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Terahertz Heterodyne HEB Receiver Arrays:
Expected Performance and Challenges

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Motivation

- In a typical NASA mission, the instrument requirements flow down from a Science Traceability Matrix.
- But it is useful to communicate backwards to inform the correct expectation given certain boundary conditions
- JPL went through a small exercise "Team-X" to price a 1-meter class FIR heterodyne mission with a cost cap of ~$200M.

What kind of instrument can we shoe-horn into the spacecraft ?

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Stand-alone mission: basic performance data

Science case built on informed performance

- Baseline 16 pixel array of NbN mixers:
  - Tsys < 1000 K DSB up to 4 GHz.
  - Nominal frequency of operation is 1.9 THz.
- Existing class of SiGe LNA
- Existing class of solid state local oscillators
- Existing class of ~4 GHz bandwidth spectrometers
- Existing class of 4 K cryocoolers

Price a ready-to-go mission with no technology development

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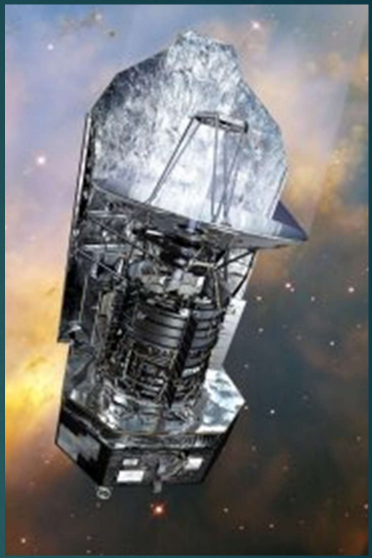
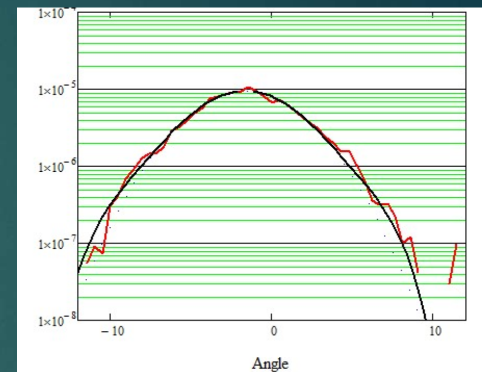
Conclusion of Study



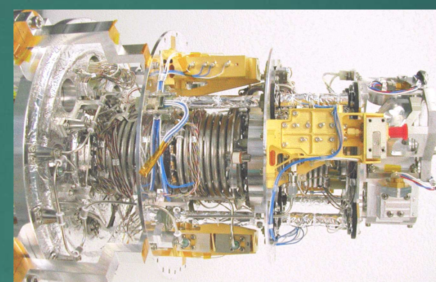
- A cryogenic mission didn't initially pass the "laugh test"
  - Cryogenic subsystem has JWST cost heritage and it alone would consume 25-50% of the total budget
  - So we obtained quotes from vendors and we went back to the lab….
- Primary conclusion is that a LEO spacecraft fits the budget with required 30% reserves
  - 3-year science mission
  - Utilize existing cryocooler technology
  - Use standard low-cost bus, with upgrades for pointing, power and thermal

What are the resources available for a future HFPA?

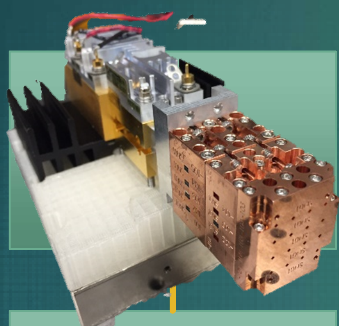
A 16-pixel receiver might have components that look like the following:



