FERMILAB-SLIDES-25-0142-PPD

Frequency-Selectable Laser Source (FLS) Calibrator for CMB Bandpass Characterization

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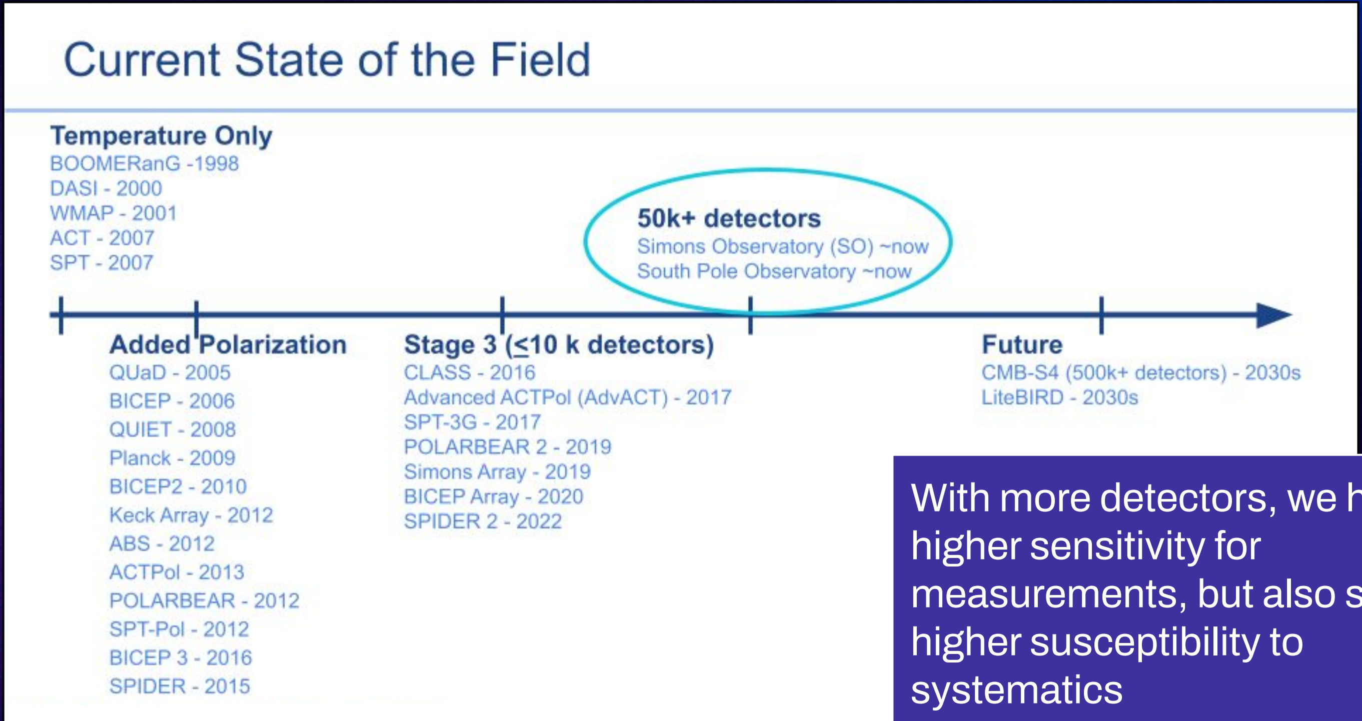
mm Universe | June 23, 2025

Key Takeaways

- Upcoming experiments will make the most sensitive CMB measurements to date!
  - Support this with better understanding of systematics
- Detector bandpass
  - Current calibrators: 1-3% level accuracy, systematics limited
  - Need ~0.2-0.3% level for high-ell science, ~0.1% level for SZ science
  - Frequency dependence of detectors → frequency dependence of beam
- We designed a new calibrator!
  - Combined with existing technology, we will be able to reach 0.1% level accuracy
- We built a prototype and characterized its behavior
  - Also updated the design based on experience, assembling now!
    - Will use it for measurements later this summer
- Working toward maturity of the new calibrator for future microwave experiments

Sensitivity and Systematics



Credit: S. Simon, slide from CMB-CAL @ Bicocca (2024)

With more detectors, we have higher sensitivity for measurements, but also see higher susceptibility to systematics

