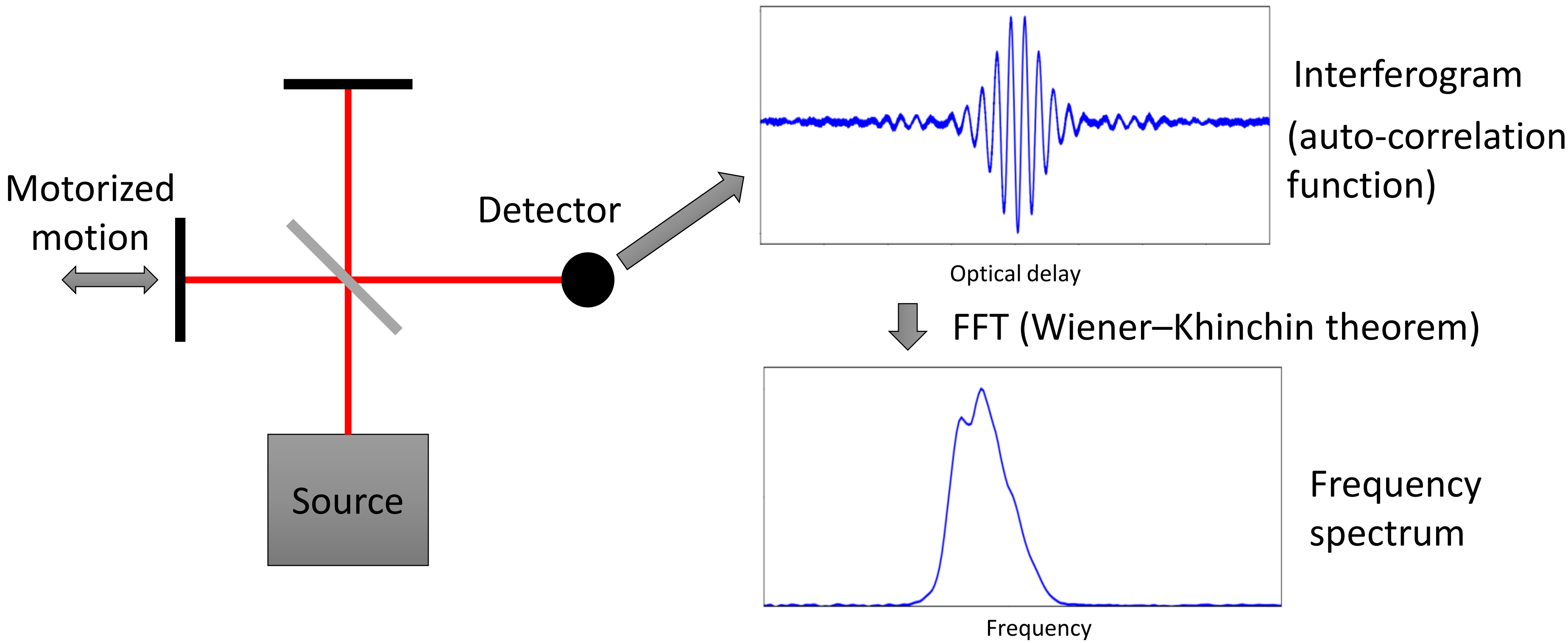
A Compact Millimeter-Wavelength Fourier-Transform Spectrometer

Zhaodi Pan
The University of Chicago, KICP

Results to be published in Applied Optics

Fourier-Transform Spectrometer (FTS)

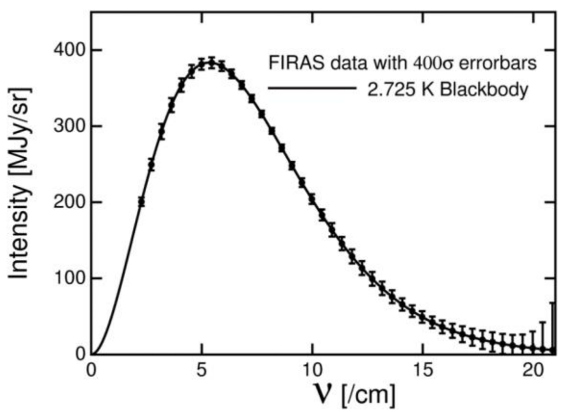


- Detector measures power vs. optical delay (auto-correlation function of the source's radiation).
- FFT of power vs. optical delay is the power spectrum of the source, including the detector's response function.

Motivation: PIXIE prototype

For measuring the Cosmic Microwave Background (CMB)

COBE satellite

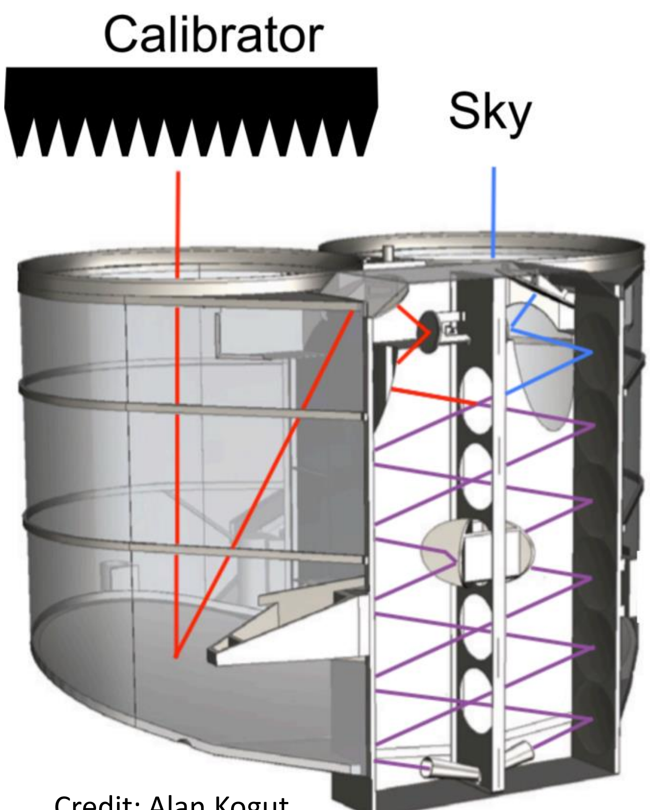


Credit: NASA COBE team

No spectral distortion beyond blackbody was detected.

