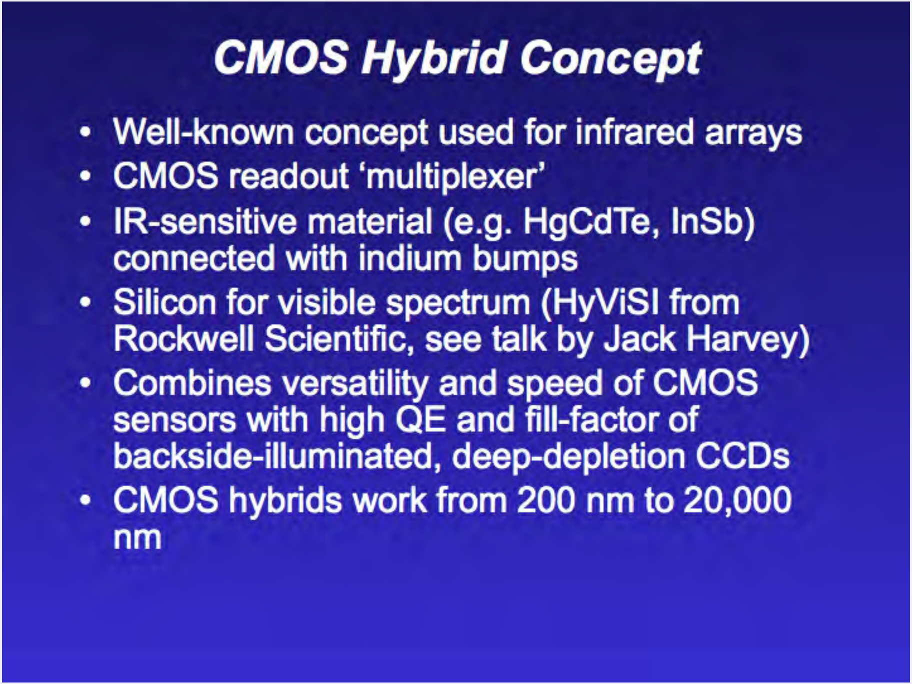


Courtesy Achim Gandorfer



ZIMPOL II Issues

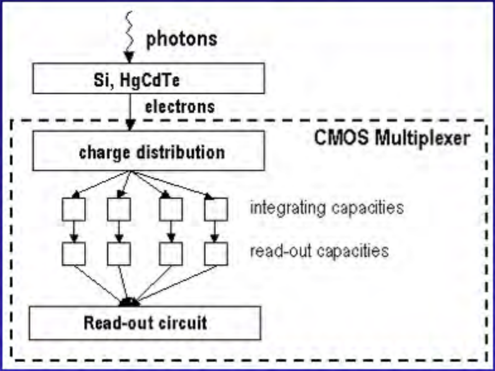
- UV ZIMPOL II with e2v open-electrode CCD works very well down to 300 nm
- Microlenses to avoid loss on mask never worked well for various reasons
- Quantum efficiency limited by front-side illuminated CCD
- Required mask placement accuracy cannot be achieved with commercial backside processing
- No useful extension to infrared detector technology