Bandpass and mm-Wavelength Science

- Bandpass: frequency and gain response of detectors
- To separate foregrounds (astrophysical and atmospheric) from the CMB signal, we need to understand detector bandpasses:
  - **CMB *r*** constraints: need bandpass uncertainty <1% [3]
  - **CMB N_{eff}** and **CIB** constraints: need to know band central frequency to the ~0.5% level [2]
  - **SZ** constraints: SZ signal has frequency dependence, so tighter requirements (~0.1% level accuracy) for fitting spectra [2]

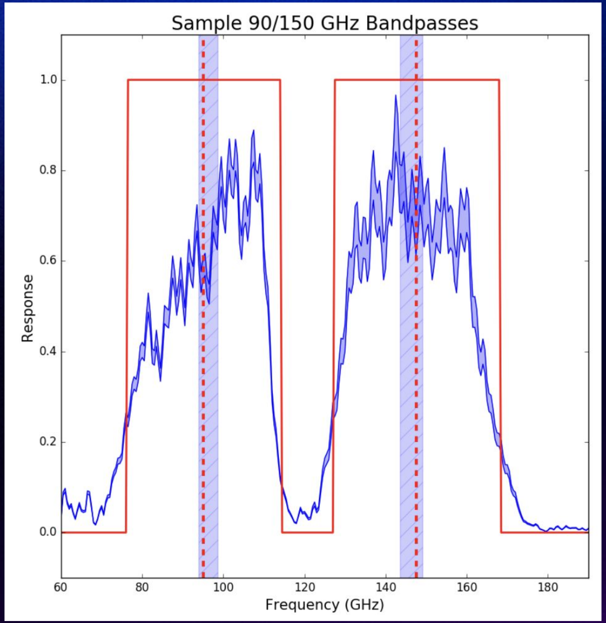


Image: Ward, J.T., et al. (2018)

Current State of Bandpass Calibration

Fourier Transform Spectrometer (FTS)

- Can currently achieve 1-3%-level accuracy for bandpass measurements
- Limitations:
  - Broadband sources: don't have good source characterization
  - FTS transfer function: not perfectly uniform across frequencies, difficult to characterize
  - Can't adjust power level of source without introducing potential systematics

Systematically limited, so difficult to improve on design

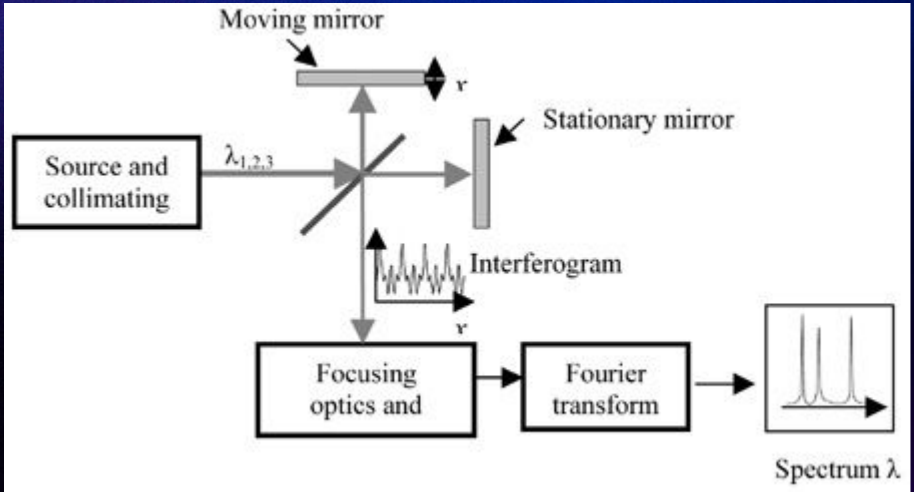
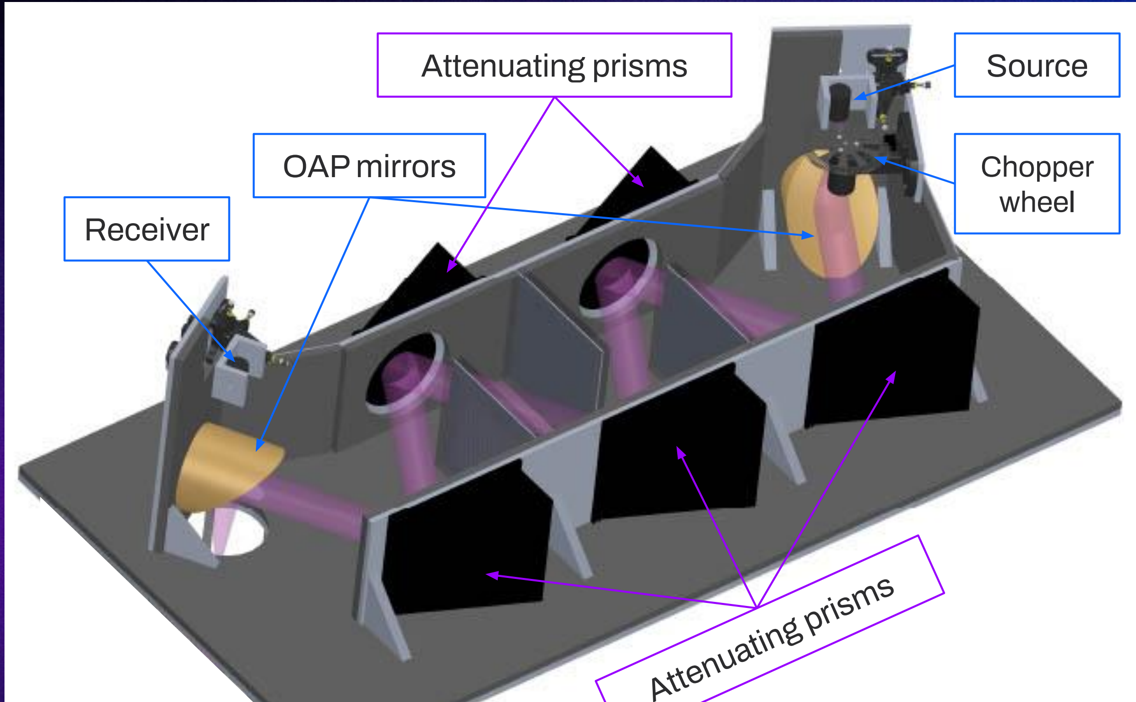


