A Compact Millimeter-Wavelength Fourier-Transform Spectrometer

Zhaodi Pan

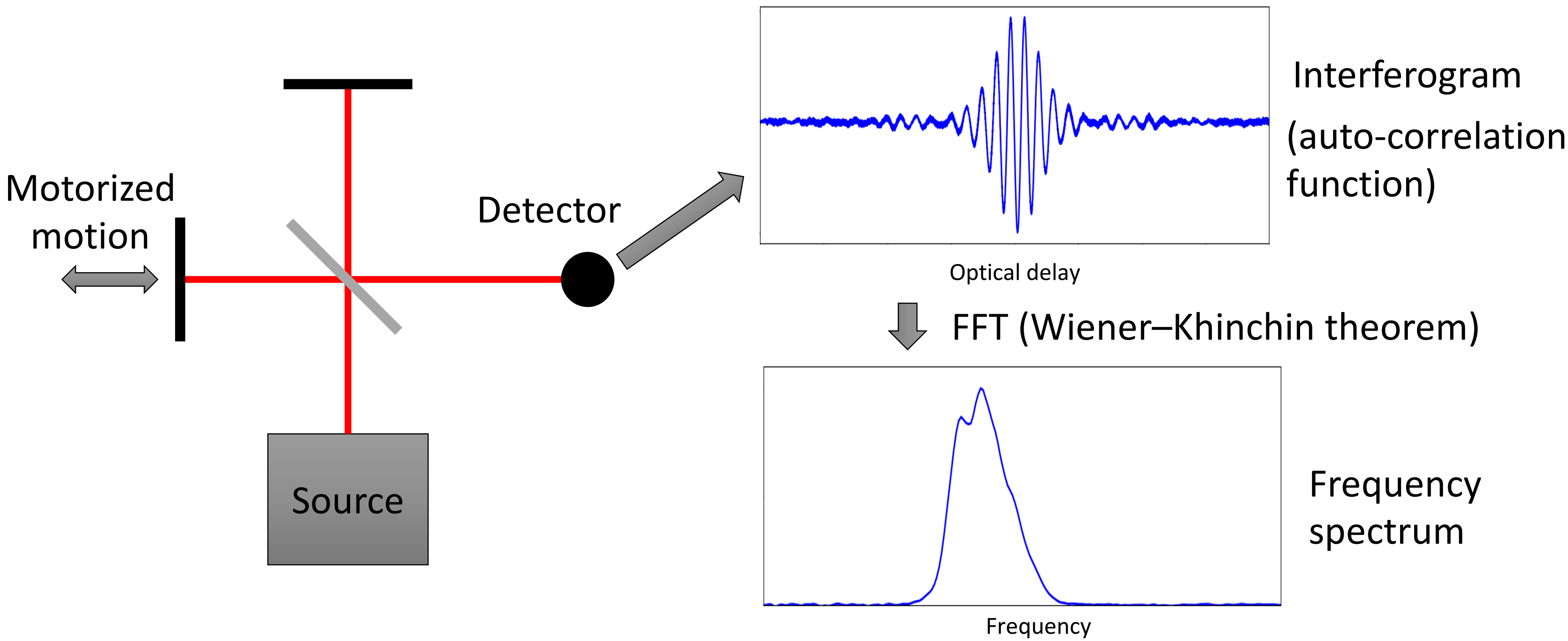
Argonne National Laboratory

Collaborators:

Mira Liu (UChicago), Ritoban Basu Thakur (Caltech), Bradford Benson (Uchicago, Fermilab), Dale J. Fixsen (Goddard), Hazal Goksu (ETH Zürich), Eleanor Rath (MIT), and Stephan Meyer (Uchicago, **PI**)

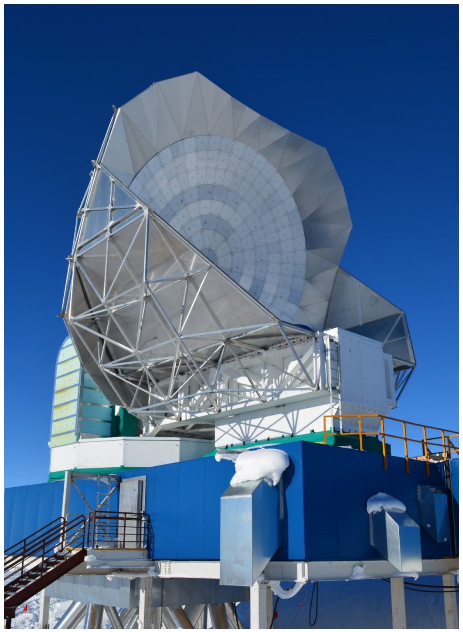
Applied optics 58 (23), 6257-6267, 2019
Applied Optics 59 (25), 7726-7733, 2020

Fourier-Transform Spectrometer (FTS)

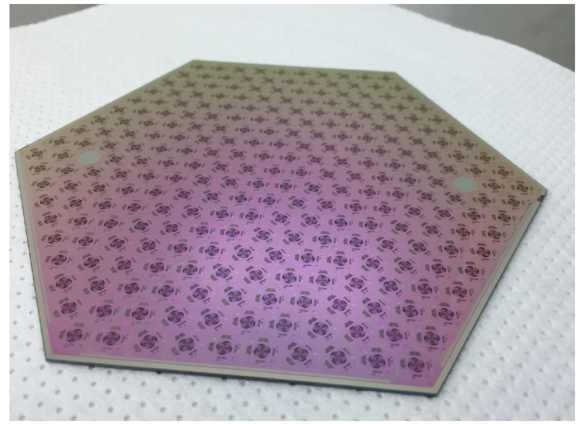


- Detector measures power vs. optical delay (auto-correlation function of the source's radiation).
- FFT of power vs. optical delay is the power spectrum of the source, including the detector's response function.

Motivation – SPT detector characterization



South Pole Telescope (SPT), a 10m telescope for measuring the CMB.