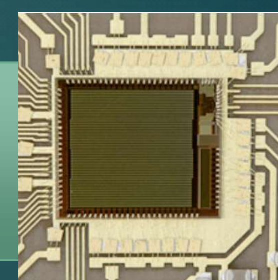
Sumitomo



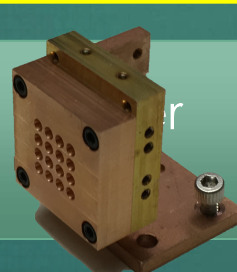
See J. Siles

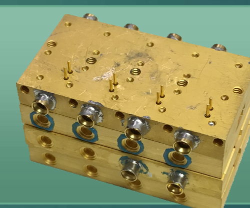


Omnisys



D. Russell





Optical/calibration

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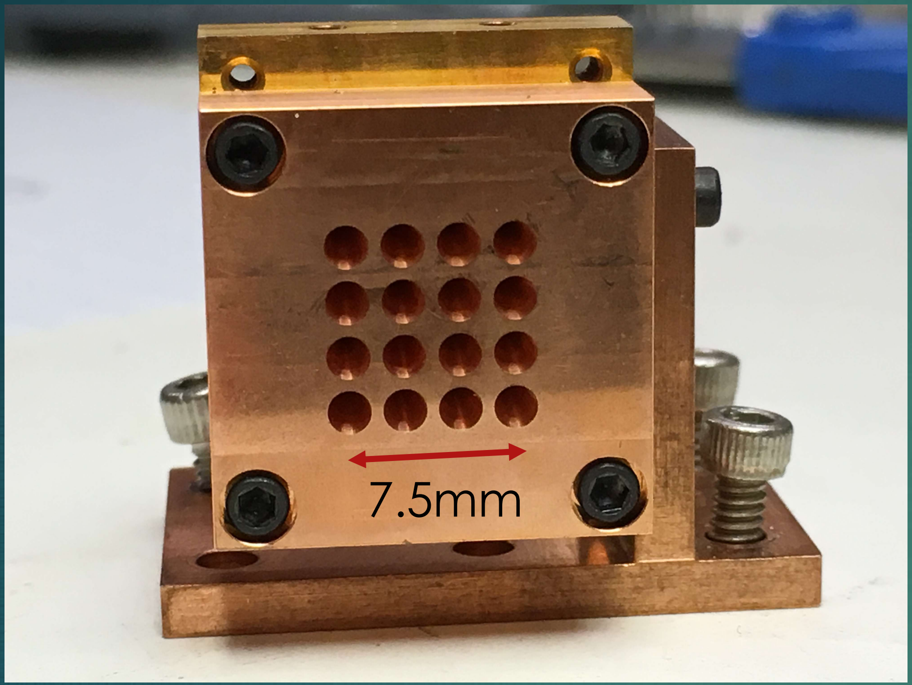
Thermal linkages to cryogenic stages

Electronics

Critical subsystems are reasonably well-developed

16-pixel mixer

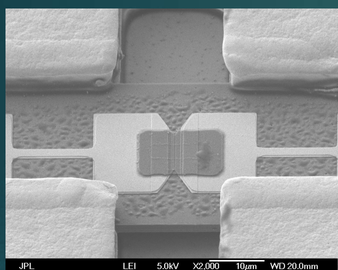


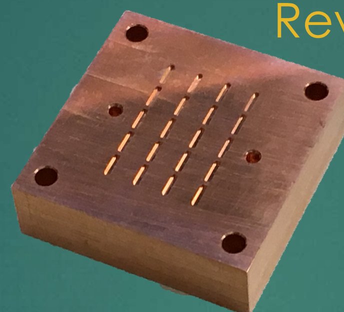
16-pixel mixer as tested.

- 2.5 mm spacing
- 2 mm diameter profiled horn with integrated circular-to-waveguide transition
- GPPO IF output connectors
- Compatible with existing stock of 1.9 THz SOI mixers with microplated insert