PIXIE was proposed!

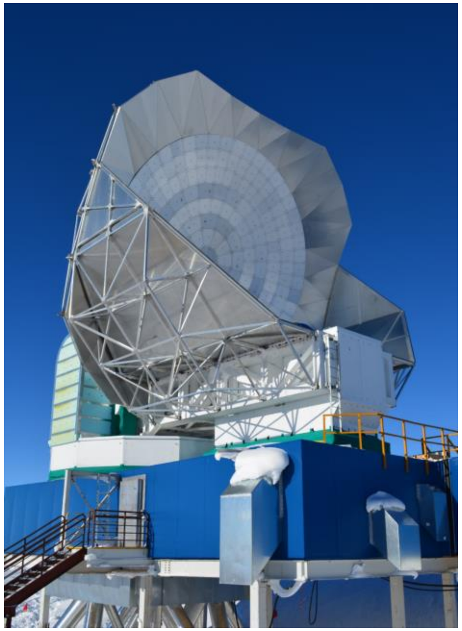
The Primordial Inflation Explorer (PIXIE)



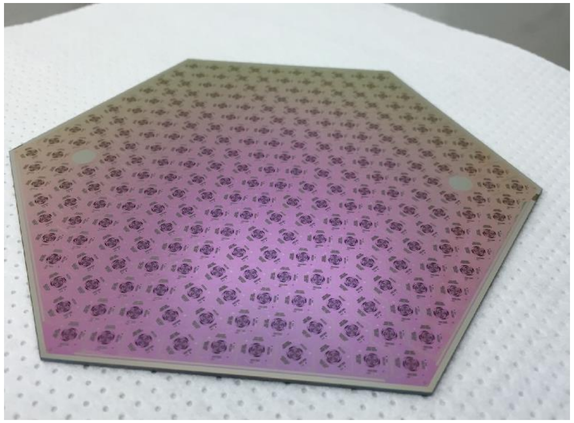
Credit: Alan Kogut

Collaborated with Stephan Meyer and Dale Fixsen from the PIXIE team

Motivation- SPT detector characterization

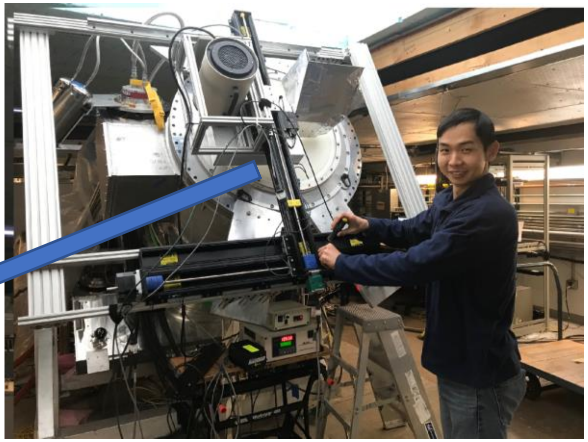


South Pole Telescope (SPT), a 10m telescope for measuring the CMB.



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

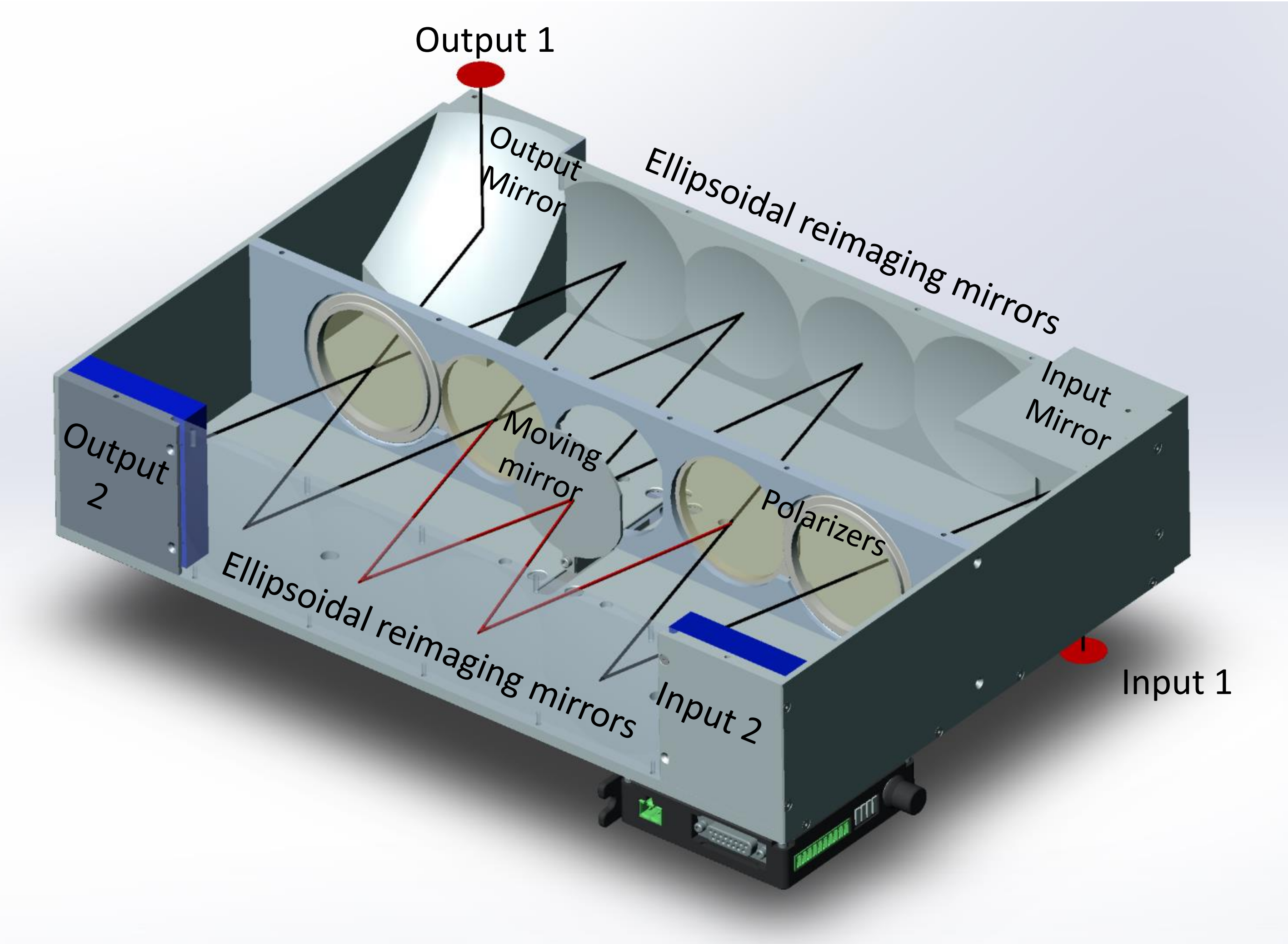
Detector spectral band calibration at the South Pole!