SPT detectors, with frequency bands centered at 95GHz, 150GHz, and 220GHz

Detector spectral band calibration at the South Pole

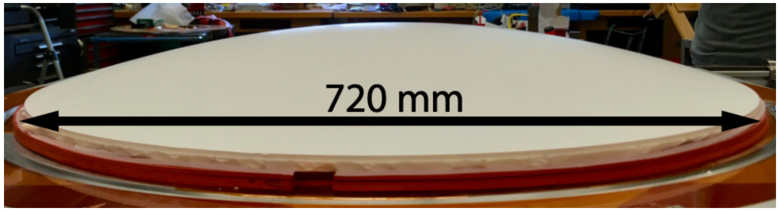
This FTS mounted on a X-Y stage

1300K Thermal source

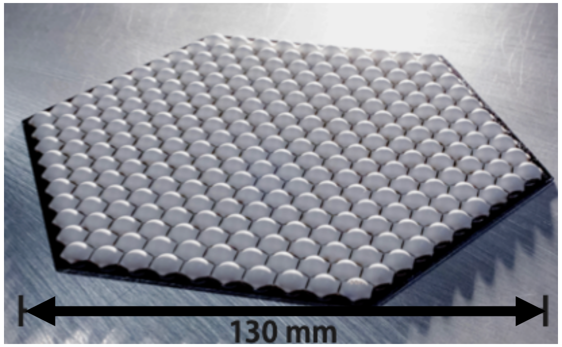
FTS

Collaborated with the SPT team

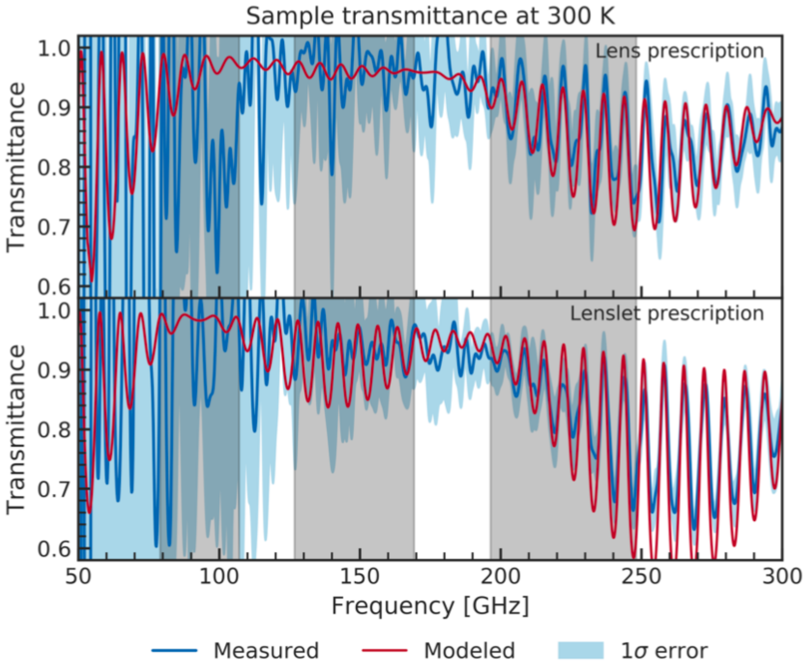
Motivation – optical system characterization



A lens for SPT-3G



A lenslet array for SPT-3G



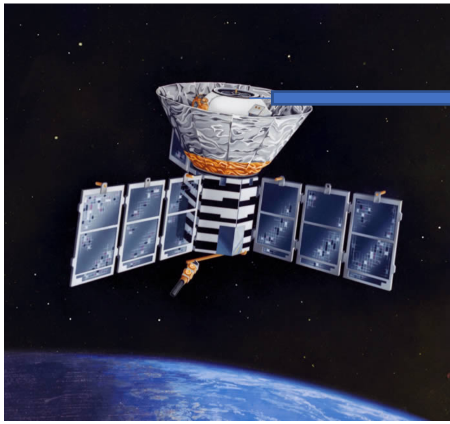
Transmissions of the 3-layer AR-coated lens and lenslet

Testing setup

Nadolski, A, et ,al, Applied Optics 59.10 (2020): 3285-3295

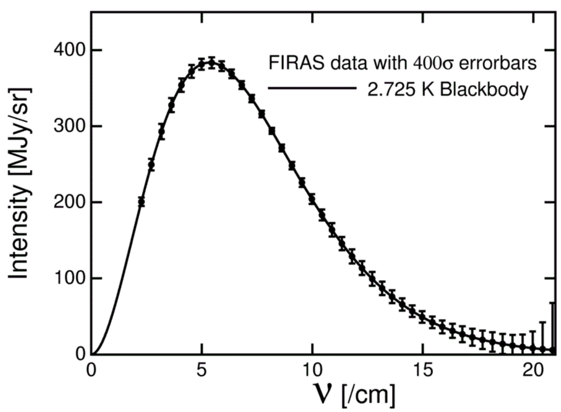
Motivation – a PIXIE prototype

Primarily for measuring the Cosmic Microwave Background (CMB) spectrum and B-mode



FIRAS FTS

COBE satellite

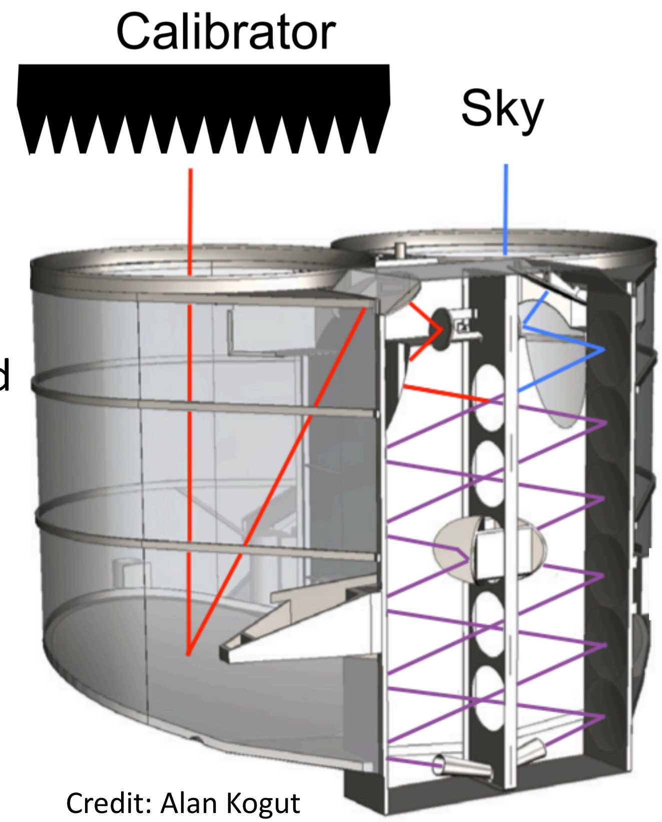


Credit: NASA COBE team

No spectral distortion beyond blackbody was detected.

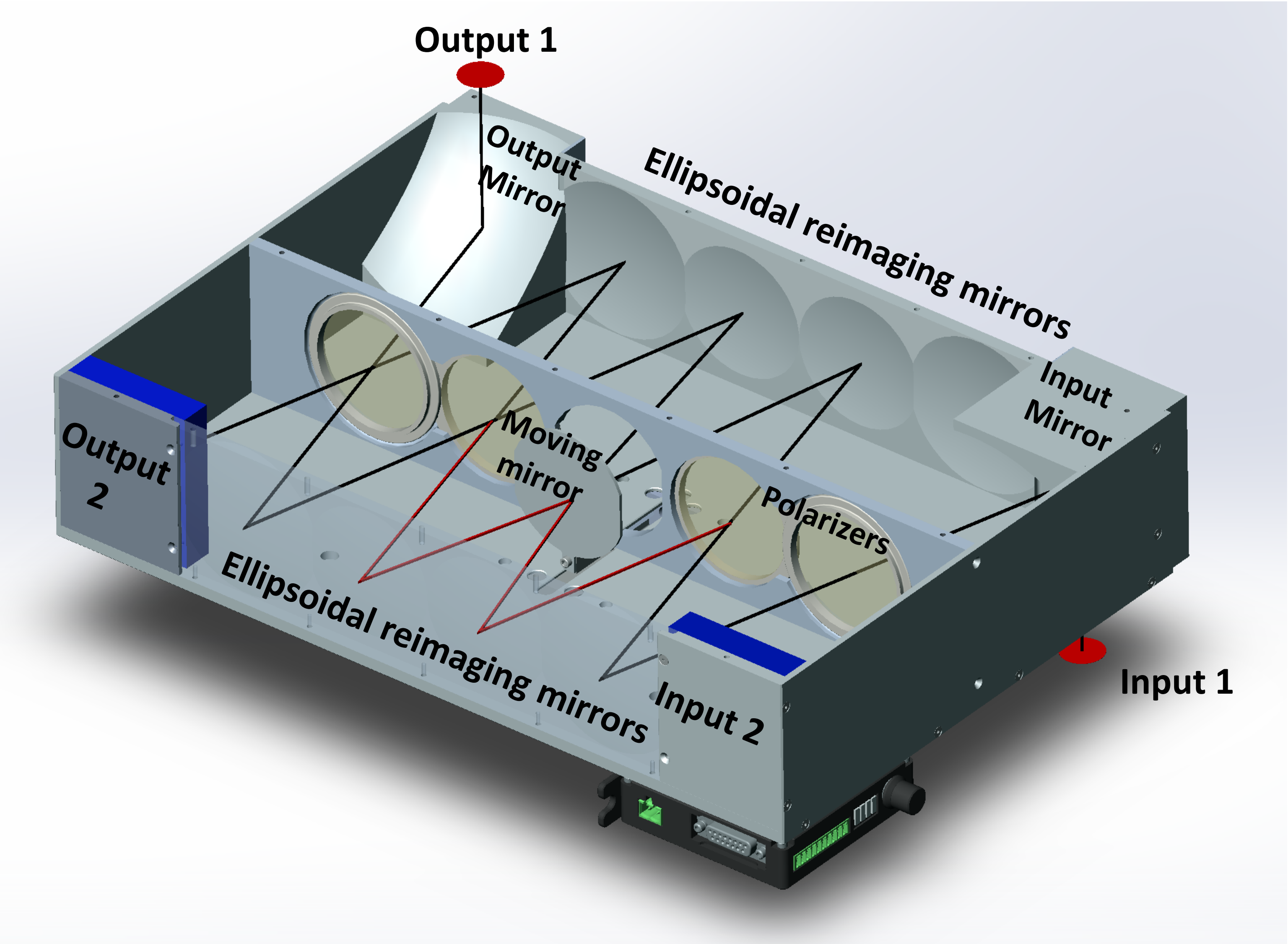
PIXIE was proposed (Al's talk)