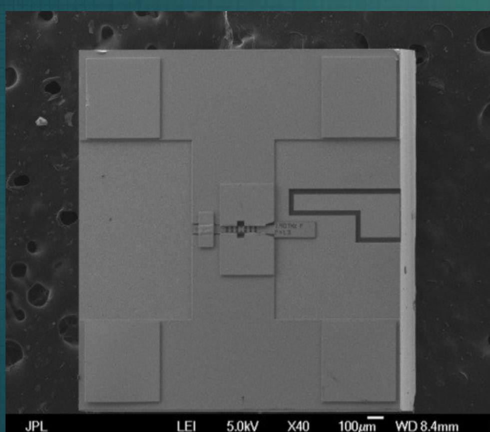
16-pixel mixer

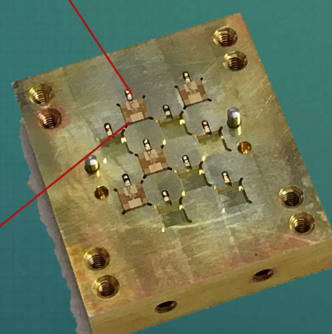
View of mating surfaces



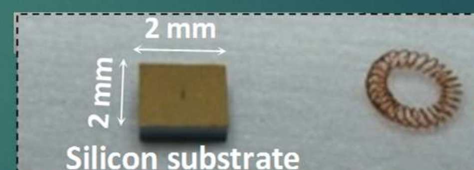


Reverse side of horn section





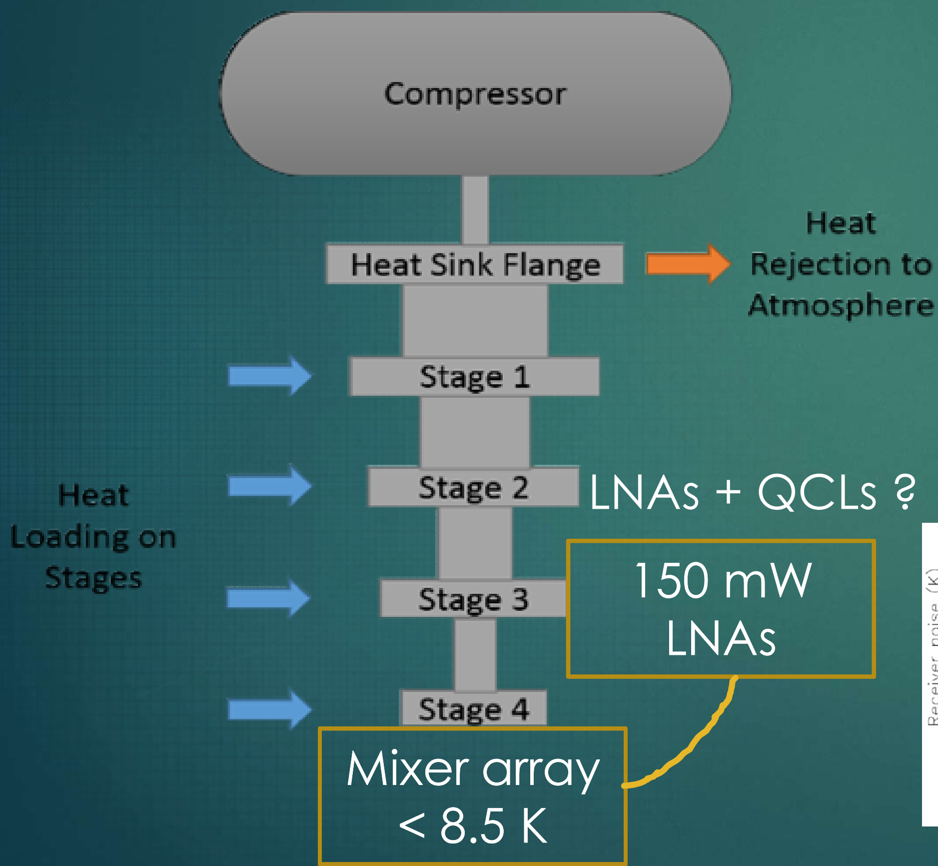
Back section with mixers installed. Block can be opened and replaced individually.



Backpiece with mixer Installed.

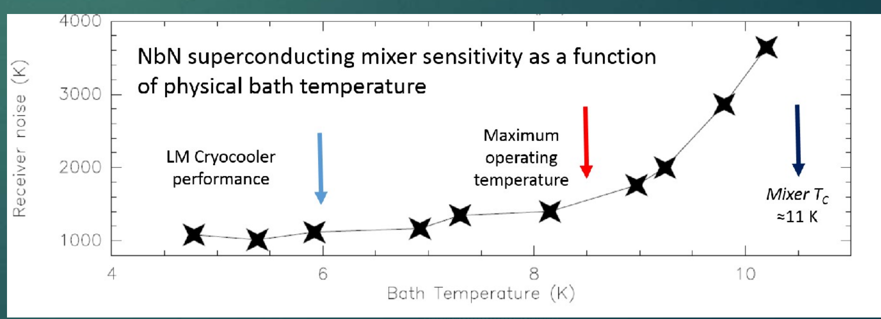
Checkboard pattern to allow all horns to be tested with existing devices

ACTDP-benchmarked cooling capability appears to be well-matched to a >16 pixel heterodyne receiver system



Are the interfaces well-defined and simple?

Proposals require system heritage before PDR: quite impractical owing to high cost and lead time of space coolers



Cryocoolers for space

We can buy a cryocooler subsystem for less than $10M

- Obtained ROM from Sumitomo for SMILES JT+2-stage Stirling cryocooler (Astro-H)
- Lockheed Martin PTR at JPL

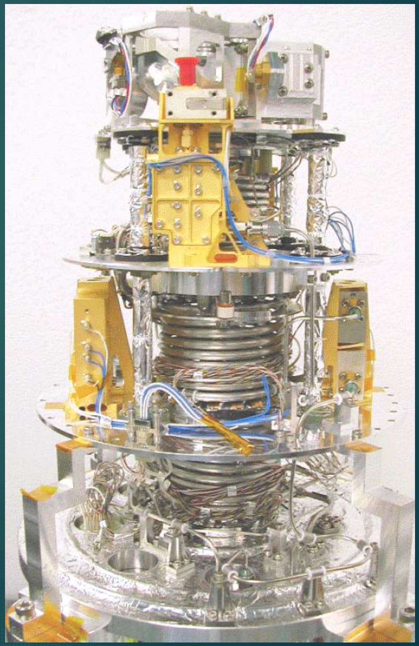
To go forward, funding agencies will want to see design maturity and system and cost heritage

- Foreign agency (mission class etc.)
- Imager vs single pixel limb sounder.