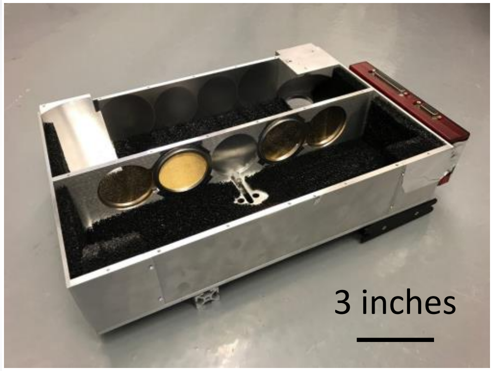
Our PIXIE-style FTS mounted on a 2D linear driver

Collaborated with the SPT team

Design overview



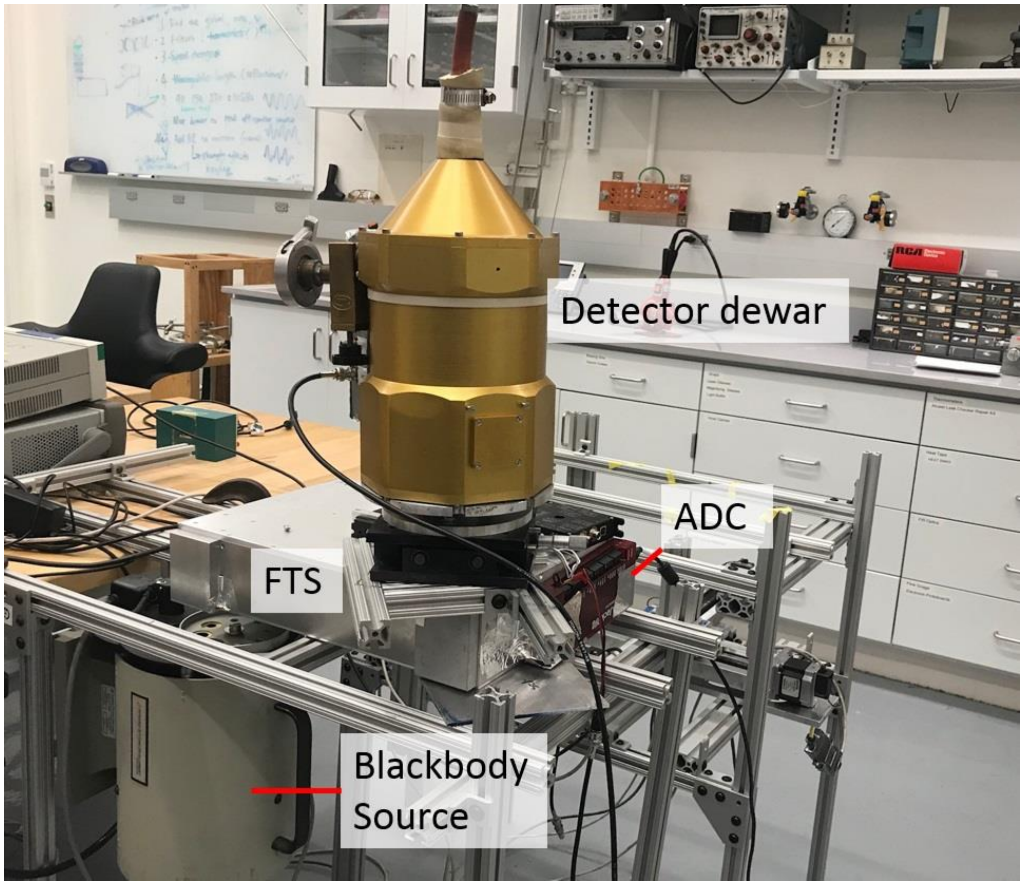
- Symmetric design: systematics control
- Two inputs and two outputs: differential output
- Two polarizations: no polarization loss
- Ellipsoidal mirrors: high density of beams
- Moving mirror: add optical delay



Fabricated FTS
Only 15''x10''x3''!!

Frequency range: 50-330 GHz, étendu: 100 $mm^2 sr$, resolution: 4GHz.

