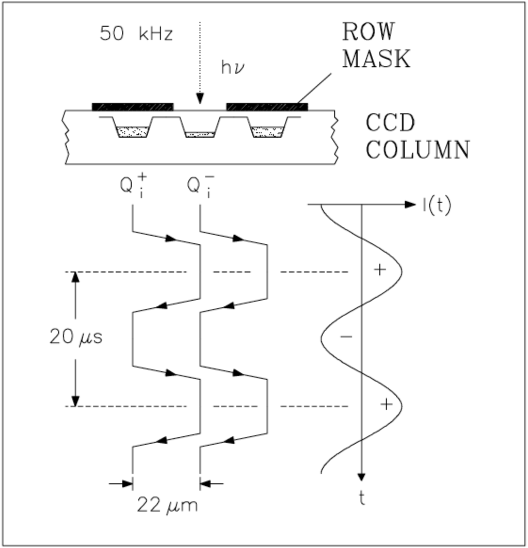
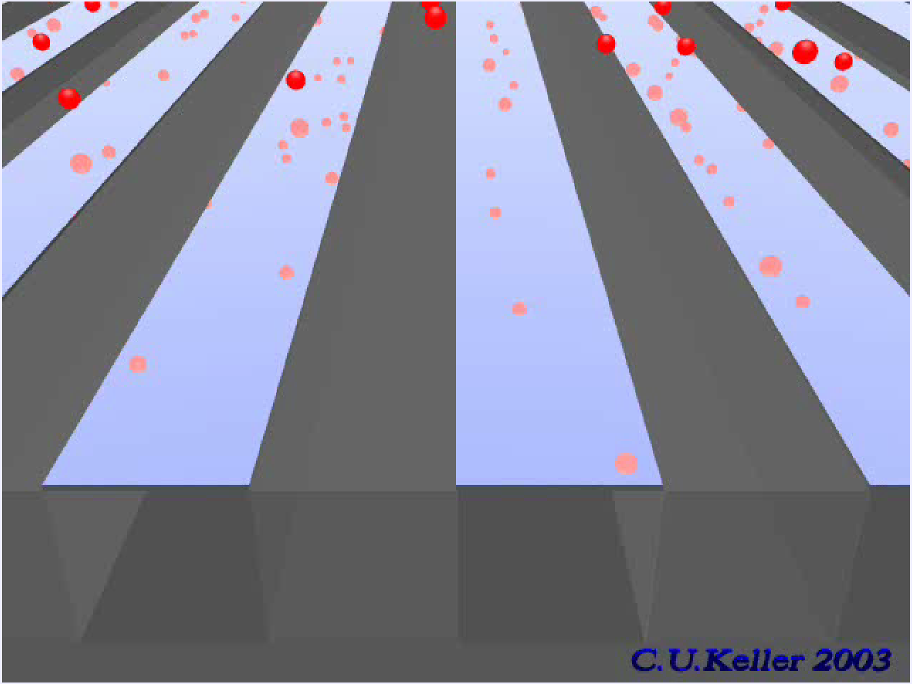
Lecture 14: Advanced Polarimeters

Outline

1. ZIMPOL
2. C3Po
3. SPEX

CCD Array as Fast Demodulator

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CCD Array as Fast Demodulator

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

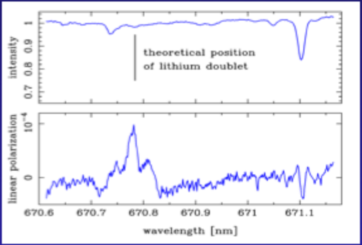
$$I'(t) = \frac{1}{2}\left(I + Q\sqrt{2}J_2(A)\cos(2\Omega_1 t) + U\sqrt{2}J_2(A)\cos(2\Omega_2 t) + V\sqrt{2}J_1(A)\sin(\Omega_1 t)\right)$$

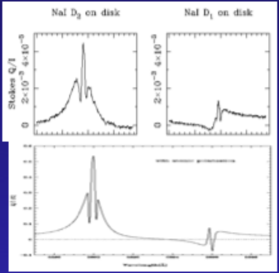
- frequencies of PEMs given by Ω_1, Ω_2
- amplitudes of both PEMs, A, chosen such that $J_0(A) = 0$
- for vector polarimetry: 3 synchronous demodulators, each sensitive to one of $2\Omega_1$, $2\Omega_2$, Ω_1
- development of demodulating CCD by Povel and coworkers about 20 years ago
- fractional polarization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

