Heterodyne Receivers for AtLAST

Martina Wiedner
(LIRA, Observatoire de Paris)

for Heterodyne Instrumentation Community

Heterodyne Receiver Specifications For AtLast (by AtLAST team)

1) Heterodyne receiver focal plane arrays
    - ~ 1000 feeds and
    - spectral resolution R~10^6 or 10^7 (< 1 km/s).
    - Bands likely 70-116 GHz, 200-400, GHz, 580-720 GHz, and 850-950 GHz
    - with IF ≥32 GHz instantaneous bandwidth.

2) Single beam, multi-band receivers for mmVLBI and EHT campaigns

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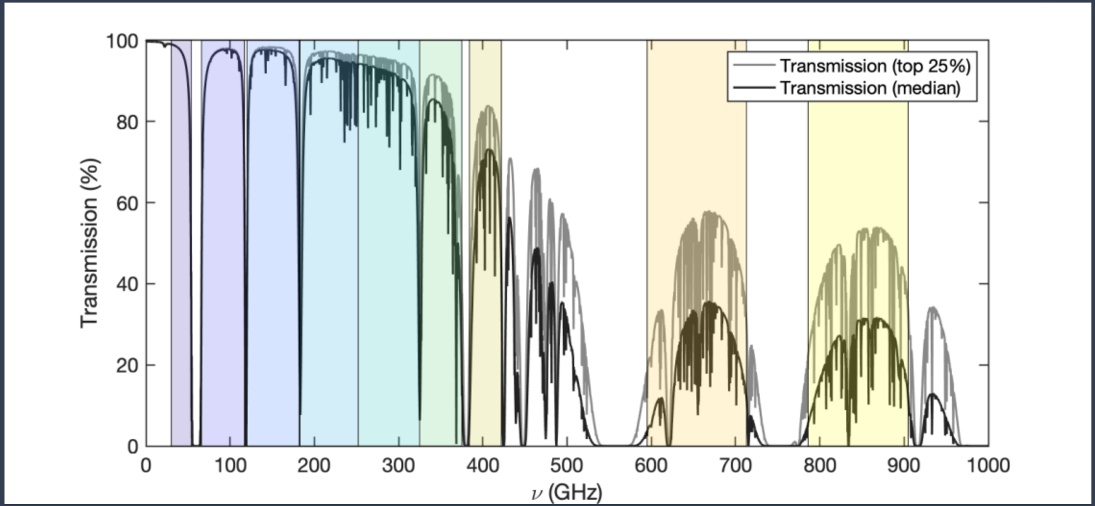
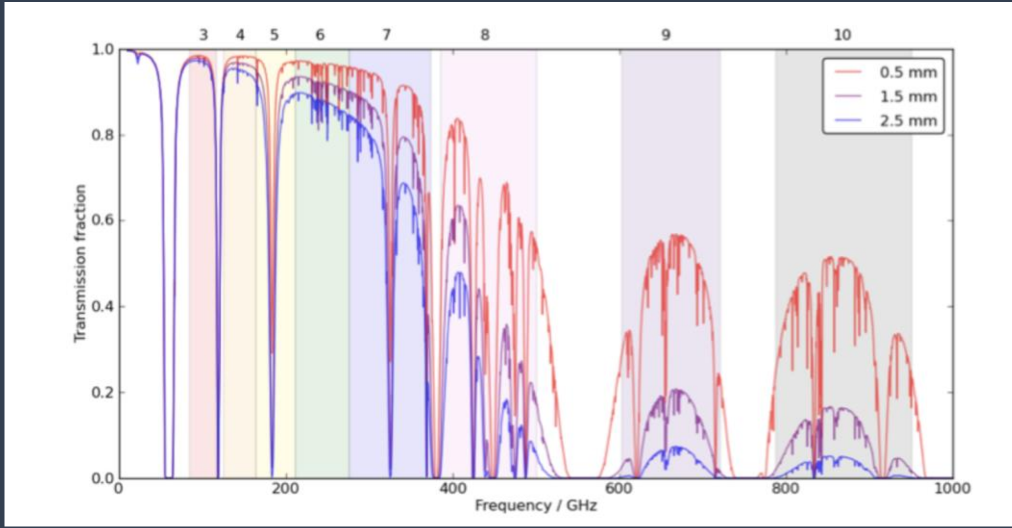
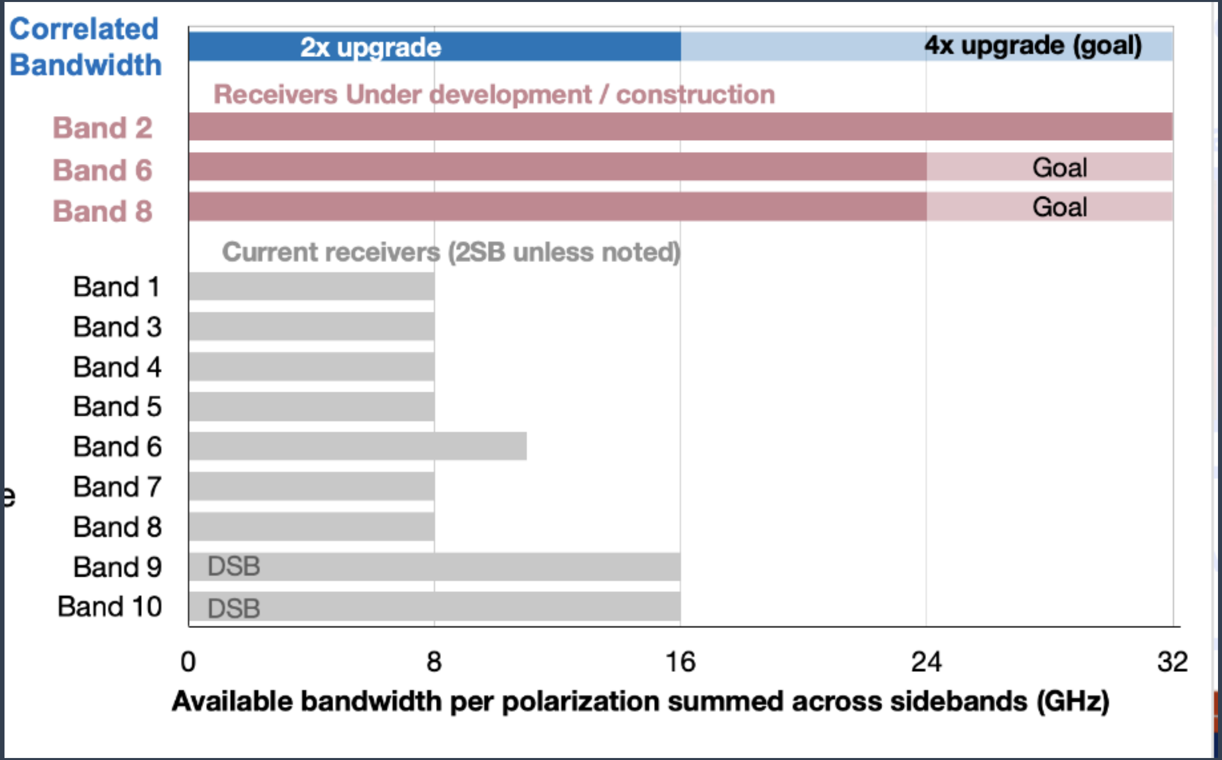