The Primordial Inflation Explorer (PIXIE)

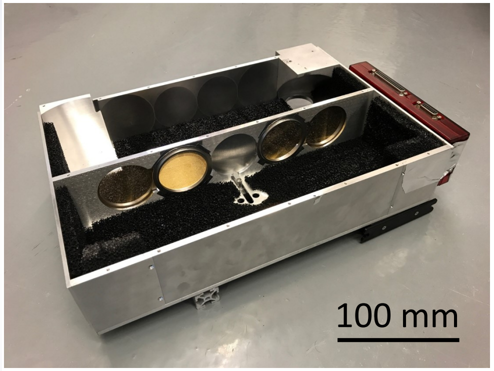


Credit: Alan Kogut

Design overview



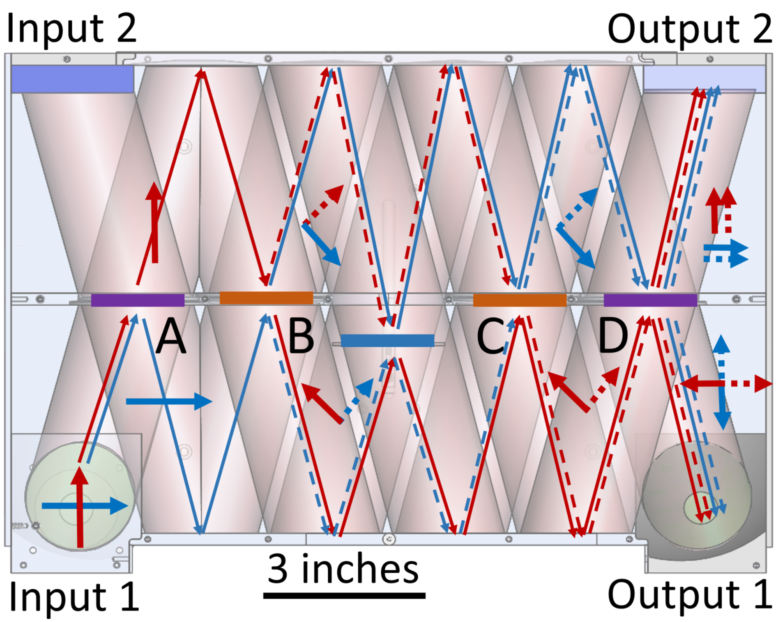
- Symmetric design: systematics control
- Two inputs and two outputs: differential output
- Two polarizations: no polarization loss
- Ellipsoidal mirrors: high density of beams
- Moving mirror: add optical delay



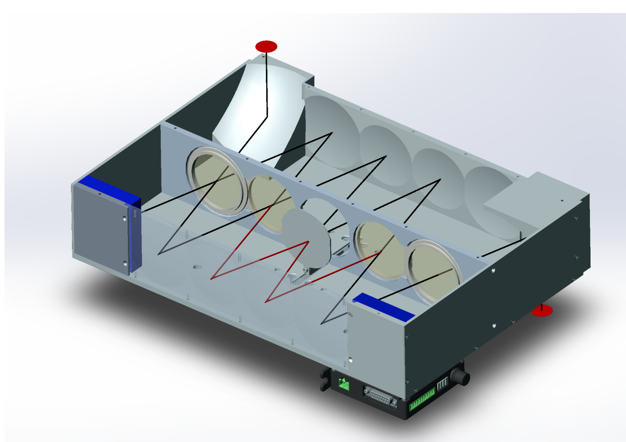
Fabricated FTS
380x250x76 mm

Frequency range: 50-330 GHz, étendu: 100 $\mathrm{mm}^2\mathrm{sr}$, resolution: 4GHz.
Driven by detector characterization, can be tuned for other purposes

Polarization transfer

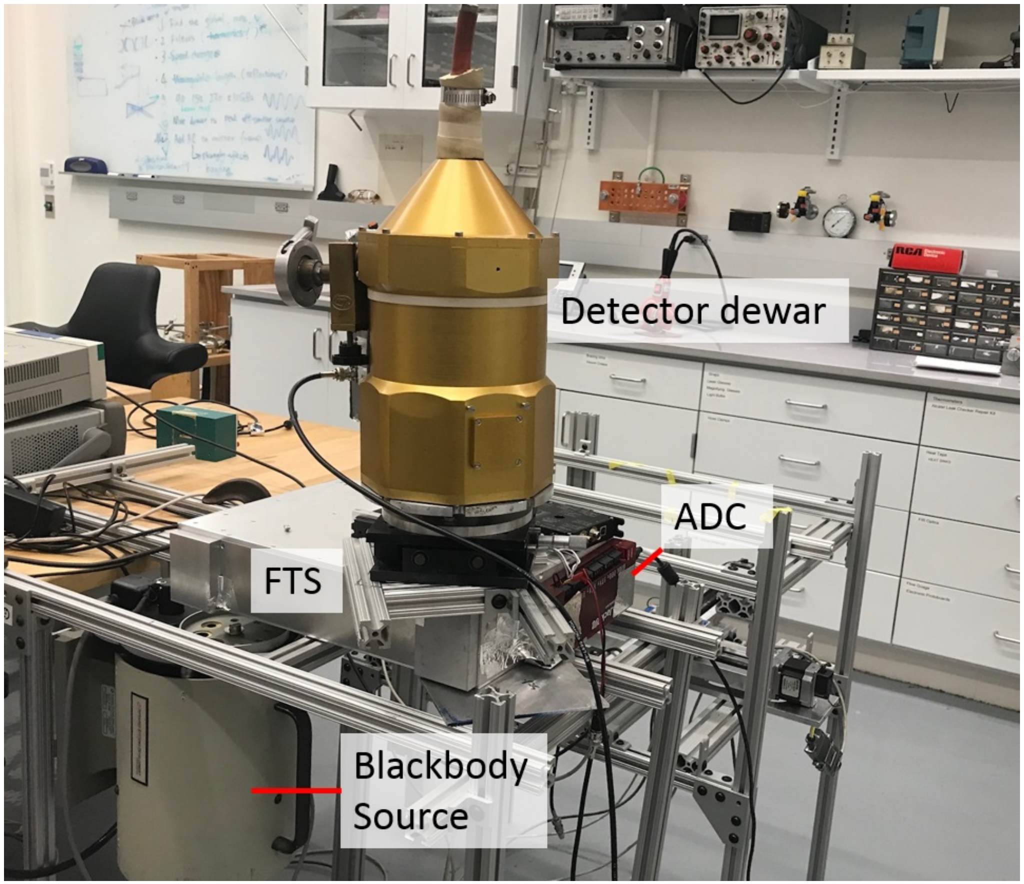


Thin arrows: optical paths.
Thick arrows: polarizations



- Trace radiation from Input 1
- Polarizer A, B, C and D are made from gold plated tungsten wires
- Polarizer A polarizes the input radiation
- Polarizer B is 45° to polarizer A and mixes the radiation.
- Center mirror (Blue) Add phase delay.
- Polarizer C is vertical to B and recombines the polarizations.
- Polarizer D is parallel to A and splits radiation to two outputs.