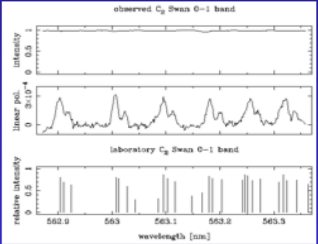
Zurich Imaging Polarimeters I, II

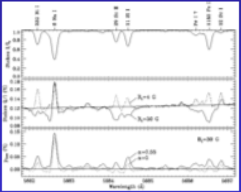
- Developed at ETH Zurich, Switzerland starting in the late 1980's by Povel, Egger, Steiner, Aebersold[2], Keller, Bernasconi, Gandorfer, Stenflo et al.
- Works with Piezo-Elastic Modulators (PEM) at 20-100kHz
- Synchronous demodulation with specially masked CCDs
- Up to 10 frames per second and up to 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

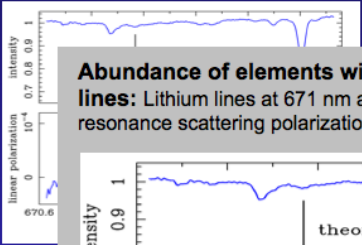


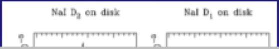




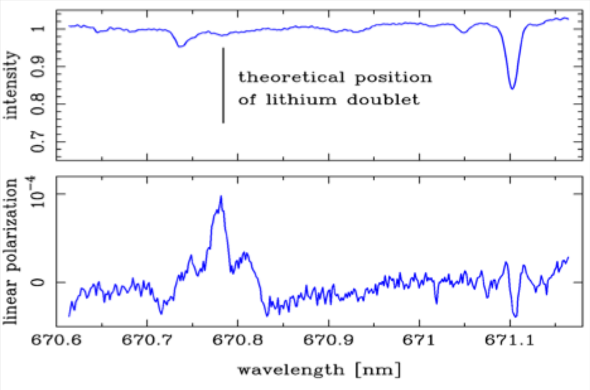


Scattering Polarization



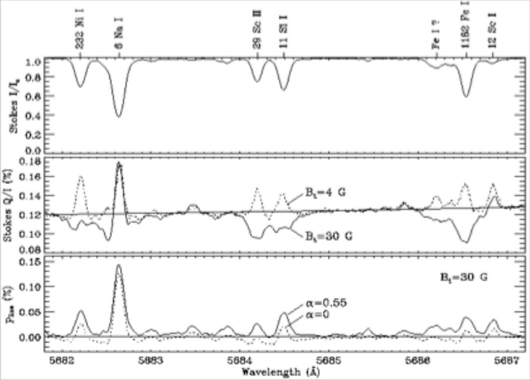


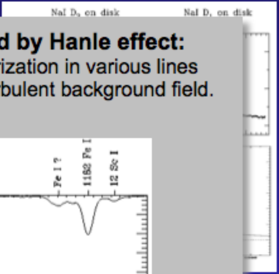
Abundance of elements without detectable absorption lines: Lithium lines at 671 nm are resonance lines that exhibit resonance scattering polarization.

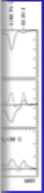


Scattering Polarization

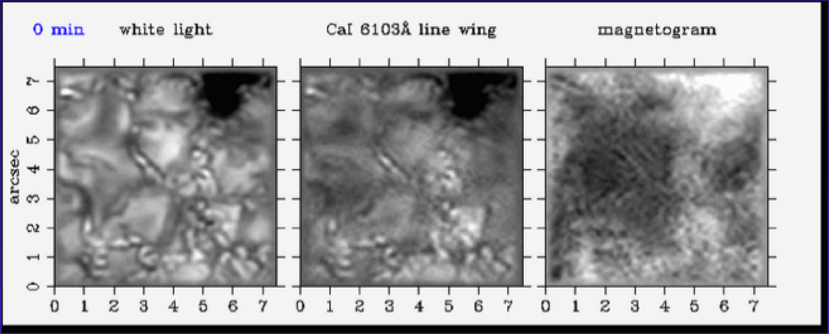
Turbulent background field revealed by Hanle effect:
The differential variation of scattering polarization in various lines can be explained by a spatially varying, turbulent background field.