Characterization



Testing setup

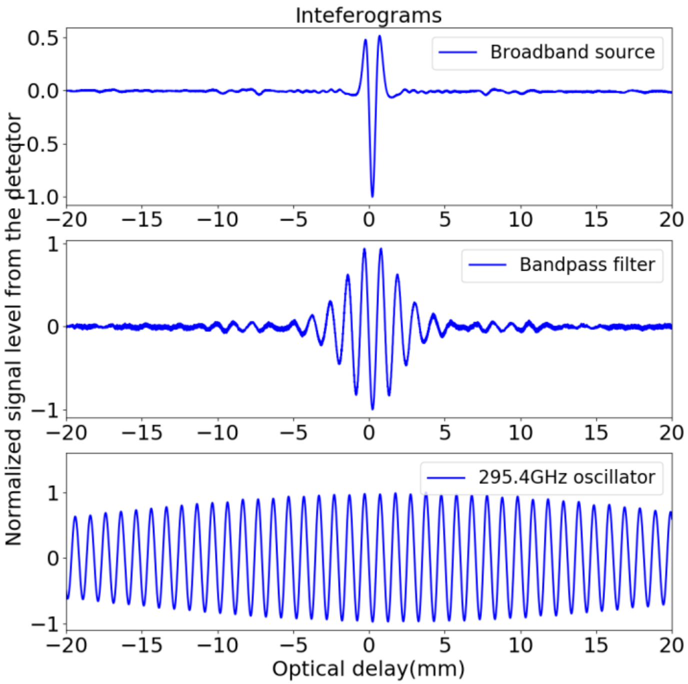
- Input1 is coupled to a radiation source (broadband blackbody, or narrow-band Gunn oscillator)
- Output 1 is coupled to a bolometer (within the detector dewar)

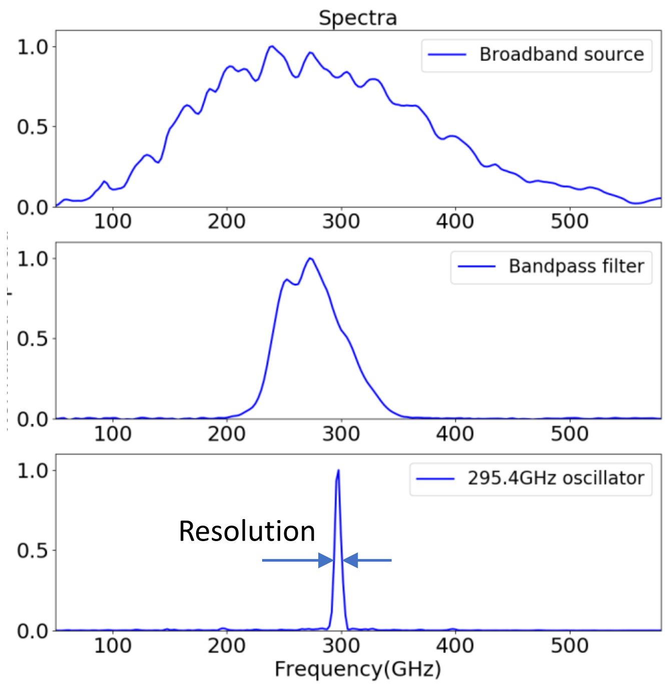
Tests

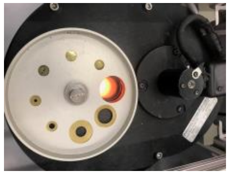
- Sample spectra measurements
- Transfer efficiency
- Frequency resolution (precision) and distortion (accuracy)
- Apparatus function

Sample interferograms and spectra

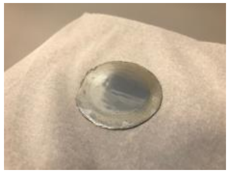
Interferograms of different sources —FFT→ Spectra







1300K Blackbody



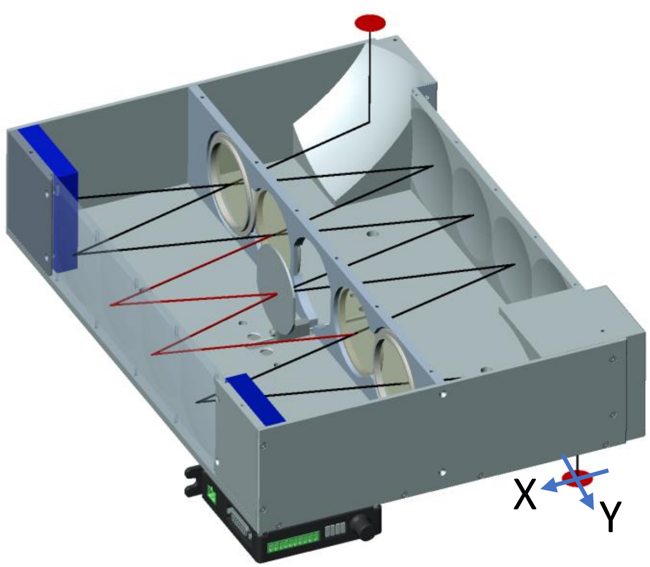
Metal-mesh filter

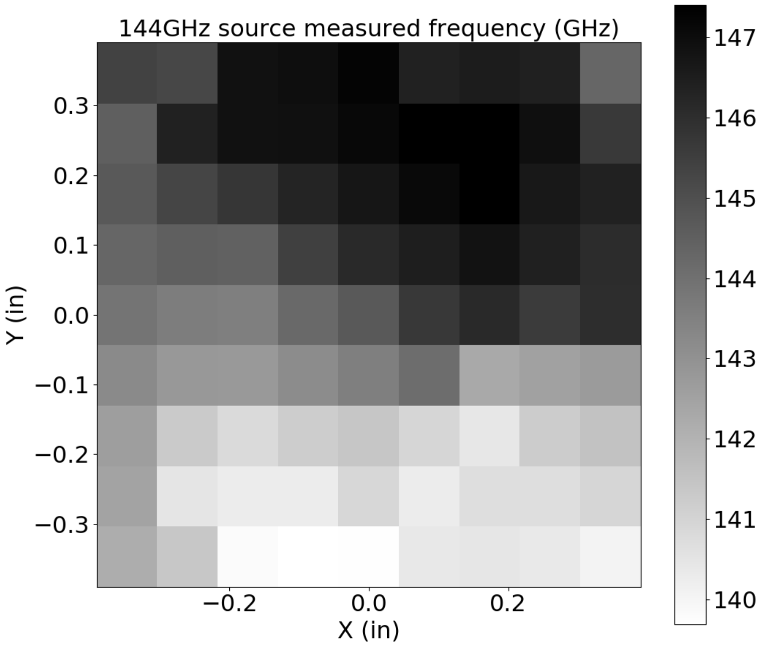
Gunn oscillator

- The bands for these sources match our expectations.
- The narrower the band, the longer the coherence length.
- Transfer efficiency is 92±5%.