Image: V. Saptari, *Fourier-Transform Spectroscopy Instrumentation Engineering*, SPIE Press, Bellingham, WA (2003).

Frequency-selectable Laser Source (FLS)



Credit: S. Sutariya (adapted by L. Saunders)

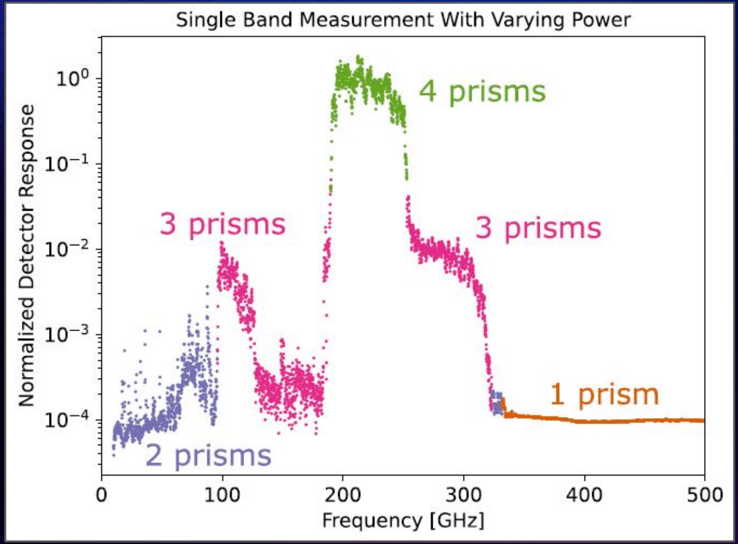
Off-the-shelf Toptica source: 20-1200 GHz, with 0.01 GHz step size

Nylon prisms each attenuate ~94% of laser signal

Absorber on internal surfaces prevents reflections that could interfere with the signal

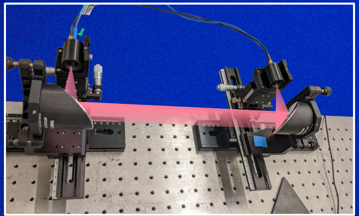
FLS Advantages

- Source is characterizable across frequency range
  - Measurements are repeatable
- Removable attenuators allow control over power on detectors
  - Attenuate signal to avoid overloading detectors in-band
  - Increase power to study out-of-band signal
- Frequency step size is much smaller than we could achieve with a similar-footprint FTS
  - Especially important for narrow-band experiments like SPT-SLIM