Characterization



Testing setup

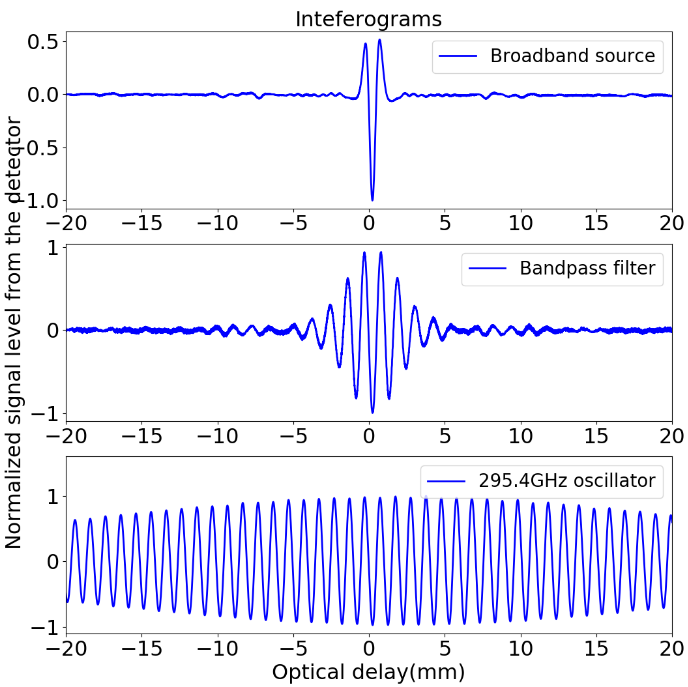
- Input1 is coupled to a radiation source (broadband blackbody, or narrow-band Gunn oscillator)
- Output 1 is coupled to a bolometer (within the detector dewar)
- The other ports are covered with HR20 absorber

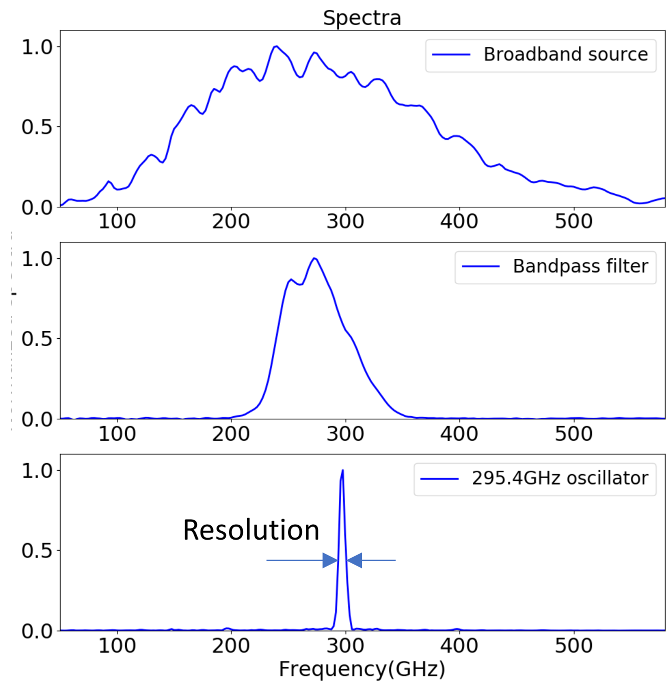
Tests

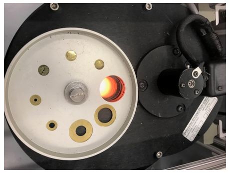
- Sample spectra measurements
- Transfer efficiency
- Frequency resolution and shift (accuracy)
- Instrument delay window function

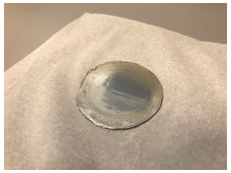
Sample interferograms and spectra

Interferograms of different sources $\xrightarrow{\text{FFT}}$ Spectra






1300K Blackbody

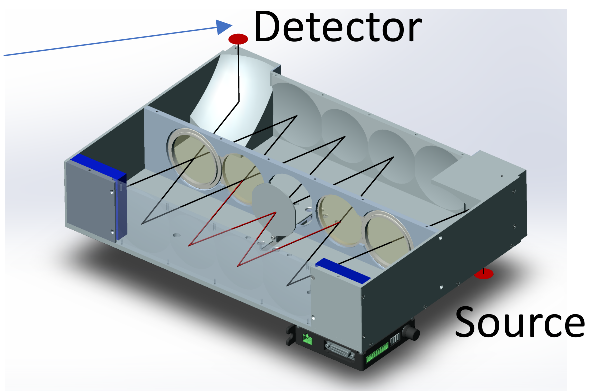

Metal-mesh filter


Gunn oscillator

- The bands for these sources match our expectations.
- The narrower the band, the longer the coherence length.