AtLAST bands and atmospheric transmission



ALMA bands and atmospheric transmission

Instantaneous Receiver Bandwidth; 32 GHz



ALMA Wideband Sensitivity Upgrade

Rich Heritage of Heterodyne Receivers

Herschel

Spitzer

Blast, STO, Gusto

SOFIA

CSO, JCMT, SMA

ALMA

Rich Heritage of Heterodyne Receivers and Array Receivers

Herschel

Spitzer

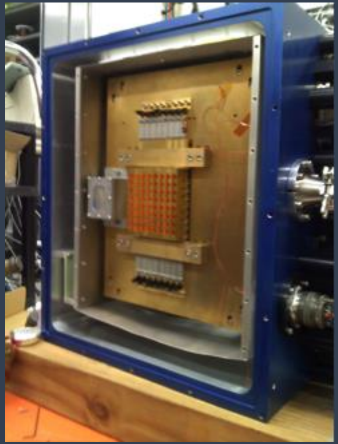
Blast, STO, Gusto

SOFIA

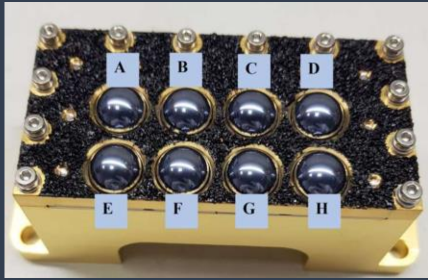
CSO, JCMT, SMA

ALMA

UpGREAT, 7 x 2 pixel

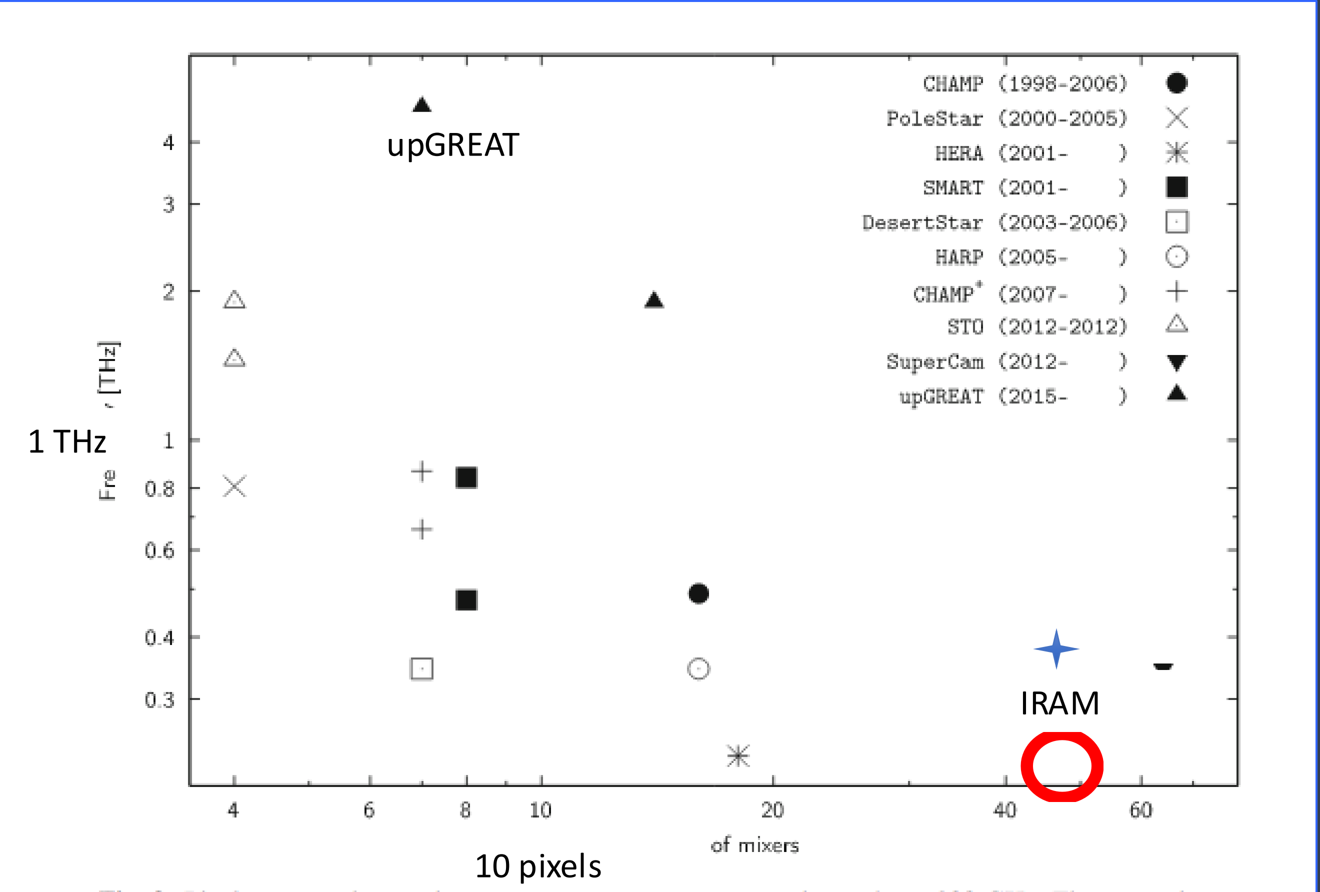


SuperCam 8 x 8 pixels, far-IR X 8000, Uni. of Arizona, USA



GUSTO, 8 pixel

Previous Heterodyne Array Rx



CHAI; CCAT/FYST

Graf et al. 2015

Requirements for Large Heterodyne Array Rx

Large?

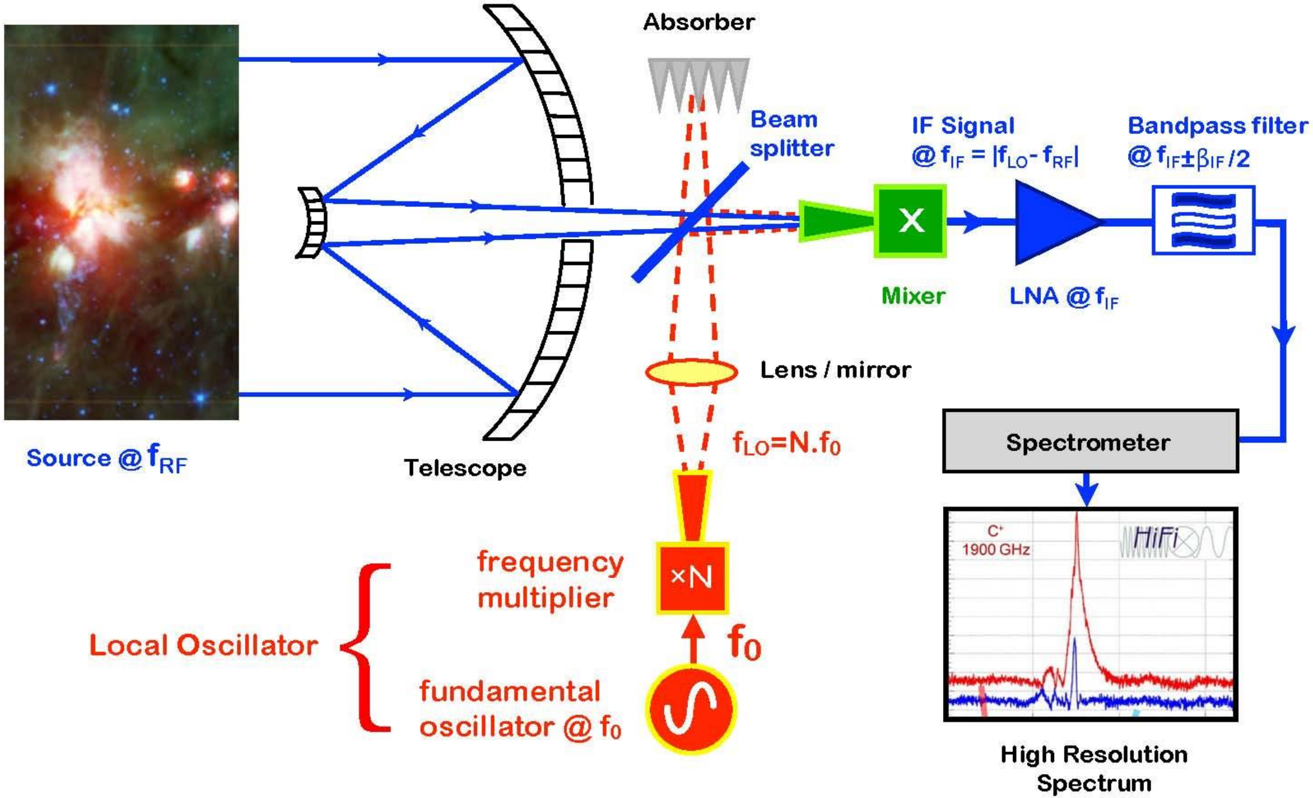
50m dish → single beam 2'' @690GHz (430μm)

FoV 1° → 810 000 pixels

~4 orders of mag!