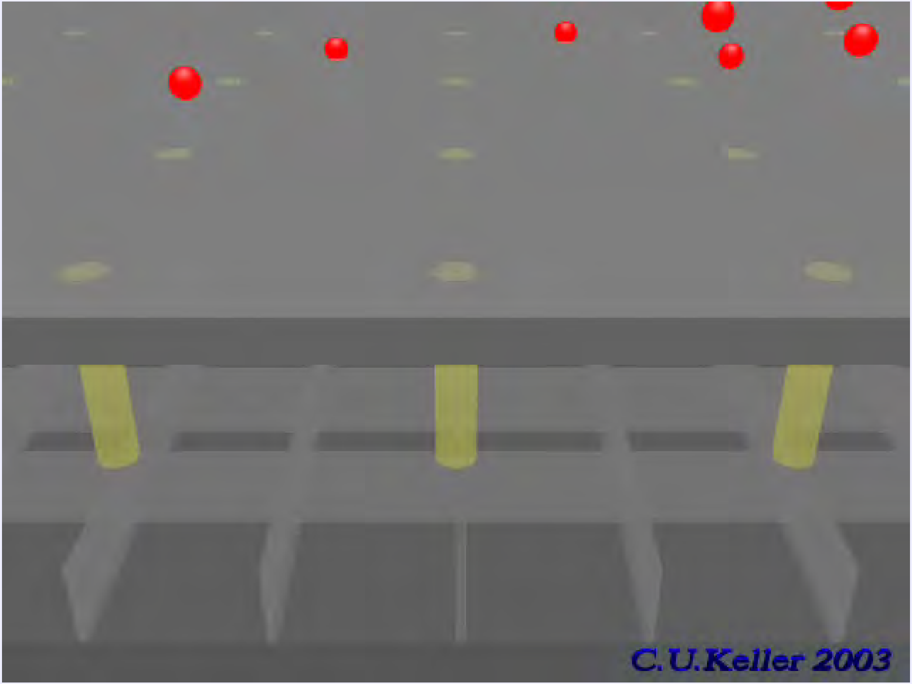
CMOS Hybrid Concept

- Well-known concept used for infrared arrays
- CMOS readout ‘multiplexer’
- IR-sensitive material (e.g. HgCdTe, InSb) connected with indium bumps
- Silicon for visible spectrum (HyViSI from Rockwell Scientific, see talk by Jack Harvey)
- Combines versatility and speed of CMOS sensors with high QE and fill-factor of backside-illuminated, deep-depletion CCDs
- CMOS hybrids work from 200 nm to 20,000 nm

C^3Po Pixel



- 8 capacitors per pixel; transistors to demodulate 4 states while previous images are read out
- 18 µm pixel has 6 mio. electron capacity
- Multiplexers with up to 27 transistors per pixel have been built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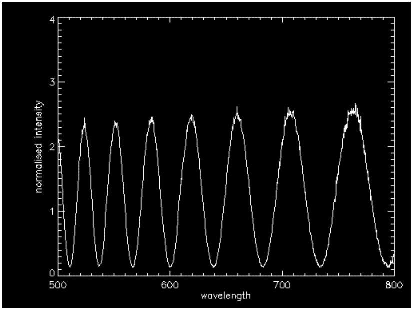
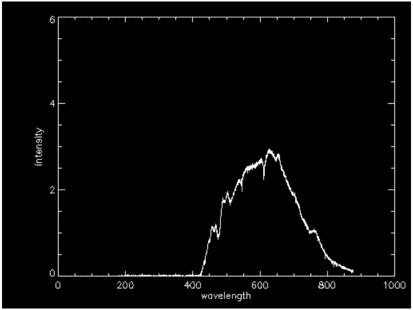
Spectral Modulation

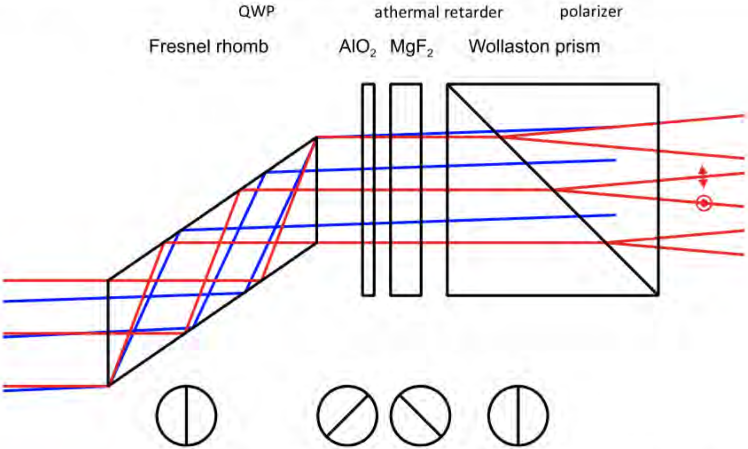
Introduction





- optically add modulation to intensity spectrum:
  - modulation amplitude = degree of linear polarization $(\sqrt{Q^2+U^2}/i)$
  - modulation phase = orientation of linear polarization $(\mathrm{a}rctanQ/U)$
- Advantages of spectral modulation:
  - Fully passive
  - Scalable
  - One-shot measurement
  - No differential effects