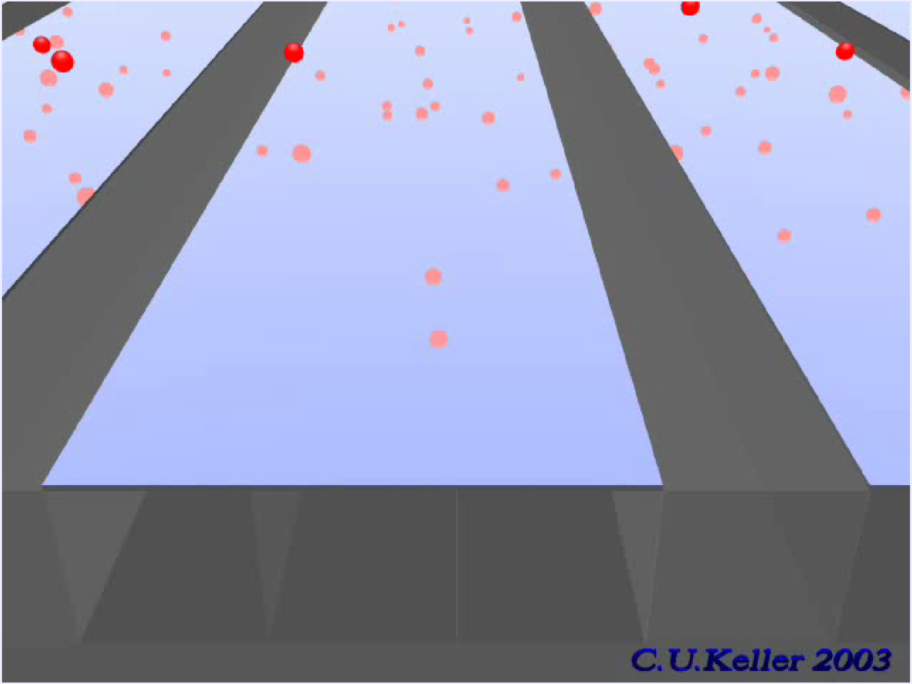
Polarimetry and Adaptive Optics



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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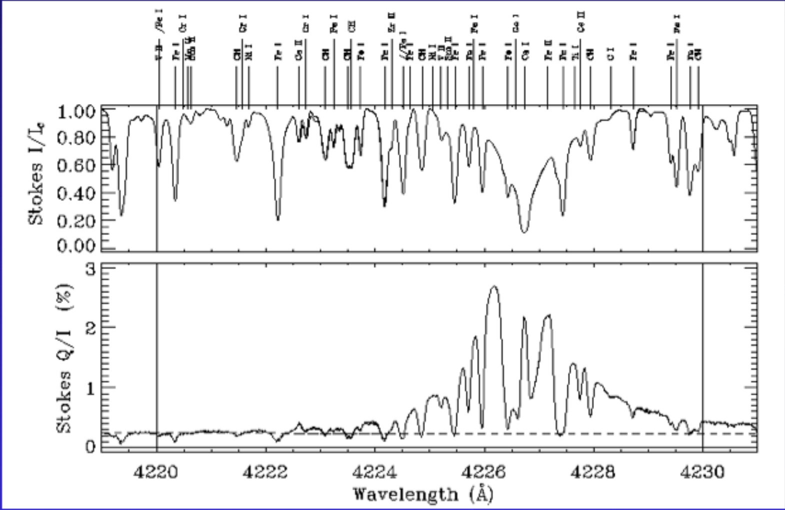
Scattering Polarization Atlas