Largest to date 64 pixels

Heterodyne detection chain

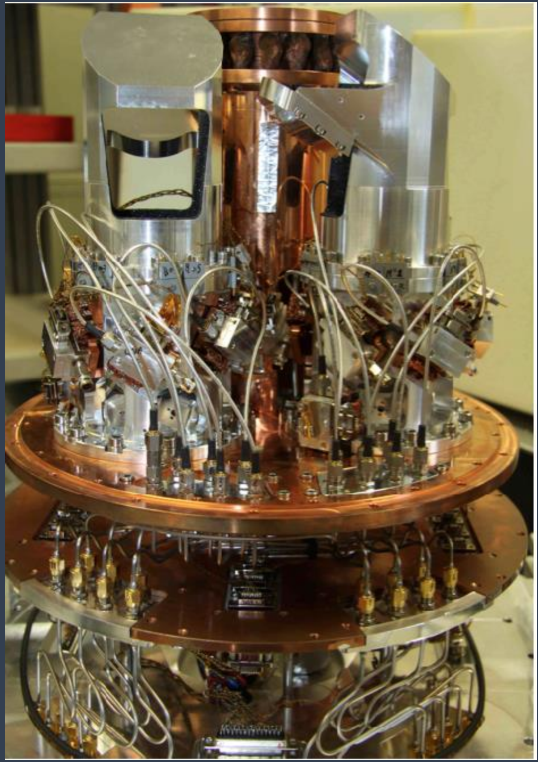


Requirements for Large Heterodyne Array Rx

- Efficient : $t_{int} \sim 1/N$, $t_{int} \sim T_{rx}^{2}$

upGREAT, SOFIA – 2 x 7 pixels

- 1830 - 2070GHz (/2500GHz)
- SOFIA



Risacher et al.

Requirements for Large Heterodyne Array Rx

- Efficient ($t_{int} \sim 1/N$, $t_{int} \sim T_{rx}^{2}$)
- Cost 25kEuro/pixel (Graf) + time!

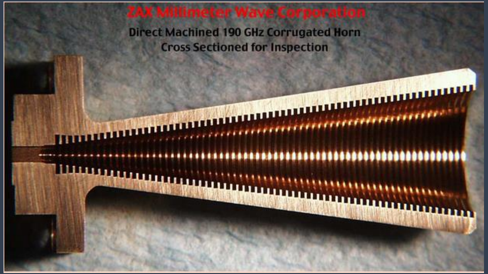
Requirements for Large Heterodyne Array Rx

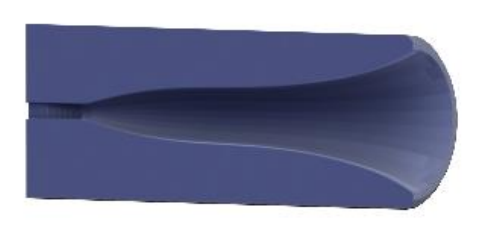
- Efficient ($t_{int} \sim 1/N$, $t_{int} \sim T_{rx}^{2}$)
- Cost
- Simplified structures for fabrication

Some ideas to simplify

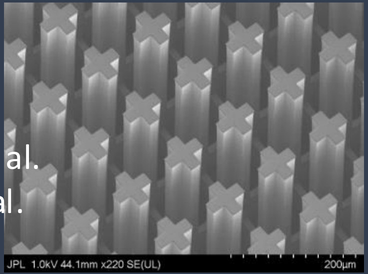
Horns: corrugated --->

- smoothed walled
- pyramidal, pyramidal with smooth walls
- pressed
- Silicon horns
- flat lenses