Credit: S. Sutariya

Laser source characterization

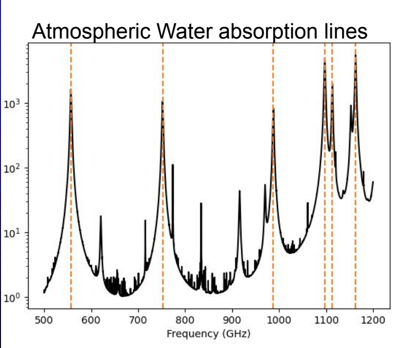


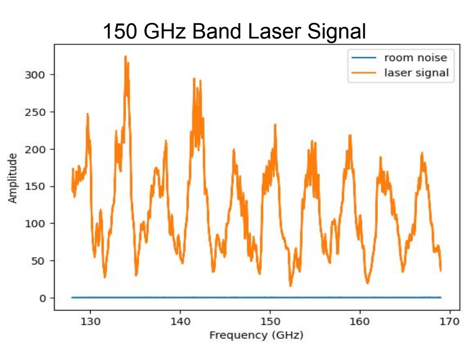
Laser image credit:
S. Sutariya

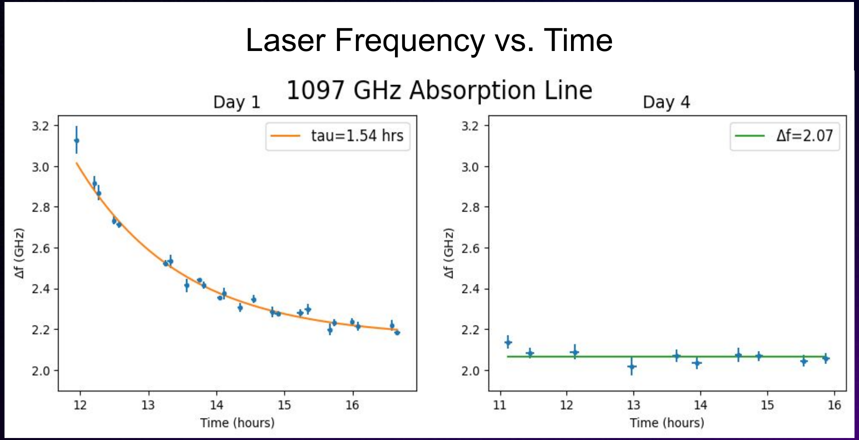
We characterized the Toptica laser source:

- Reflections in the laser transmitter/receiver cause oscillations in signal → correct for this signal
- Frequency calibration with atmospheric water vapor lines
- Source frequency settles over time → found time constant, updated testing procedures

Any time we use a new laser source, we will need to characterize again.