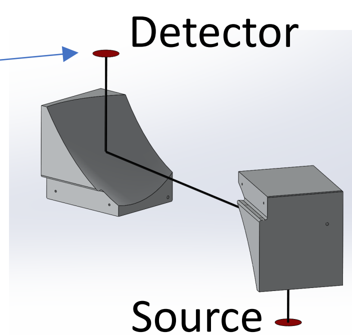
Transfer efficiency

2x Output through the FTS



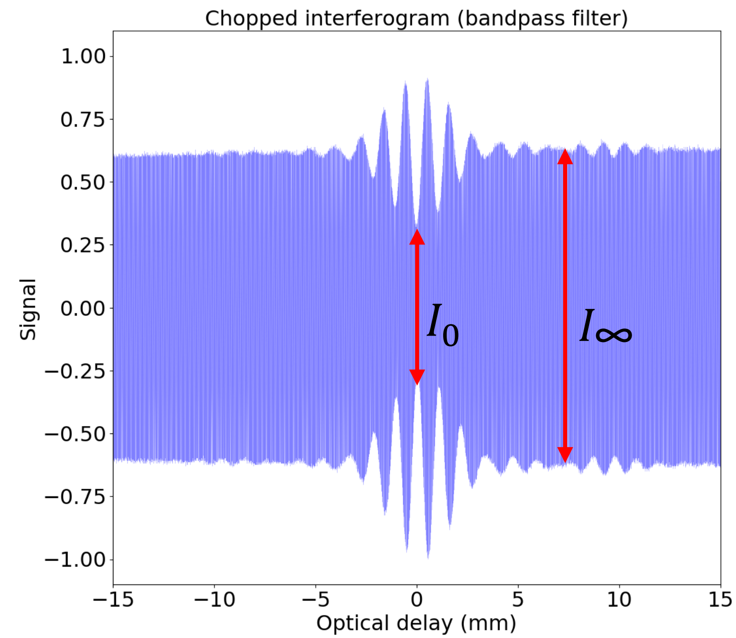
Divided by

Output through two coupling mirrors



Measured transfer efficiency with mirror centered: 92±5%

Modulation contrast



Destructive interference at the center

Modulation contrast definition

$C = I_0 / I_\infty - 1$

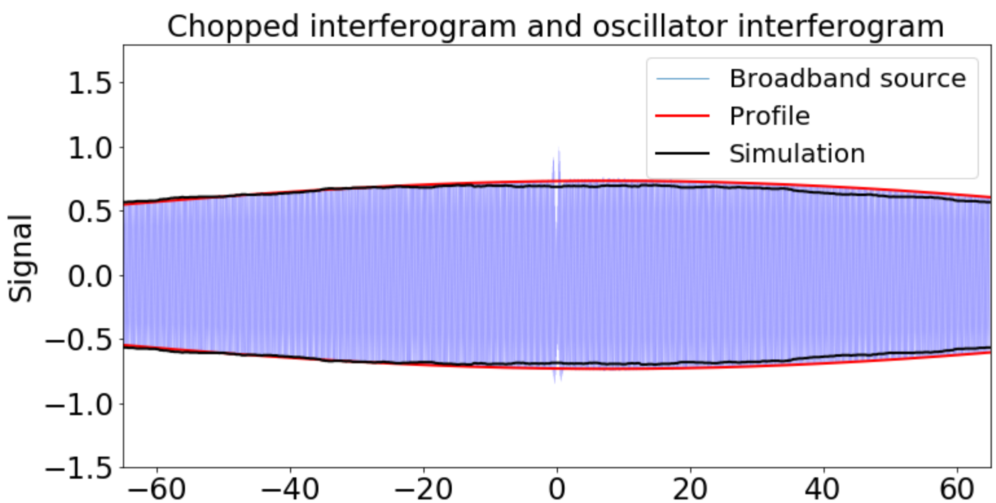
Ideally, I_0=0, C=-100%

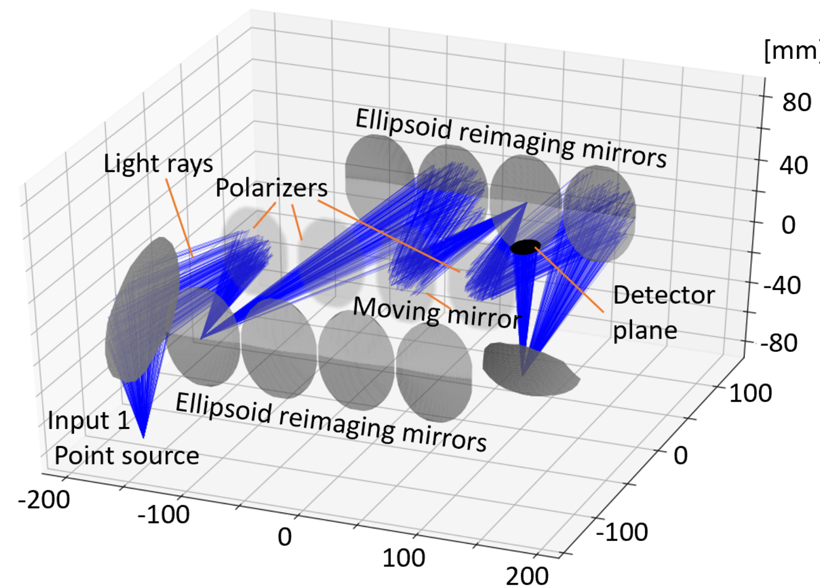
Measured modulation contrast: -55±3%

Frequency resolution – limiting factors

- Frequency spectrum is the FFT of the optical power vs. delay (interferogram)
- Frequency resolution is the FFT FWHM of the window function on the interferogram
- From the instrument, scanning weight, and later apodization
- Limiting factors from instrument
  - Maximum optical delay (scan length), set by hardware
  - **Transfer efficiency loss** – more beam is lost at higher delay
  - **Coherence reduces at higher optical delays**
    - Recombined beam from the two optical paths separate as delay increases
    - Non-uniform optical delays for light rays within the beam
  - **Frequency shift for extended sources**
    - Light rays within a finite area travel along different paths and have different delays

Transfer efficiency loss

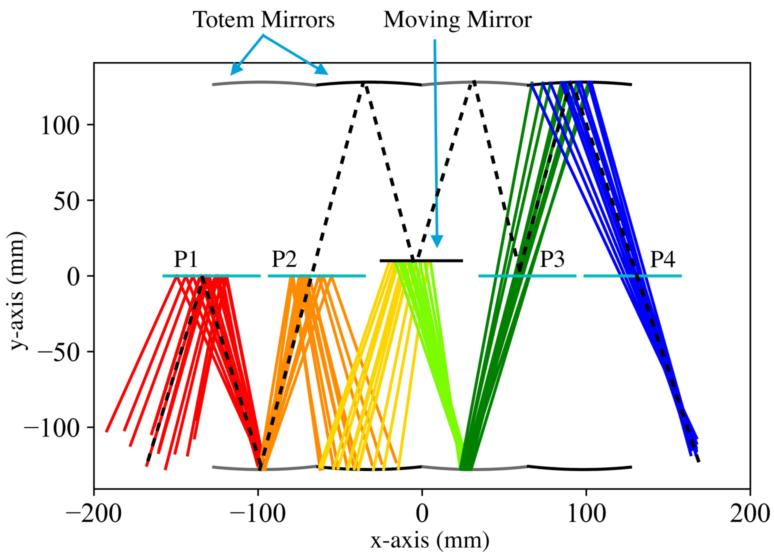


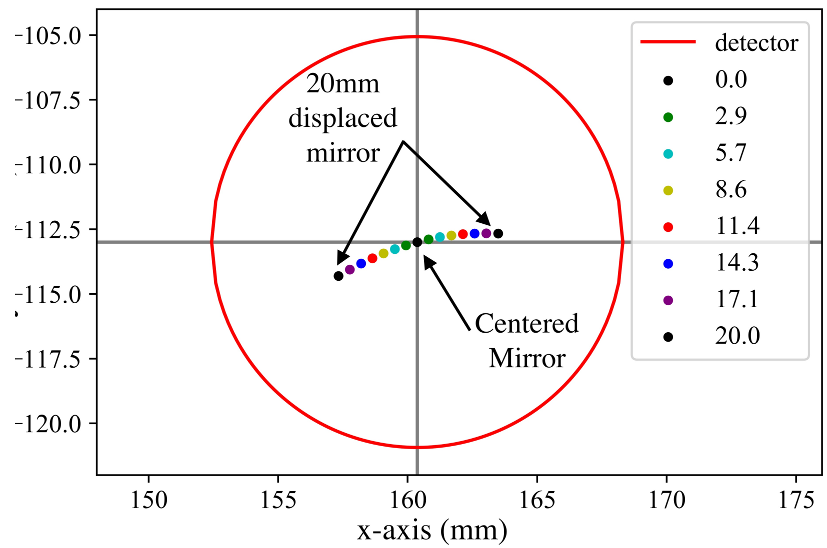


- Blue is 100% modulated interferogram
- Red is the profile of the blue, proportional to the transfer efficiency
- Black is simulation

- Geometric effect
- Can be simulated by tracing the light rays and discard those not captured by the optical elements