Yes, obviously. Planck and SMILES used 4K-class cooler. And so will JWST. Cost heritage is not good.

Further, heritage for instruments cooled to liquid helium temperatures is available only for large missions: Herschel, Spitzer, Planck….and JWST.

JAXA SMILES instrument aboard the ISS



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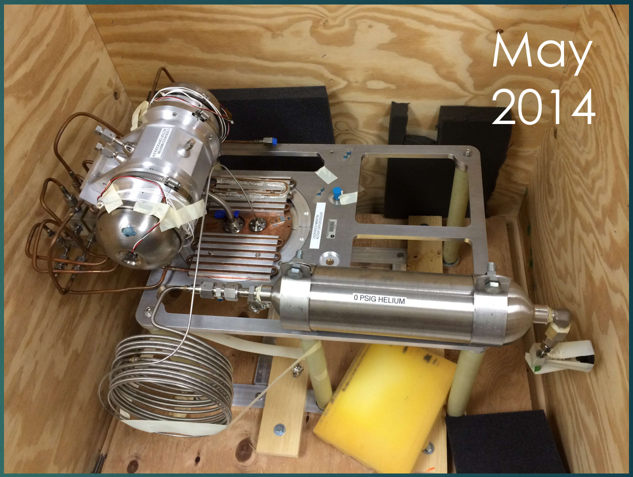
Lockheed Martin ACTDP "6K" Cryocooler



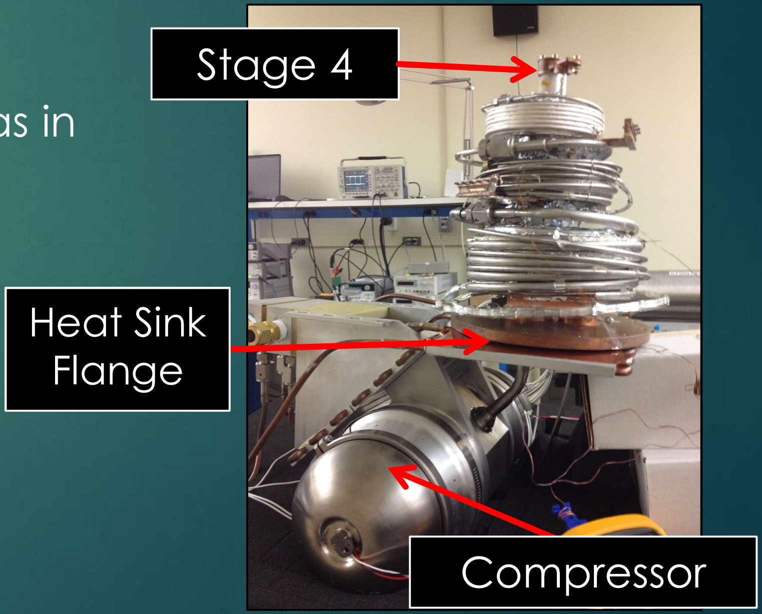
- Four stage inertance pulse tube cryocooler.
- EM developed under NASA's Advanced Cryocooler Technology Development Program that addressed the needs of James Webb Telescope Mid Infrared Instrument (MIRI).
- Northrup-Grumman cryocooler (JT+PTR) was chosen for implementation. The LM cooler was in storage past ~10 years.
- Nominal cooling capabilities using He4 as refrigerant