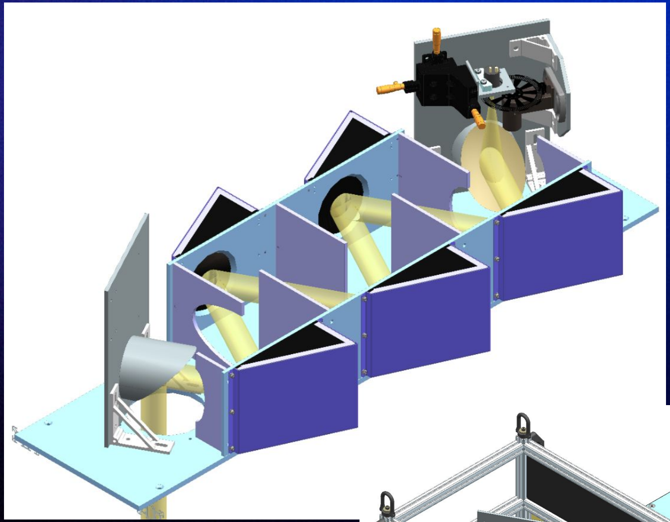


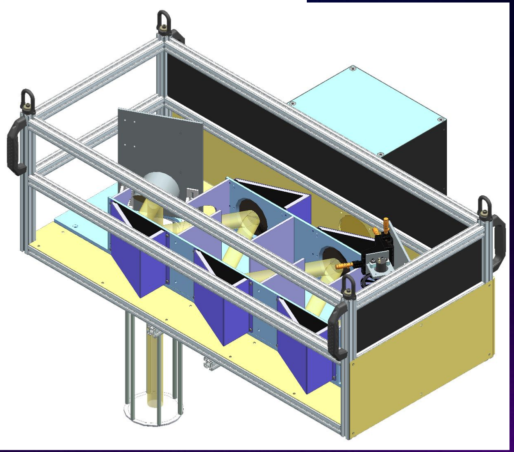


Upgraded FLS Version 2

- Lighter weight → easier for in-field measurements
  - Move most electronics to an external location → less weight carried by a moving FLS
- Baffles, absorption boxes integrated into design
- Improved alignment features, verified with CMM measurements
- Intentional design for output flexibility
- Side modules that can house an on-board power meter and spectrometer

Upgraded version designed, assembly in progress!





Upcoming work

- Characterize the new Toptica source at FNAL, compare behavior with the UChicago Toptica source
- Build FLS v2.0 and characterize behavior
- Use new FLS to make bandpass measurements with CMB-S4 detectors in the lab this summer, compare to FTS measurements
- Demonstrate the FLS for bandpass measurements with SO (in Chile)

The FLS can be a great tool for bandpass measurements, and an important complement to the FTS for understanding systematics as we move toward ever-higher precision instruments!

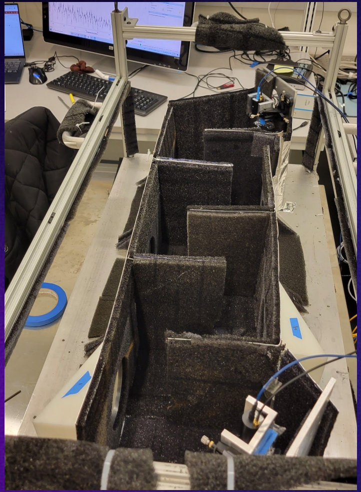
Questions?

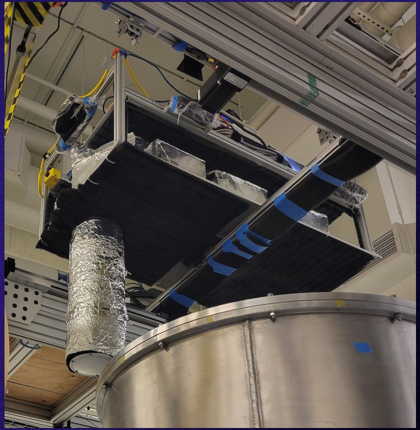
References

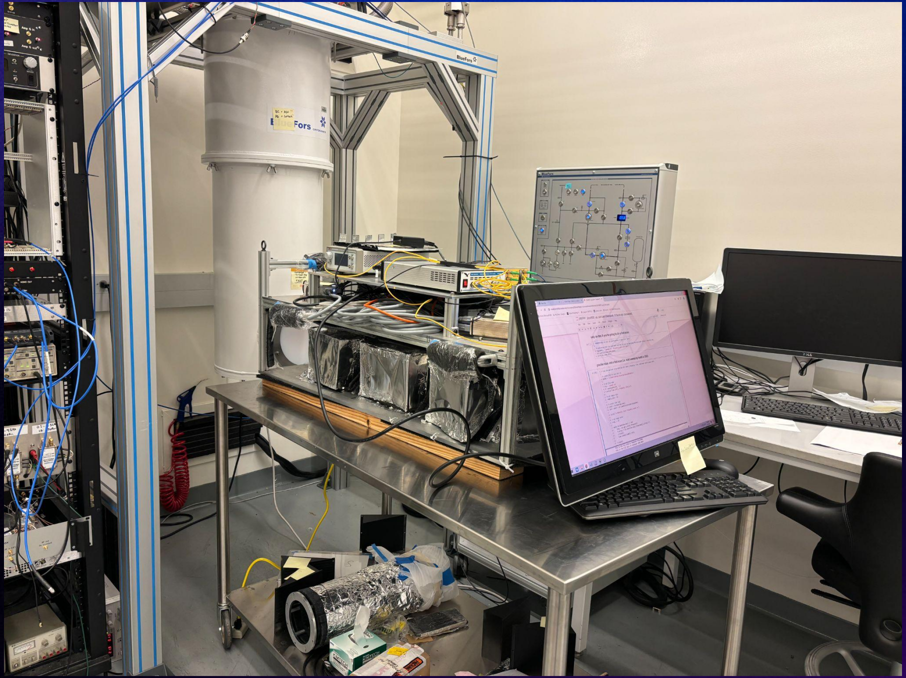
1. Church, S., Knox, L., and White, M.J. *The effect of bandpass uncertainties on component separation*. Astrophys.J.Lett. 582 (2018), L63-L66, Astrophys.J. 582 (2003), L63-L66. Accessed at https://arxiv.org/pdf/astro-ph/0210247.
2. Giardiello, S., et al. *The Simons Observatory: impact of bandpass, polarization angle and calibration uncertainties on small-scale power spectrum analysis*. https://arxiv.org/pdf/2403.05242v2.
3. Ward, J.T., et al. *The effects of bandpass variations on foreground removal forecasts for future CMB experiments.* https://arxiv.org/pdf/1803.07630.
4. V. Saptari, Fourier-Transform Spectroscopy Instrumentation Engineering, SPIE Press, Bellingham, WA (2003).