Coherence loss – separation of the recombined beams

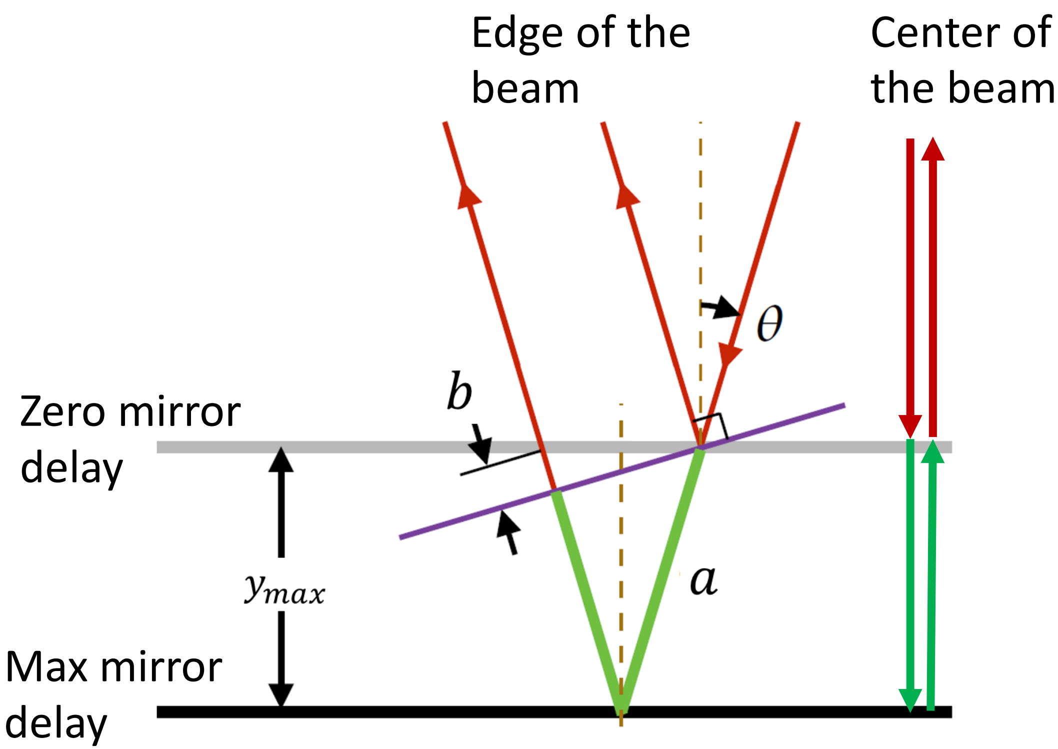




- Dashed and Solid lines are the two interfering light paths
- When the moving mirror moves off the center, the top-bottom symmetry is broken
- The distribution traces the beam profile
- Focusing optics beyond the box not shown

- Output focal plane
- Same-colored dots correspond to the recombined beam center locations of the interfering light paths at a given mirror delay
- Recombined locations separate at higher mirror delays -> less interference

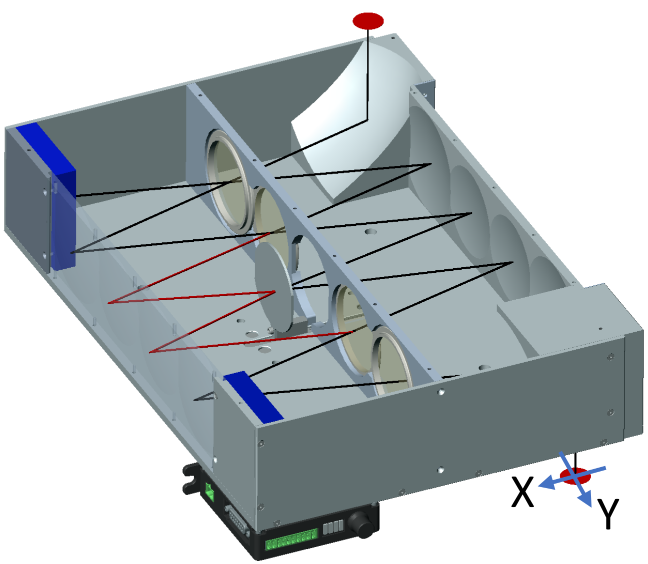
Coherence loss – non-uniform delays within the beam

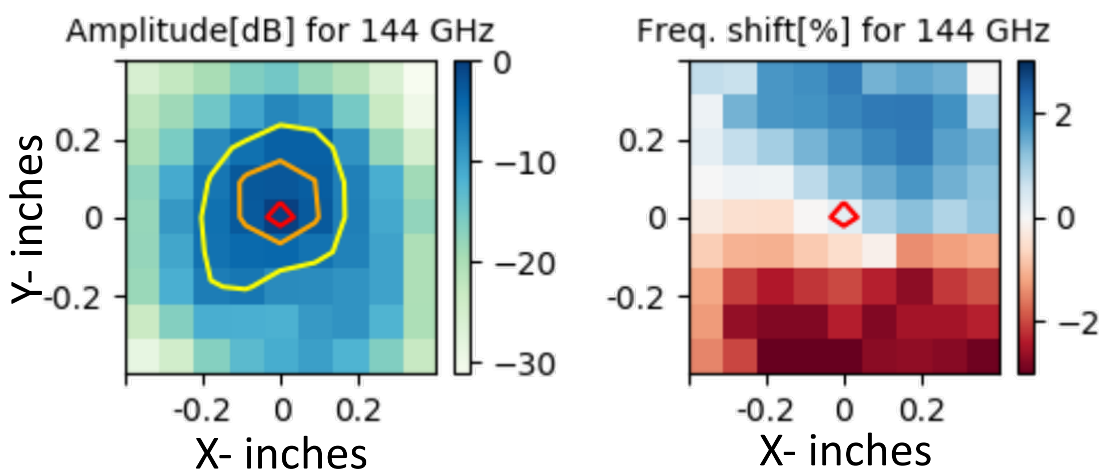


- Light rays at the center and edge of the beam have different optical delays at the same mirror displacement
- We designed the instrument such that the the path length difference between beam center and beam edge is one wavelength at the maximum delay
- Any FTS with a finite beam has this effect
- Our FTS has a large throughput, so we need to balance the nonidealities.

Frequency shift for extended sources

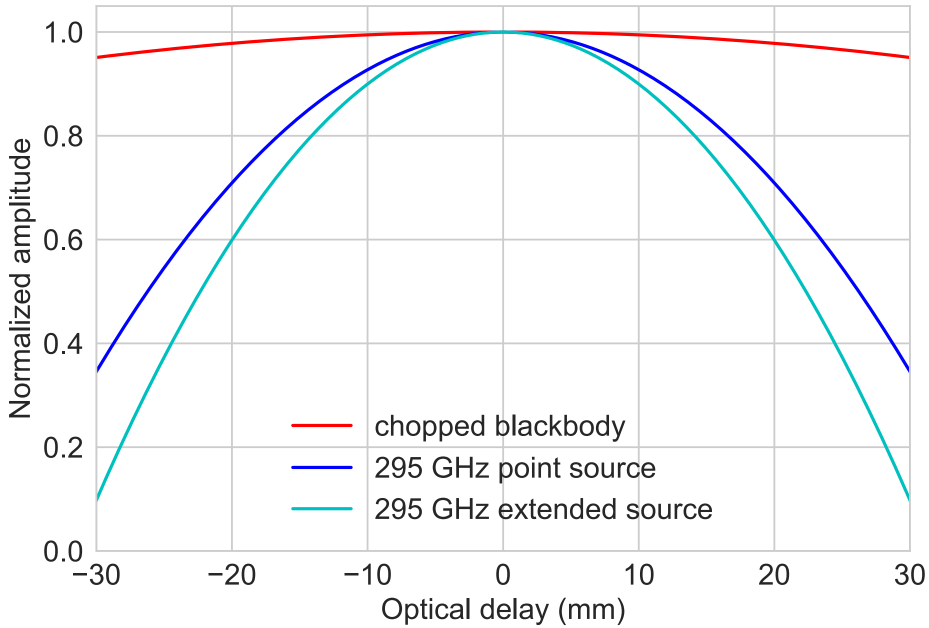
- Light rays from different source locations have slightly different delays
- Frequency shift is mapped using a Gunn oscillator.
- The frequency shift is ± 4 GHz.
- The FWHM widths for the interference intensity map are 8, 5, and 3 mm (0.3, 0.2, 0.1 in) for 90, 144, and 294 GHz sources.
- Can be pre-calibrated with a Gunn oscillator or simulation (geometric effect)