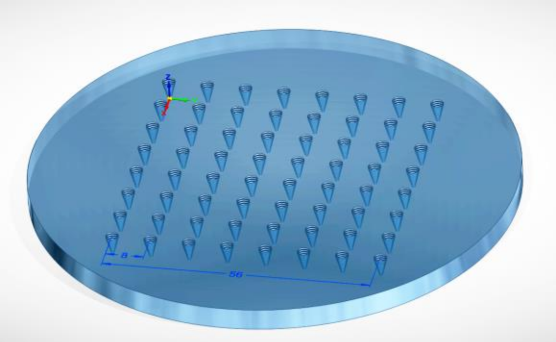




Gibson et al.



Gao et al.
Defrance et al.
Sauleau et al.



Delorme, Valentin

Some ideas to simplify

LO beam divider:

- in waveguide
- phase gratings
- or integrated LO

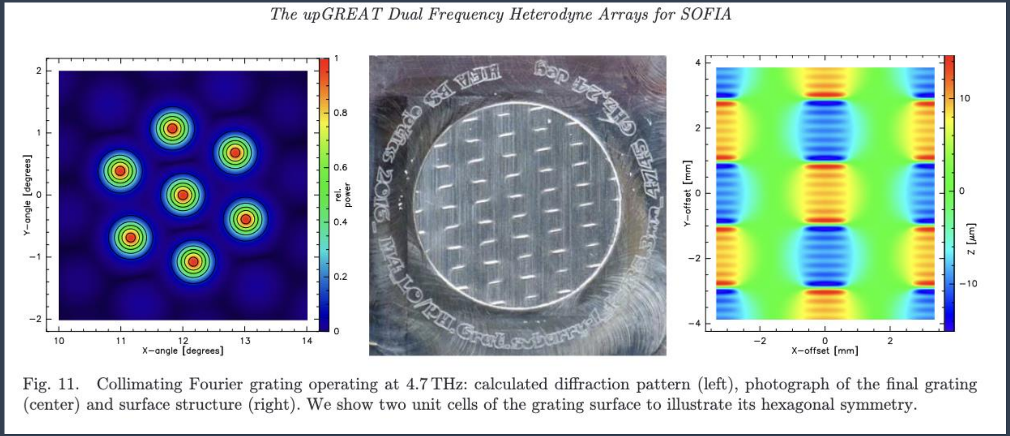
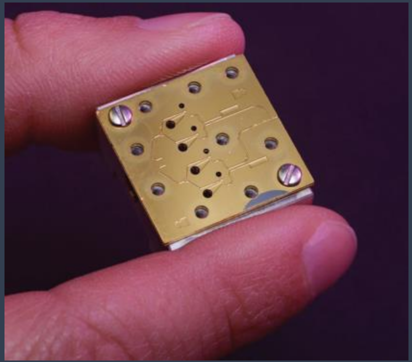


Fig. 11. Collimating Fourier grating operating at 4.7 THz: calculated diffraction pattern (left), photograph of the final grating (center) and surface structure (right). We show two unit cells of the grating surface to illustrate its hexagonal symmetry.

upGREAT team



JPL, The 500–600-GHz spectrometer front end, with a close-up of the heart of the instrument showing all the silicon micromachined waveguide structures.

Some ideas to simplify

Horns: corrugated --->
- smoothed walled
- pyramidal, pyramidal with smooth walls
- pressed
- Silicon
- flat lenses