Backup slides

FLS Prototype in the lab

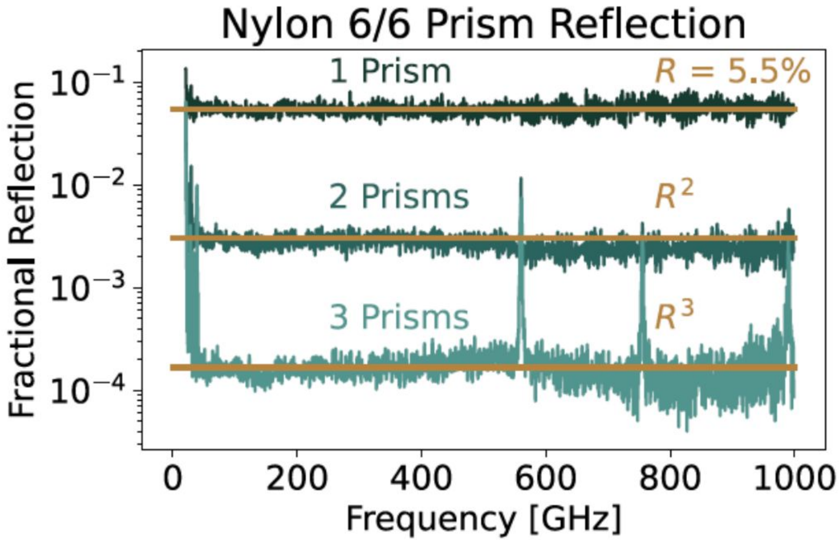






Credit: S. Sutariya

Prism reflectance



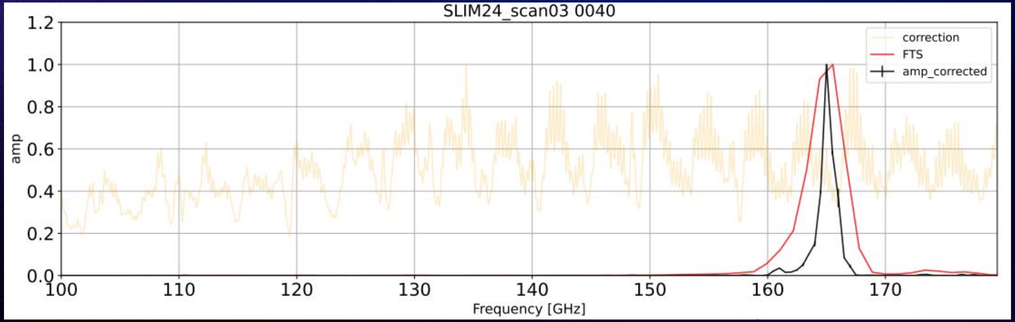
The prisms provide a neutral attenuation across a wide frequency range.

Credit: S. Sutariya
Slide from CMB-CAL 2024

SPT-SLIM Testing

After FTS testing completed, we used the FLS:

- Chose a few detectors with good performance and frequencies close together
- Checked for signal (chopper wheel)
- Stepped through frequencies
- Corrected for lens reflections
- Compared with FTS measurements



Credit: T. Natoli