Frequency resolution and distortion

- Resolution is 4 GHz, measured by a Gunn oscillator
- Frequency distortion is mapped using a Gunn oscillator. The accurate frequency is 144.3 GHz.
- The frequency distortion is ± 4GHz.
- The FWHM widths for the interference intensity map are 0.3 in, 0.2 in, and 0.1 in for 90, 144, and 294 GHz sources.

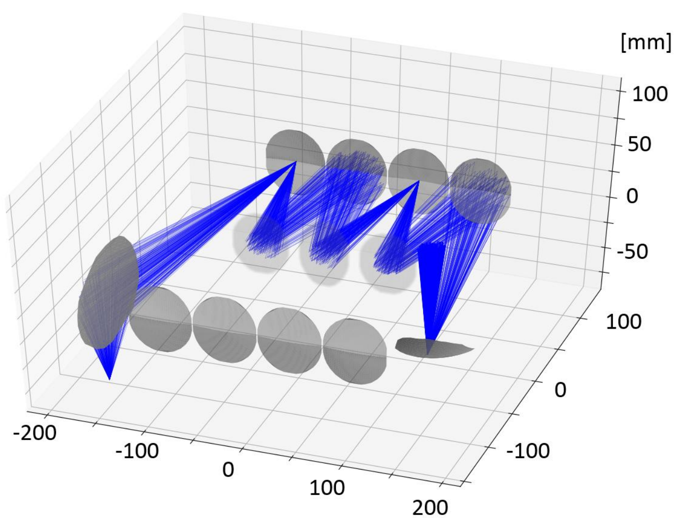




Measured frequency vs. source location

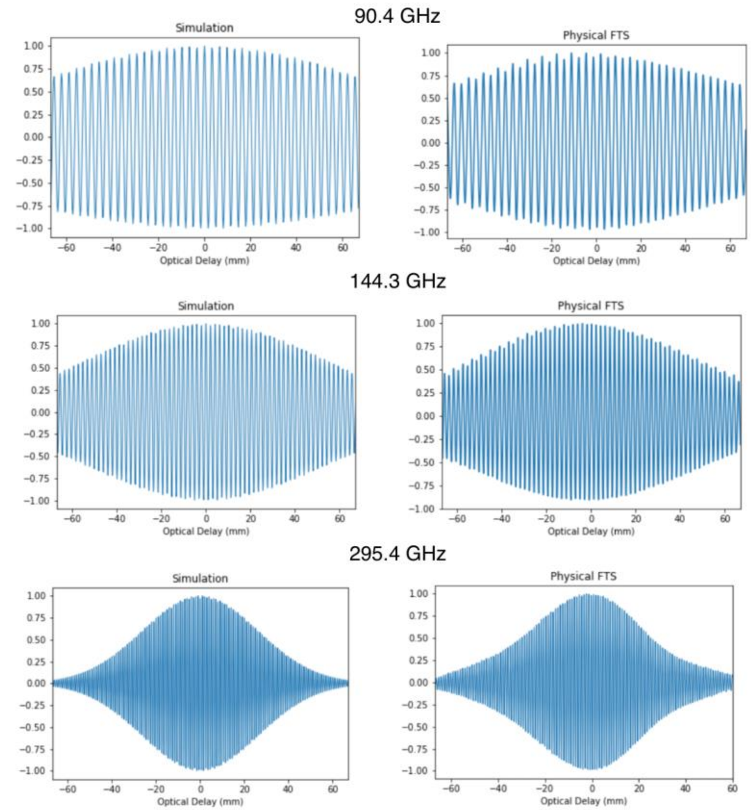
Simulation

- A bundle of light rays are transferred within the box according to principles of reflection.
- Frequency distortion pattern and the frequency-dependent resolution can be simulated