Courtesy Achim Gandorfer

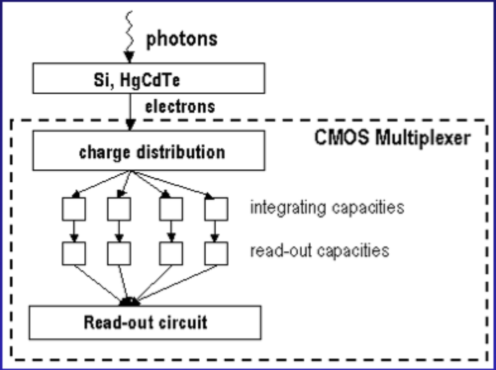
ZIMPOL II Issues

- 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

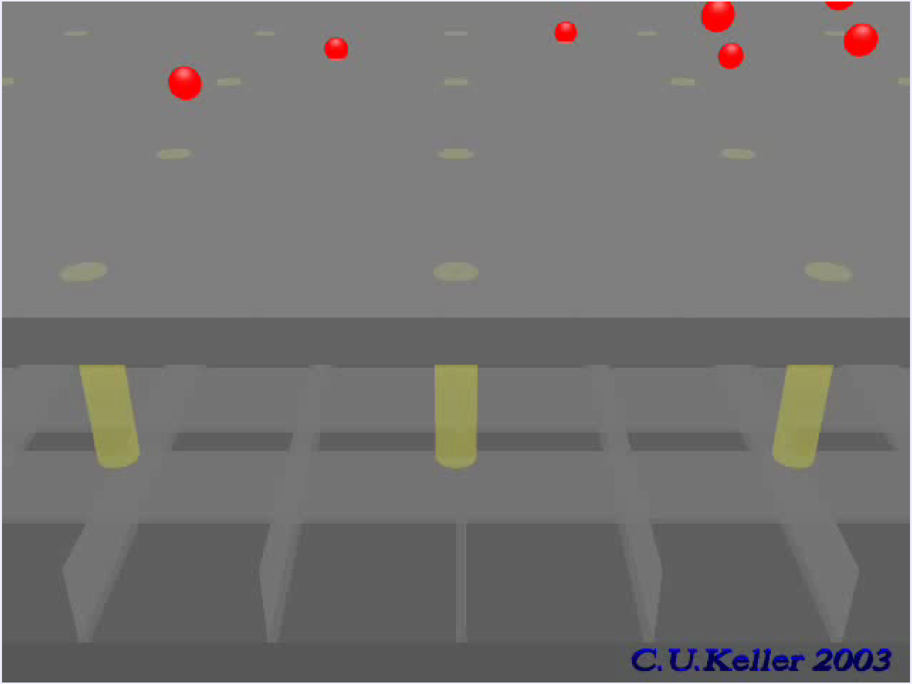
CMOS Hybrid Concept

- 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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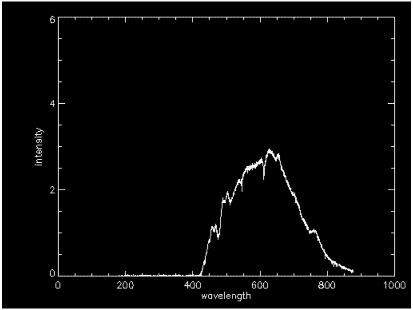
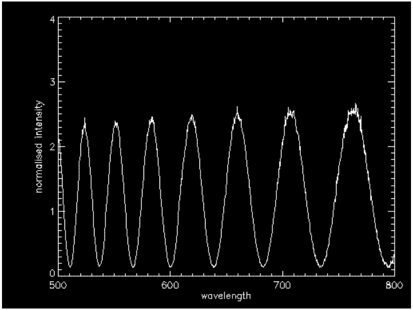
Spectral Modulation

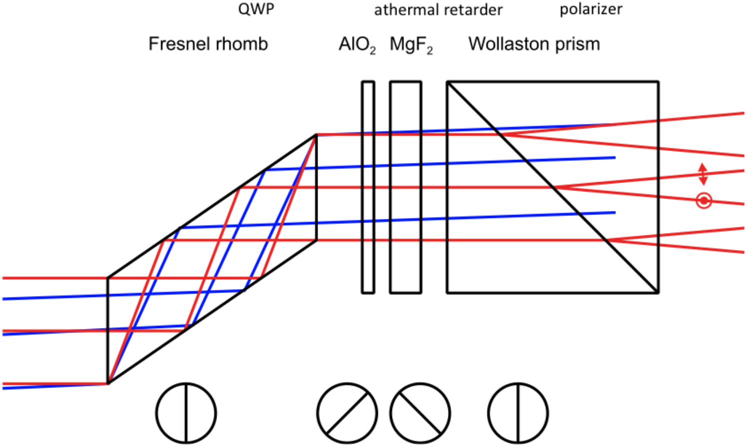
Introduction





- optically add modulation to intensity spectrum:
  - modulation amplitude = degree of linear polarization ($\sqrt{Q^2 + U^2}/i$)
  - modulation phase = orientation of linear polarization ($\mathrm{a}rctan Q/U$)
- advantages of spectral modulation:
  - no moving parts
  - 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