  Input Power: 208 W

  - Stage 4: 20 mW at 6 K

  - Stage 3: 150 mW at 18 K

  - Mass: 30 kg



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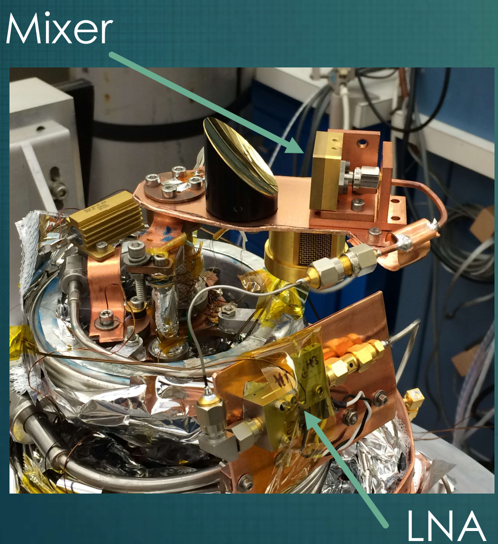
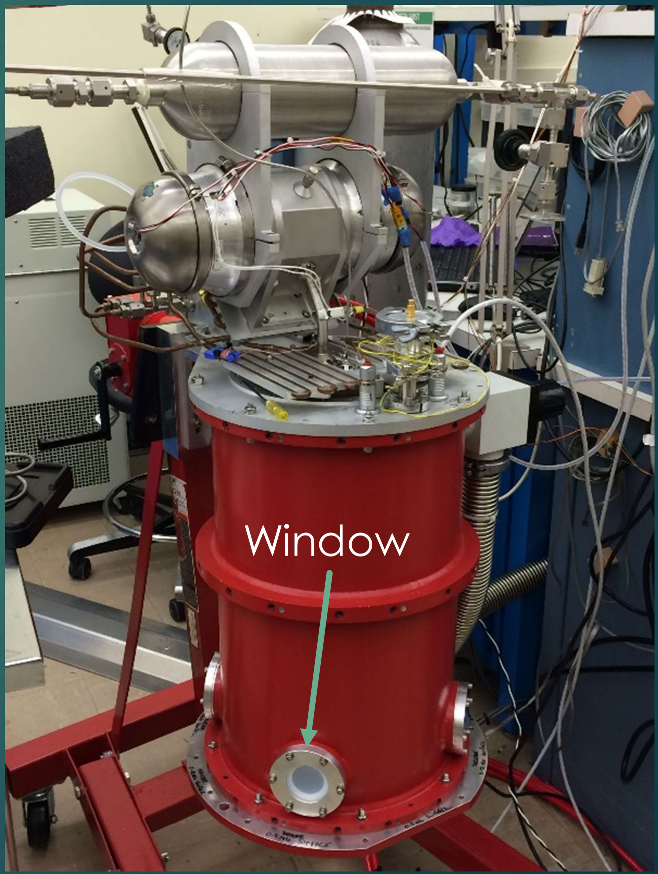
Instrument it with a single pixel 1.5 THz receiver

- Mixer (previous data TRX ~ 900 K) mounted on stage 4;
- SiGe LNA (T_{IF} = 8 K; P = 8 mW) mounted on stage 3
- HDPE vacuum window, porous Teflon IR filters
- Single coax line (pure stainless 34-mil from Stage 3 to 4.
- External local oscillator
- Ran system for 100-days (simulate GUSTO)





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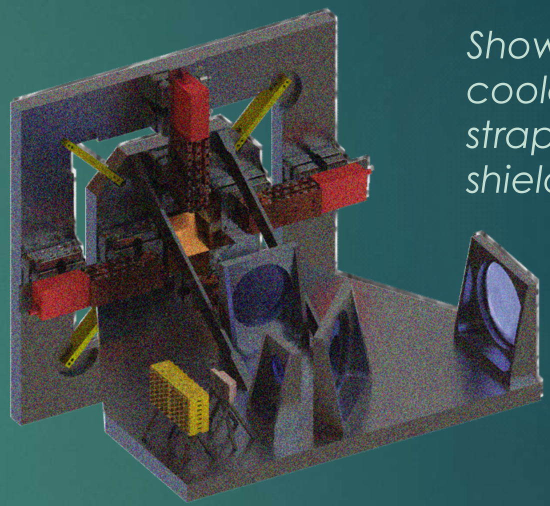
The detailed instrument design is straightforward

Completed a preliminary design for a 64-pixel 1.9 THz instrument

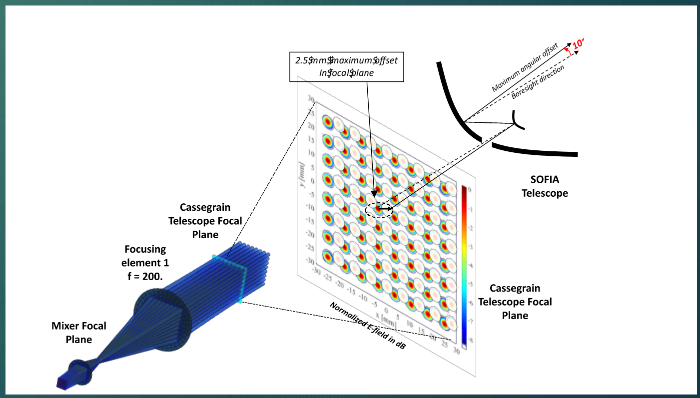
- Utilize Gaussian telescopes for LO-mixer and mixer-telescope coupling
- Use grid beam splitter
- Fan-out mixer signals to LNAs
- 1:1 LO-mixer coupling



Shown without cooler, thermal straps and radiation shields

For "free-flier" applications

- Severe restriction on cooling power
- But no vacuum jacket in space
- Direct coupling to secondary?