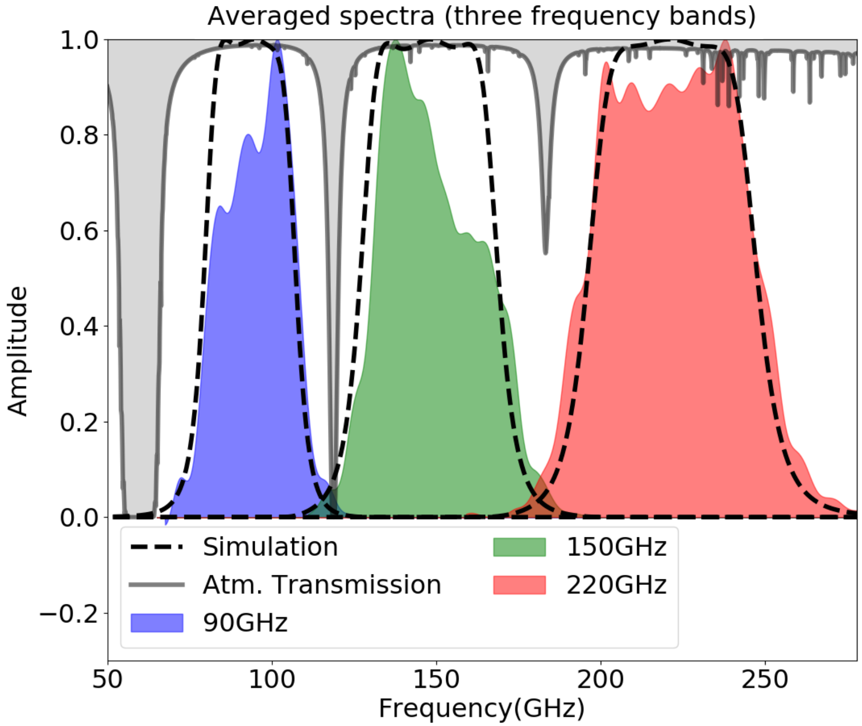
Apparatus function

Simulation Measurement

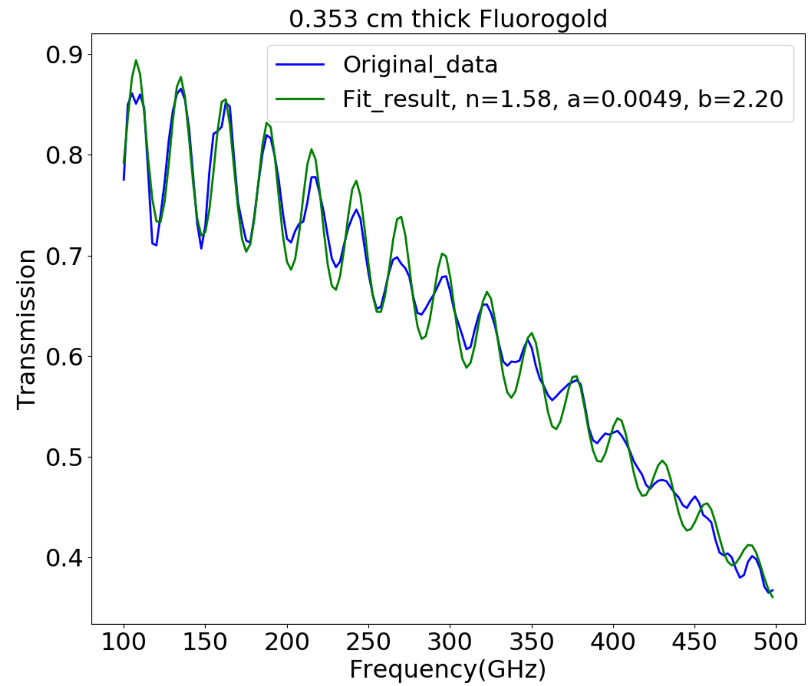


- The frequency-dependent resolution is simulated by the ray-tracing code for different frequencies and is compared to experiments.

Applications



We used the FTS to measure SPT detectors' spectral bands. The measurements agree with simulation for the three groups of detectors for 90GHz, 150GHz and 220GHZ.



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

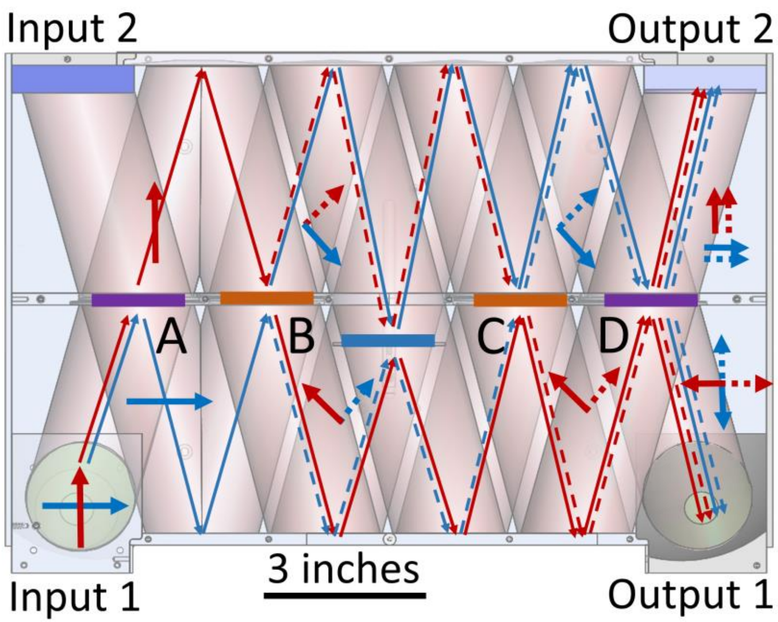
Green line is fit to equations from Halpern et, al. 1986

Summary

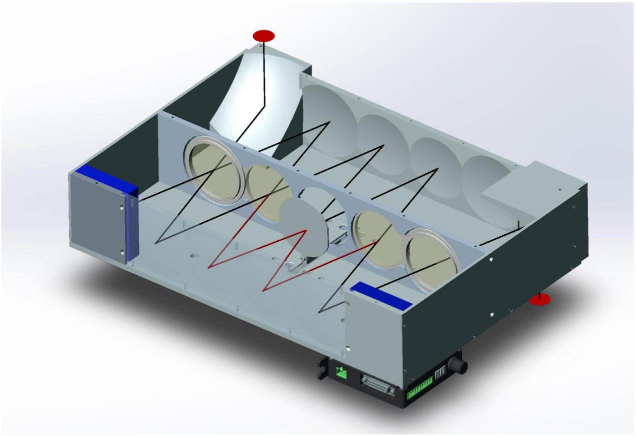
- We have developed an FTS for 50-330GHz with a large étendu (100 $mm^2 sr$).
- It is only 15’’x10’’x3’’ and weighs 15 lbs.
- The transfer efficiency is 92±5%
- The frequency resolution is 4 GHz and the frequency distortion is ~1% of the source frequency.
- We developed a simulation pipeline to trace the beam and simulate the frequency distortion and apparatus function.
- The FTS was used for South Pole Telescope detector calibration and material characterization.