Measured amplitude and frequency vs. source location

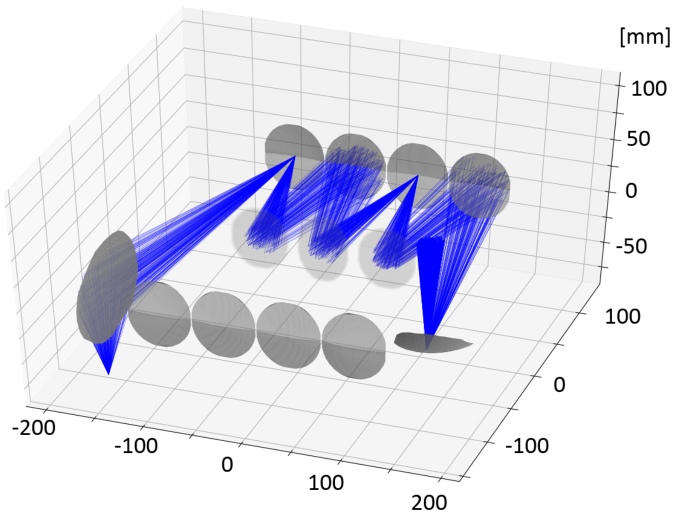
Instrument delay window function and achieved frequency resolution

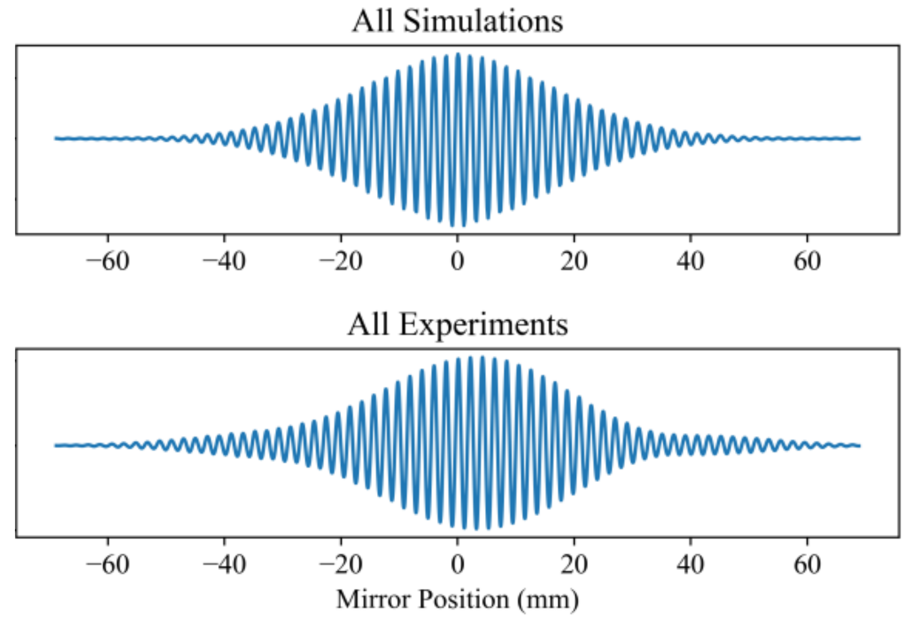


- Red is transfer efficiency
- Blue is transfer efficiency
  + non-uniform delay
- Cyan is transfer efficiency
  + non-uniform delay
  + frequency shift

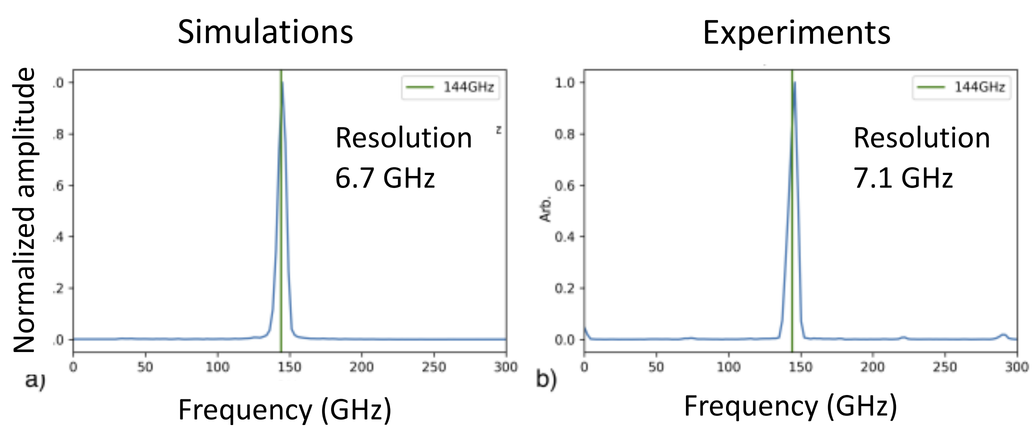
- We define instrument delay window function (DWF) as the envelope of a spectrally unresolved source's interferogram
- The FFT of the DWF is our frequency channel shape, and the FWHM of the FFT is the frequency resolution
- Red, blue, cyan correspond to frequency resolutions of 2, 4, and 6 GHz, respectively.

A raytrace-based FTS simulation





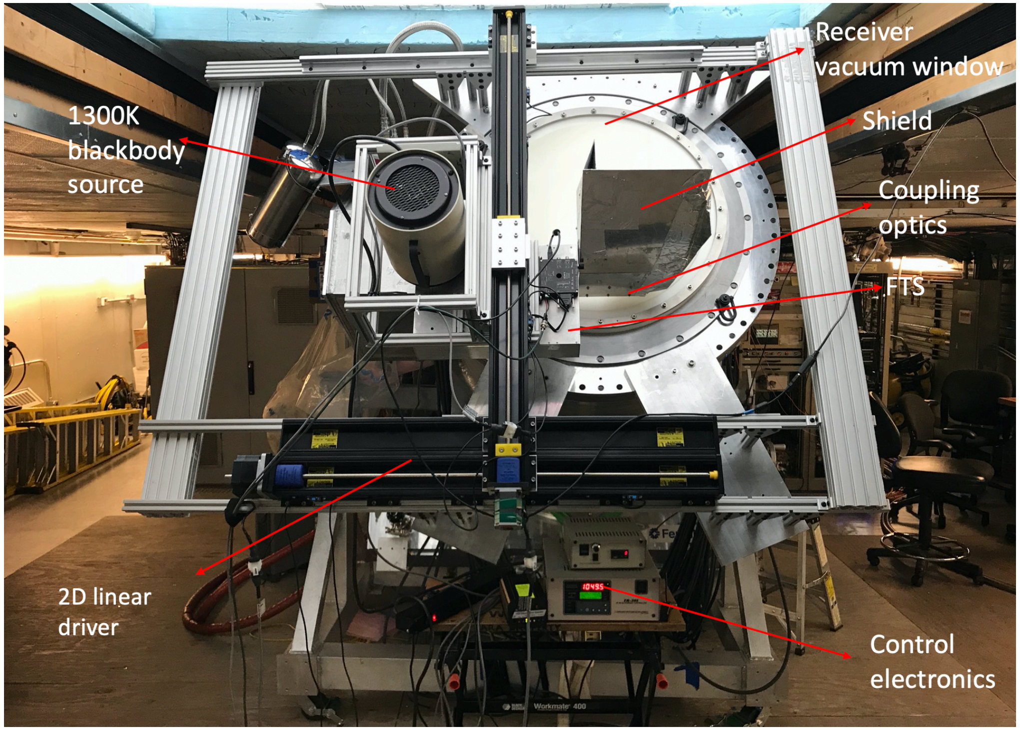
- A bundle of light rays are transferred within the box according to principles of reflection.
- Phase, amplitude, polarizations were also tracked.
- Transfer efficiency, frequency shift pattern and the frequency resolution can be simulated.
- Useful for FTS design.