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…a 16-pixel THz receiver nearly exhausts available resources

Subsystem	Baseline	Goal
Cryocooler	300 W	300 W
Spectrometers	90 W	90 W
Local oscillators	200 W	200 W
Electronics	50 W	50 W

Cryogenic	Available	Utilized
4 K	20 mW	Parasitic
20 K	200 mW	110 mW

LNAs live on 20 K stage

Can a stand-alone mission with a 16-pixel THz instrument be really worth the expense?

- Payload on a LCATS platform (e.g., balloons, aircraft)
- Piggy back on an observatory-class FIR mission (OST) or a planetary science mission

More is better; where's the threshold?

How can we realistically increase pixel count? *Chip away the power.*

Improvements in LNA design can improve things

Subsystem	Baseline	Goal
Cryocooler	300 W	300 W
Spectrometers	90 W	90 W
Local oscillators	200 W	200 W
Electronics	50 W	50 W

Cryogenic	Available	Utilized
4 K	20 mW	8 mW…3 mW?
20 K	200 mW	16 mW

Integrated first stage preamp (0.5 mW/ 1mW)

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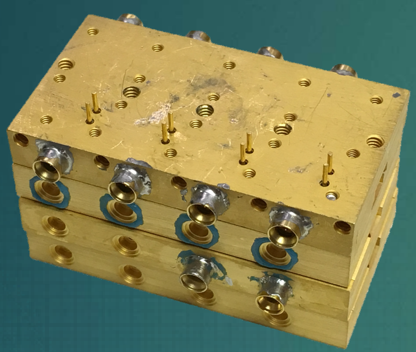
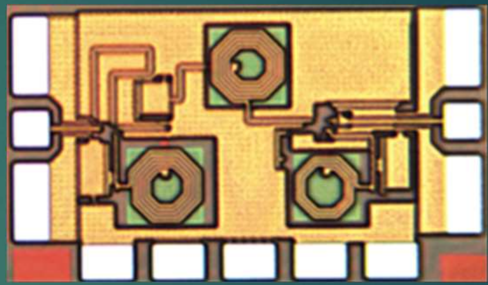
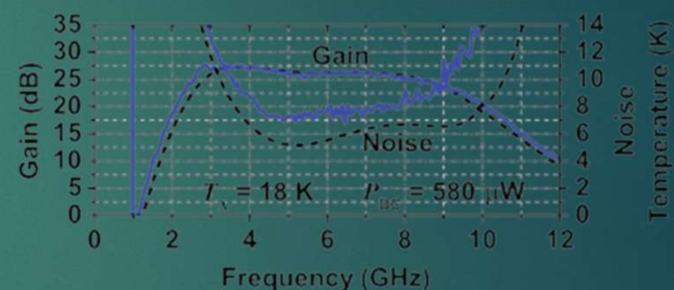
LNA technology:



- Widely used Caltech-originated P~5-10 mW per channel





- UMass-developed low power SiGe: order of magnitude reduction in power < 1 mW in cold stages
- Better system performance if first stage is integrated with mixer

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Further improvements are expected for the spectrometers

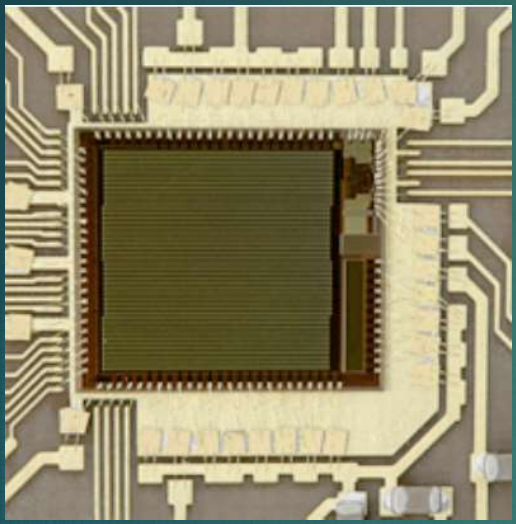
Subsystem	Baseline	Goal
Cryocooler	300 W	300 W
Spectrometers	90 W	16 W
Local oscillators	200 W	200 W
Electronics	50 W	50 W