Backup slides

Polarization transfer

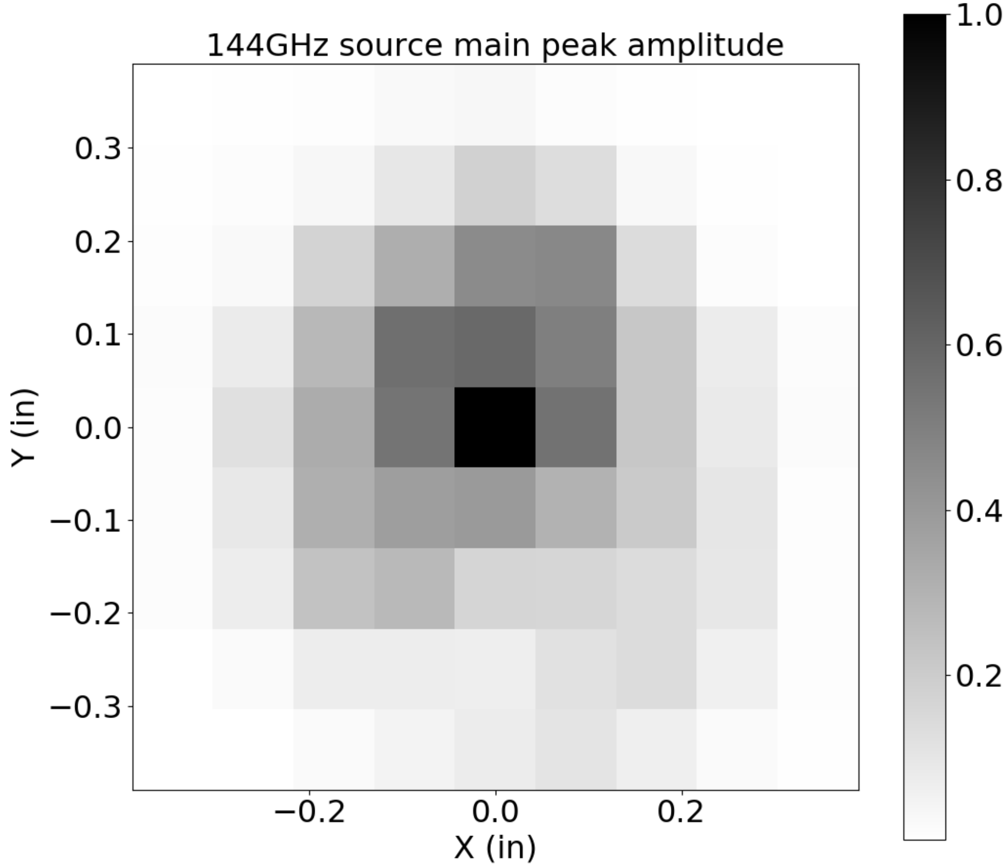


Thin arrows: optical paths.
Thick arrows: polarizations



- 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.

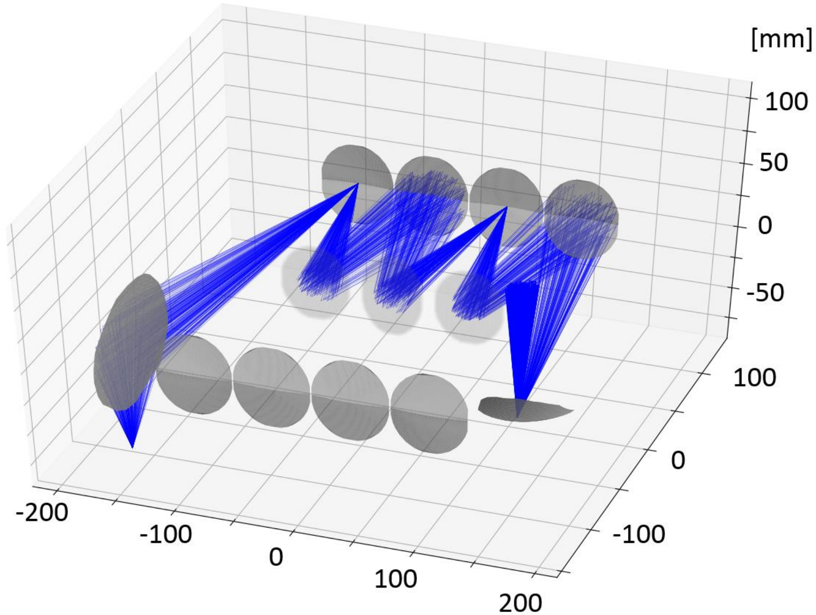
Amplitude map



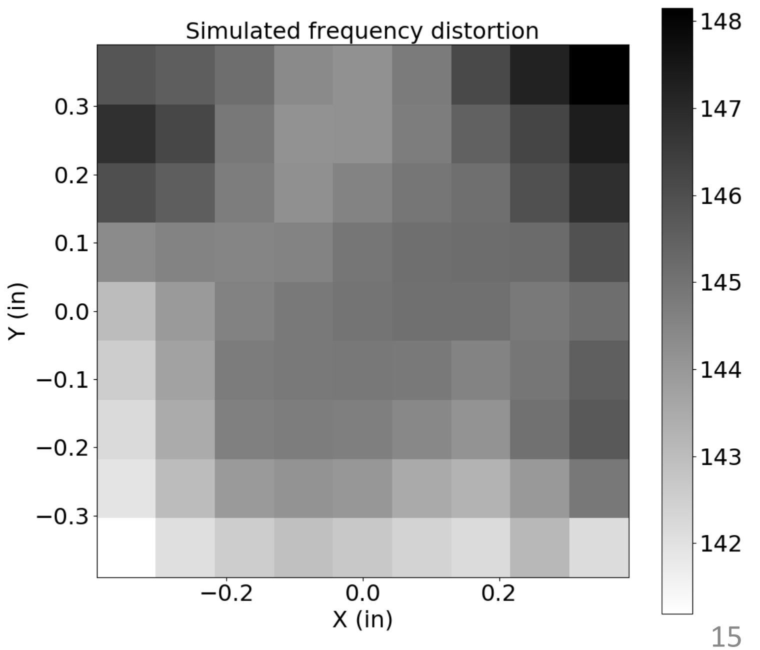
- When scanning the Gunn oscillator at the input focal plane, we also get the interference pattern's amplitude map.
- This tells us the FTS's sensitivity to an extended source.
- The FWHM widths are 0.3 in, 0.2 in, and 0.1 in for 90, 144, and 294 GHz sources.