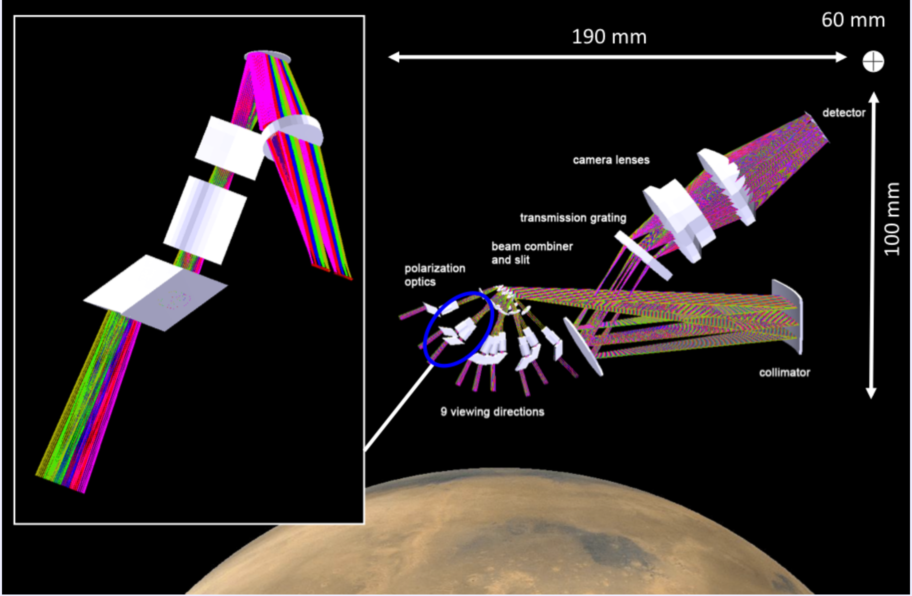
SPEX: Spectropolarimeter for Planetary EXploration

- 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 (Chinese mission)
  - Jupiter + moons (EJSM)
  - Titan (TandEM)
  - Earth from ISS
  - Earth from microsatellites (FAST)
  - Earth-as-an-exoplanet from the moon (ESA lunar lander)

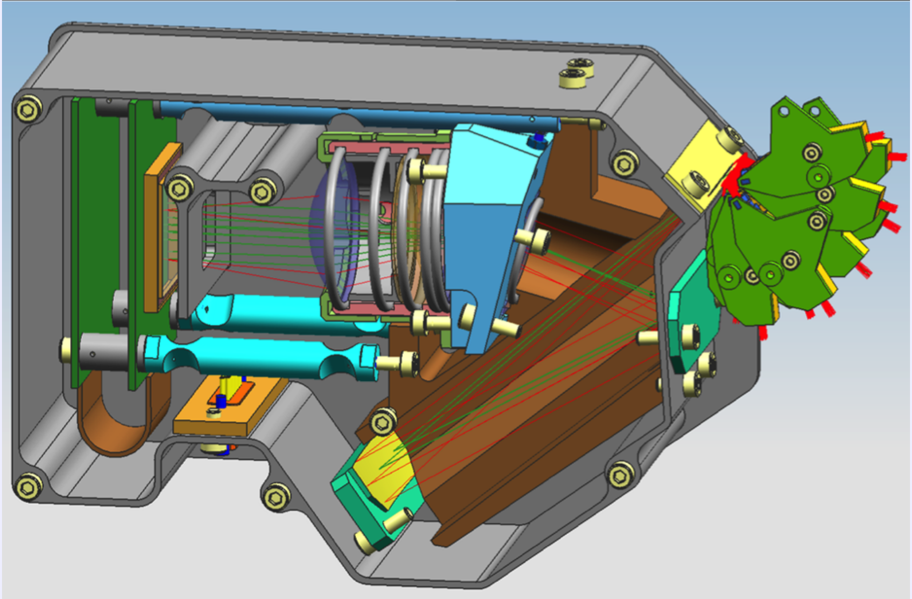
SPEX specs

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