SPEX polarimetry

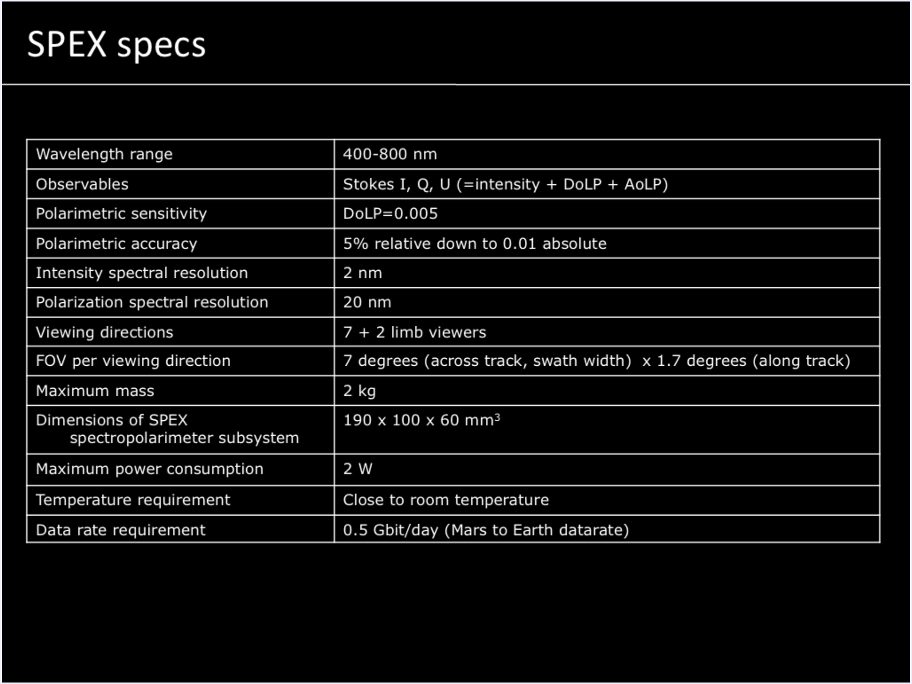


$$I(\lambda)=\tfrac{1}{2}I_0(\lambda)\left[1\pm P_L(\lambda)\cos\left(\frac{2\pi\cdot\delta(\lambda)}{\lambda}+2\varphi_L(\lambda)\right)\right]$$