Cryogenic	Available	Utilized
4 K	20 mW	3 mW?
20 K	200 mW	16 mW

Integrated first stage preamp

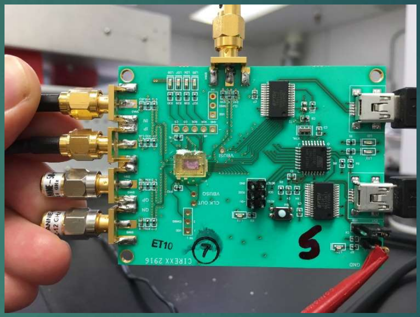
Spectrometer technology:

Omnisys HIFAS autocorrelator

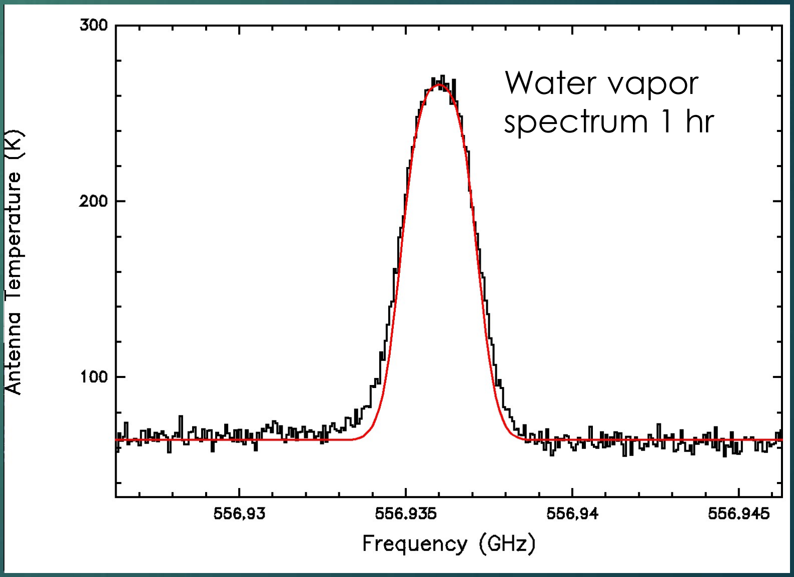


16-channel 1024-lag system (90 W)

CMOS-based PFB 1 GHz BW



1 GHz 1024 chan (0.7 W)
Next generation 2.5 GHz?



Local oscillators begin to dominate power budget…but this is a solvable problem

Subsystem	Baseline	Goal
Cryocooler	300 W	300 W
Spectrometers	90 W	16 W
Local oscillators	200 W	22 W
Electronics	50 W	50 W

Cryogenic	Available	Utilized
4 K	20 mW	3 mW?
20 K	200 mW	16 mW

Integrated first stage preamp

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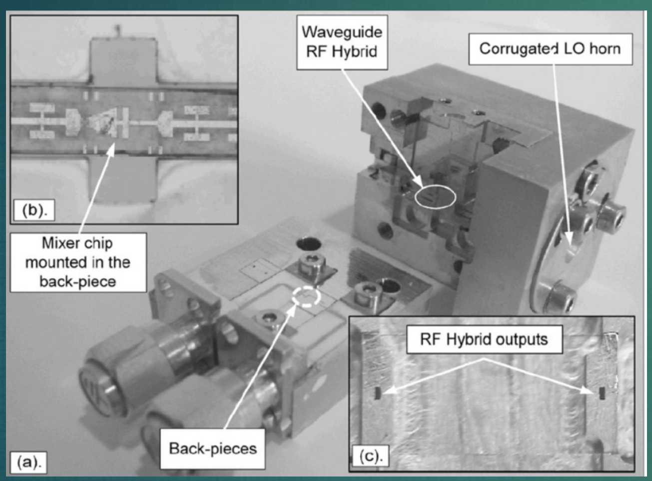
Use balanced mixers instead of single ended mixers…*increase pixel count by factor ~5* for same LO and mixer

Subsystem	Baseline	Goal
Cryocooler	300 W	300 W
Spectrometers	90 W	16 x 5 W=80 W
Local oscillators	200 W	110 W
Electronics	50 W	50 W