Simulation

- A bundle of light rays are transferred within the box according to principles of reflection.
- We move the source on the input focal plane, scan the mirror in the simulation and measure the output frequency.
- Need to align the elements within 0.3° to match experiment.

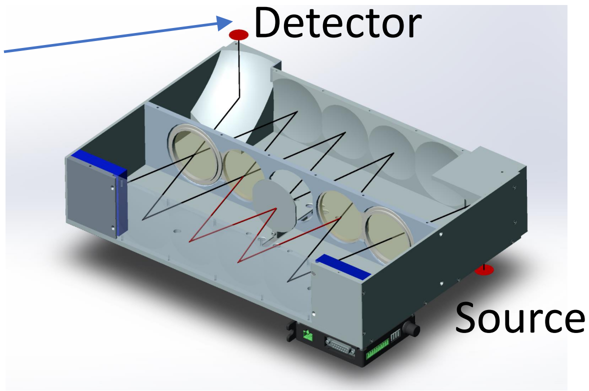


Ray-tracing for one of the two interfering light paths



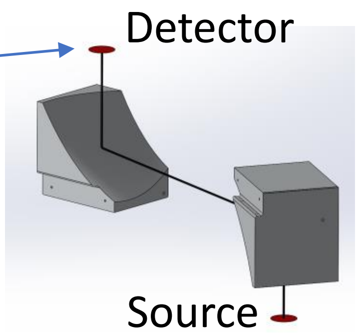
Transfer efficiency

2x Output through the FTS



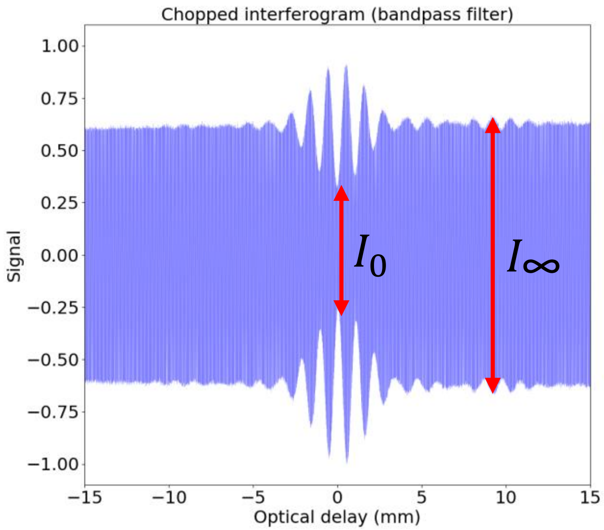
Divided by

Output through two coupling mirrors



Measured transfer efficiency: 92±5%

Modulation contrast



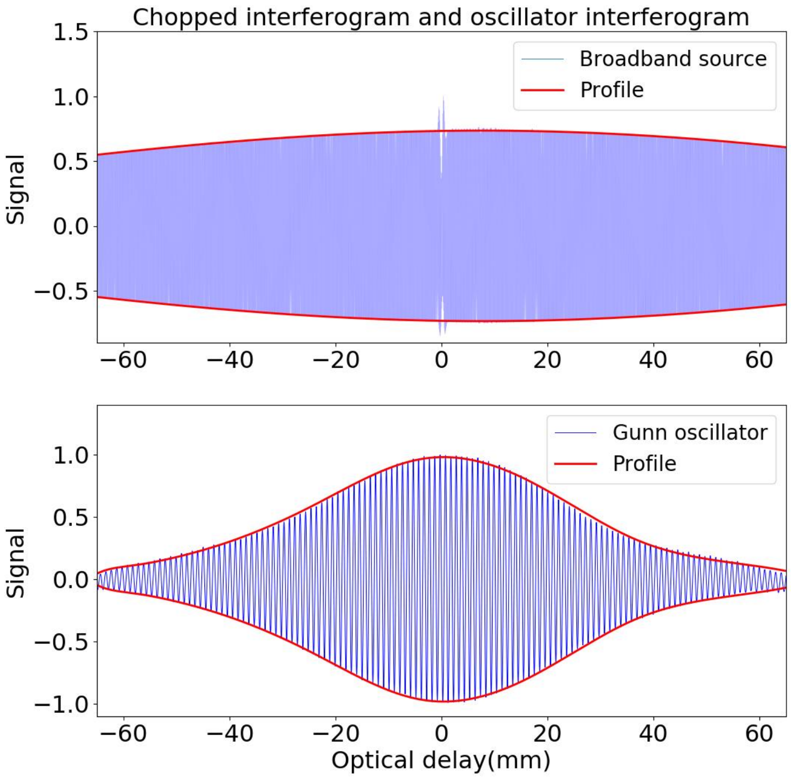
Modulation contrast definition

$$C = I_0 / I_\infty - 1$$

Ideally -100%

Measured modulation contrast: -55±3%

Beam loss and decoherence



Beam loss

Decoherence

- The upper plot is a plot of a chopped interferogram. The decay at higher optical delays is purely due to geometric reason: the moving mirror can not intercept all beams when it's away from the center.
- The lower plot is an interferogram for a Gunn oscillator. It's decaying faster because there is also decoherence effect: the diffraction patterns of the recombined beam is further apart and has less overlap as the mirror moves away from the center position.