Snik & Keller (2008) preliminary patent

SPEX: Spectropolarimeter for Planetary EXploration

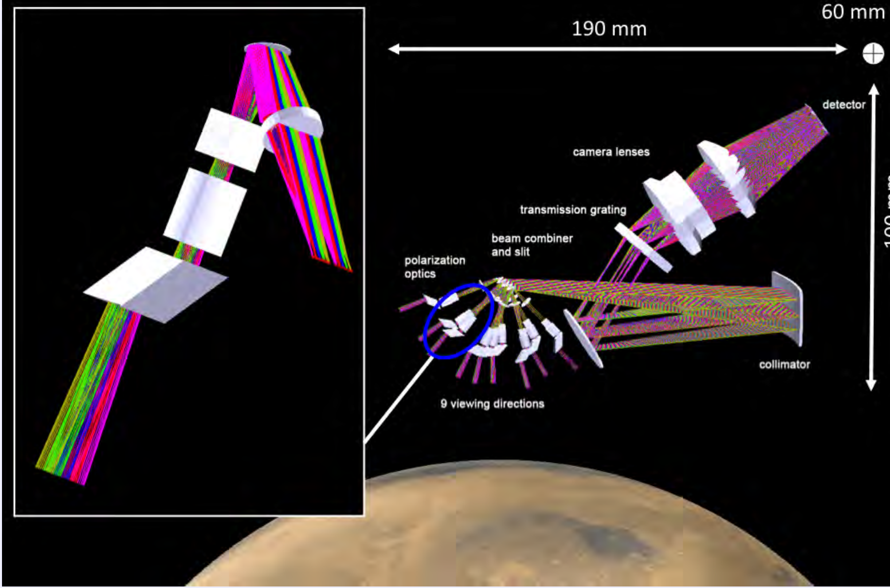
- Measure size distribution and composition of planetary atmospheres
- dust (storms) on Mars, atmosphere of Jupiter, aerosols in Earth atmosphere
- needs to cover large wavelength range,
- Outlook
  - Venus-as-an-exoplanet (prototype)
  - Earth from helicopter (prototype)
  - Mars (ExoMars)
  - Jupiter + moons (EJSM)
  - Titan (TandEM)
  - Earth from ISS
  - Earth from microsatellites (FAST)
  - Earth-as-an-exoplanet from the moon (ESA lunar lander)



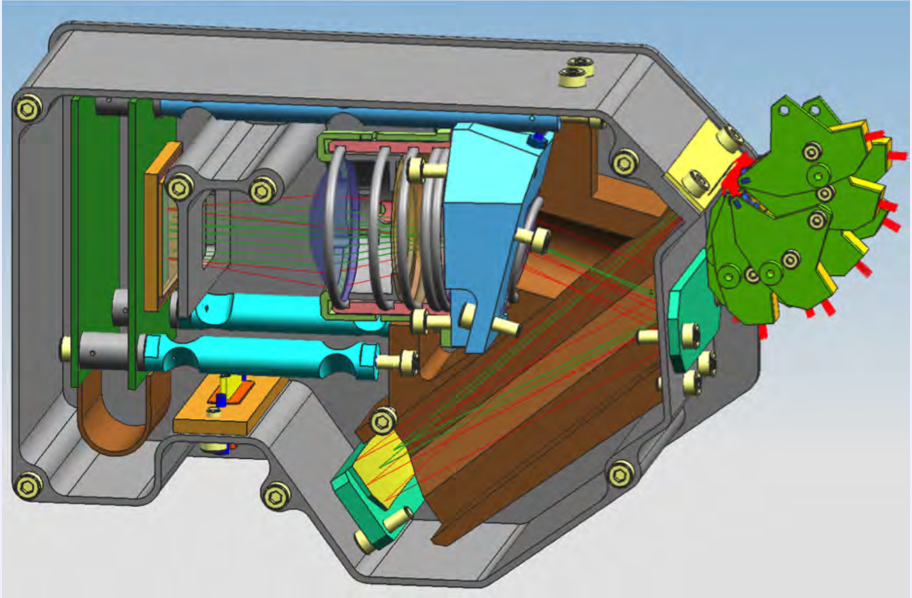
SPEX specs

Wavelength range	400-800 nm
Observables	Stokes I, Q, U (=intensity + DoLP + AoLP)
Polarimetric sensitivity	DoLP=0.005
Polarimetric accuracy	5% relative down to 0.01 absolute
Intensity spectral resolution	2 nm
Polarization spectral resolution	20 nm
Viewing directions	7 + 2 limb viewers
FOV per viewing direction	7 degrees (across track, swath width) x 1.7 degrees (along track)
Maximum mass	2 kg
Dimensions of SPEX spectropolarimeter subsystem	190 x 100 x 60 mm^3
Maximum power consumption	2 W
Temperature requirement	Close to room temperature
Data rate requirement	0.5 Gbit/day (Mars to Earth datarate)

SPEX optical design



SPEX breadboard



Polarimetric performance