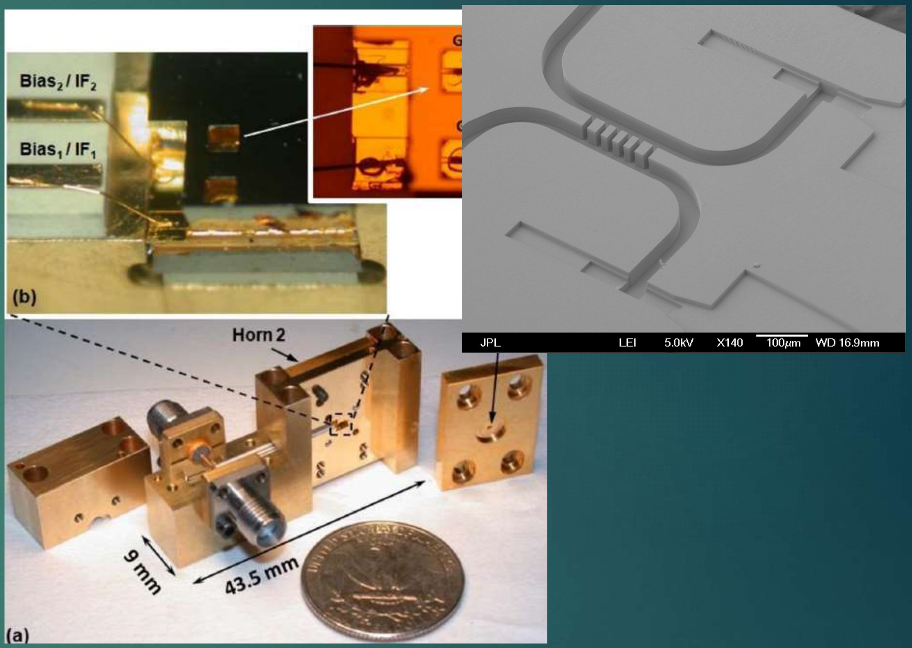
Cryogenic	Available	Utilized
4 K	20 mW	15 mW?
20 K	200 mW	80 mW

Integrated first stage preamp

Examples of balanced mixers:



A 1.4 THz balanced mixer (Meledin et al. 2009)



A 2.7 THz balanced mixer (Boussaha et al. 2014)

An 80-pixel receiver system can be powered by a ~600 W instrument.

Subsystem	Baseline (16 pixels)	Goal (80 pixels)
Cryocooler	300 W	300 W
Spectrometers	90 W	80 W
Local oscillators	200 W	110 W
Electronics	50 W	50 W

Cryogenic	Available	Utilized
4 K	20 mW	15 mW?
20 K	200 mW	80 mW

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Given NbN HEBs can operate near 6 K, we can expect 2x cooling power at the coldest stage

Subsystem	Baseline (16 pixels)	Goal (160 pixels)
Cryocooler	300 W	300 W
Spectrometers	90 W	160 W
Local oscillators	200 W	220 W
Electronics	50 W	50 W

Cryogenic	Available (6 K)	Utilized
4 K	40 mW	30 mW
20 K	200 mW	160 mW

So we managed to get 160 pixels from 16 pixels. Is this far-fetched?

4 key areas where technology is improving on short time scale:

- Low noise amplifiers ✓
- Local oscillator technology ✓
- Spectrometers ✓
- Balanced mixer arrays (6 K operation) ✗

A comfortable assumption is 32-64 pixels

Scales with resources

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Can we sell a GUSTO-like mission?

- $200M buy-in vs $35M cap for Explorer MOO
- Can probably buy more aggressive instrument
- 36 vs 3 month mission life time (factor of 10)
- GUSTO is a nice usage of NASA SPB/ULDB capability

Can we make an aggressive HFPA for SOFIA?

- GREAT sets a high bar.
- Cost becomes a constraint (last round the cap was $17M)

Only way to sell our product is that the instrument allows an order-of-magnitude leap over SOA capability.

A Heterodyne instrument as part of a suite on OST

- Power allocation
- Heat lift allocation
- Novel bolometers
  - High IF bandwidth (requires more spectrometer resources)
  - Higher operating temperature….an advantage on OST?
  - Higher LO power requirement (factor 10-100)
  - Sensitivity is usually the driving requirement (use Nb!)
- Using QCLs for >3 THz?
  - Maybe cooled by 1^{st} or 2^{nd} stage cooler
  - Add second cryocooler (< 50W/W heat lift)

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A low-power-dissipating 16-pixel demonstrator system in the near future + demo on low-power cooler

- A simple single-ended mixer array; development of a balanced receiver is important
- Integrated first stage LNA + second stage at 20-50 K
- LO generation using low power synthesizer

Can we better distinguish ourselves from an high spectral resolution (R~100,000) imager?

- A third-gen instrument HIRMES for SOFIA claims up to R = 100,000 with imaging capability
- Can be in principle much more sensitive than a heterodyne array