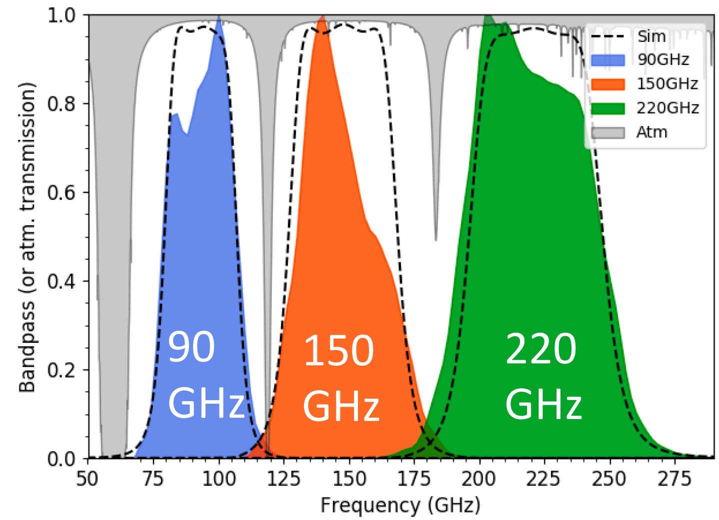
A Gunn oscillator's interferogram and spectrum
Simulation vs. experiments
Small difference can be from extra scattering in the experiment

Applied Optics, 59(25), 7726-7733 (2020)

Applicaton: SPT-3G detector band characterization



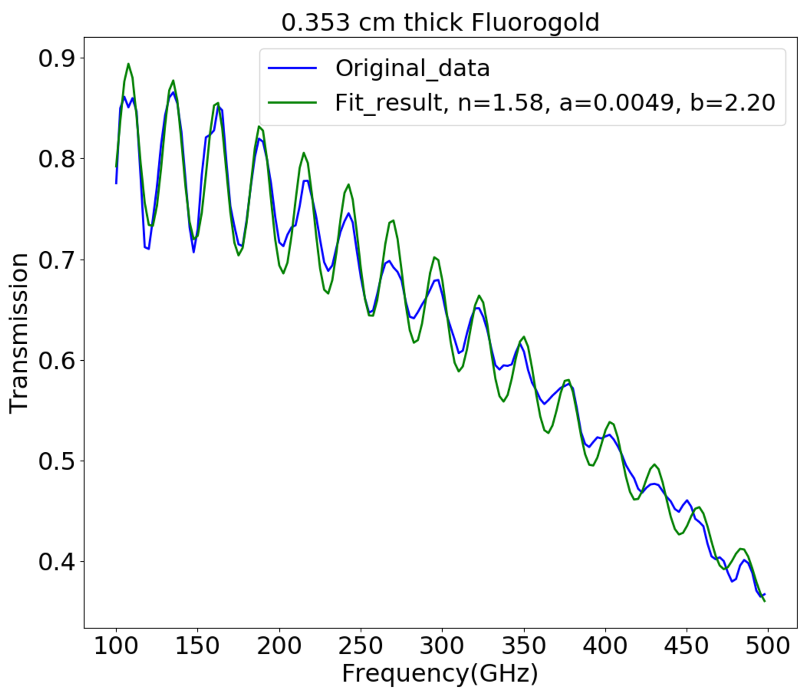
On-site measurement setup



Detector bandpasses

- The spectral bands of the detectors were measured with this FTS
- We used automated setup to map detectors in the focal plane
- Automated, scan over thousands of detectors overnight
- The band edges agree with simulation.

Application: optical material characterization

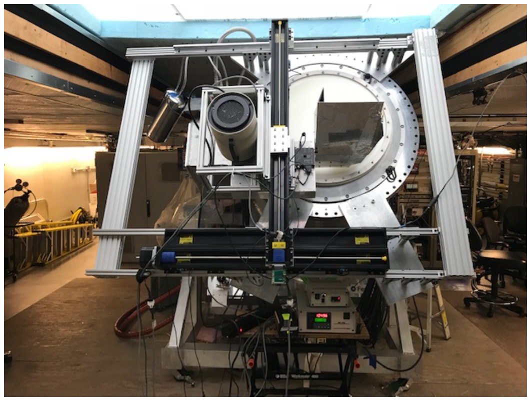


We used the FTS to measure the refraction index and loss properties of Fluorogold.

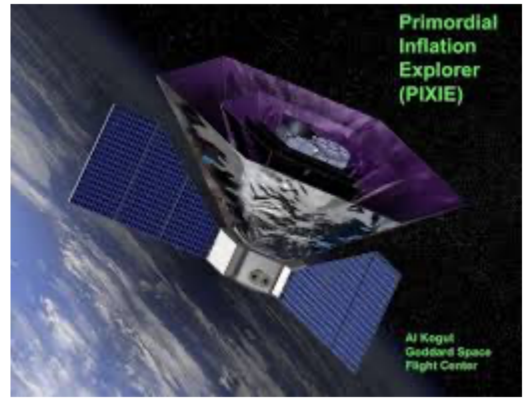
Green line is fit to equations from Halpern et, al. 1986

Can be used for lens and AR coating transmission measurements.

Comparing the different purposes



Detector characterization



PIXIE, credit to Alan Kogut

- Different frequency range, spectral resolution, and throughput requirements
- The requirements can be tuned by adjusting the dimensions in the design.
- The simulation pipeline can assist in the design process given the desired parameters.

Comparing the different purposes - systematics

- For detector and optical material characterization
  - Frequency accuracy and frequency resolution
  - Measured frequency can shift depending on the source's location
  - Can be calibrated with a tunable Gunn oscillator
- For PIXIE
  - Frequency accuracy
    - Can use line emission (C+, N+, the CO forest) to set the frequency scale to 200 Hz accuracy using only flight data
  - Spectral distortion: compares CMB and a blackbody source
    - Source needs to be well-calibrated, isothermal, and has low reflectivity
  - B-mode: T-P leakage cancellation (see Al's talk yesterday)
  - Frequency channel shape also depends on the transfer efficiency and coherence, both of which are delay-dependent

Summary

- We have developed an FTS for 50-330GHz with a large étendu ($100\ \mathrm{mm}^2\mathrm{sr}$) and a small size (380x250x76 mm, 6.8 kg)
- The FTS was used for South Pole Telescope detector calibration and material characterization (set the design parameters).
- The FTS is also similar to the design of PIXIE
- The frequency resolution is ~4 GHz and the frequency shift is ~1% of the source frequency. Can be calibrated.
- We developed a simulation pipeline to trace the beam and simulate the frequency shift and delay window function.
- Nonidealities such as transfer efficiency loss, coherence loss, and frequency shift needs to be calibrated and simulated.