LO beam divider:
- in waveguide
- phase gratings

Mixers:
- Compact mixer bias, shared B
- Multimixer array on single waver

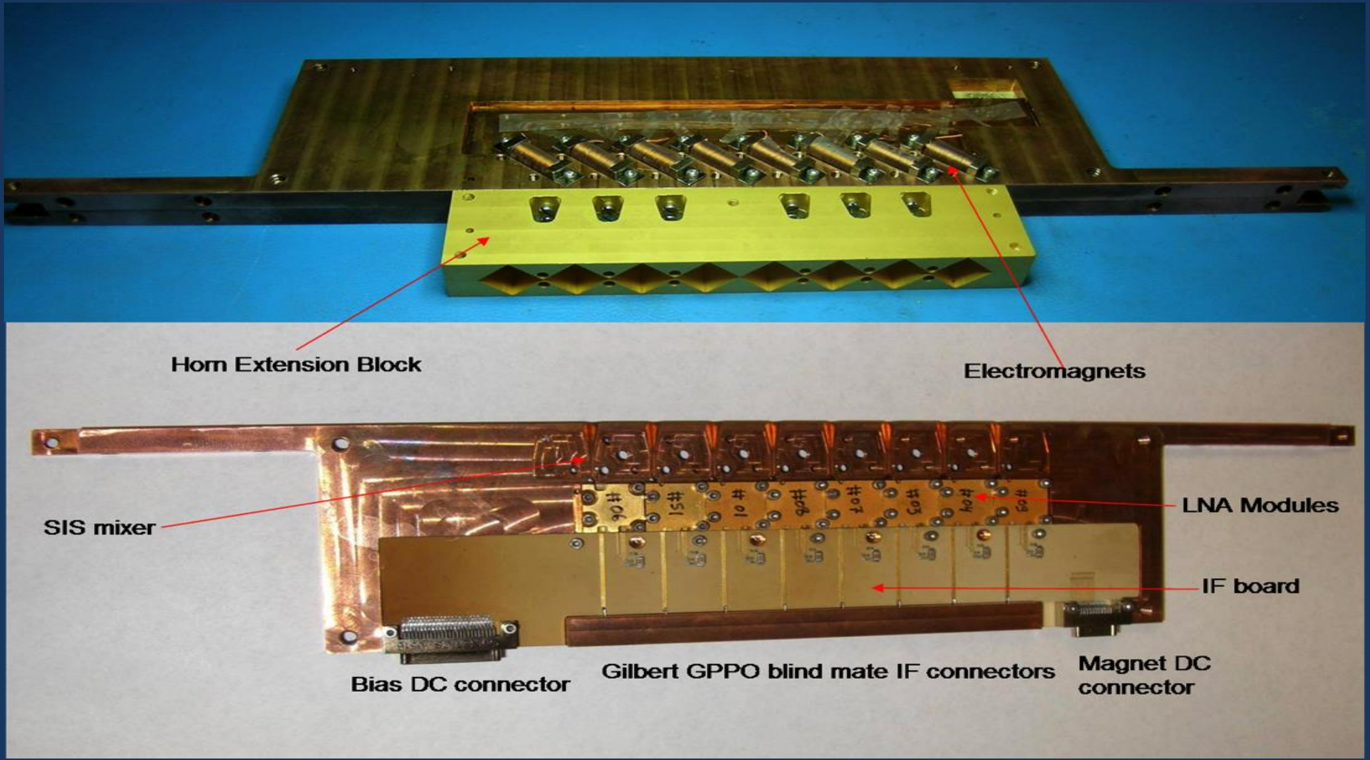
Rx on chip

IF Cabling:
- Multiline
- Superconducting
- Microstrip or Stripline

E.g. See Radioblocks

SuperCam, HHT - 64 pixels

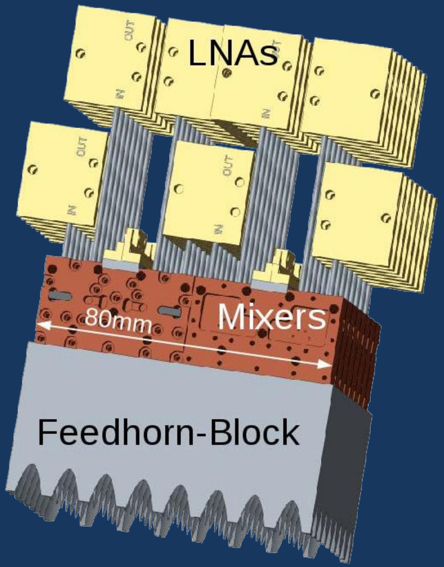
- 320 – 360 GHz on HHT
- Monolithic block with horns

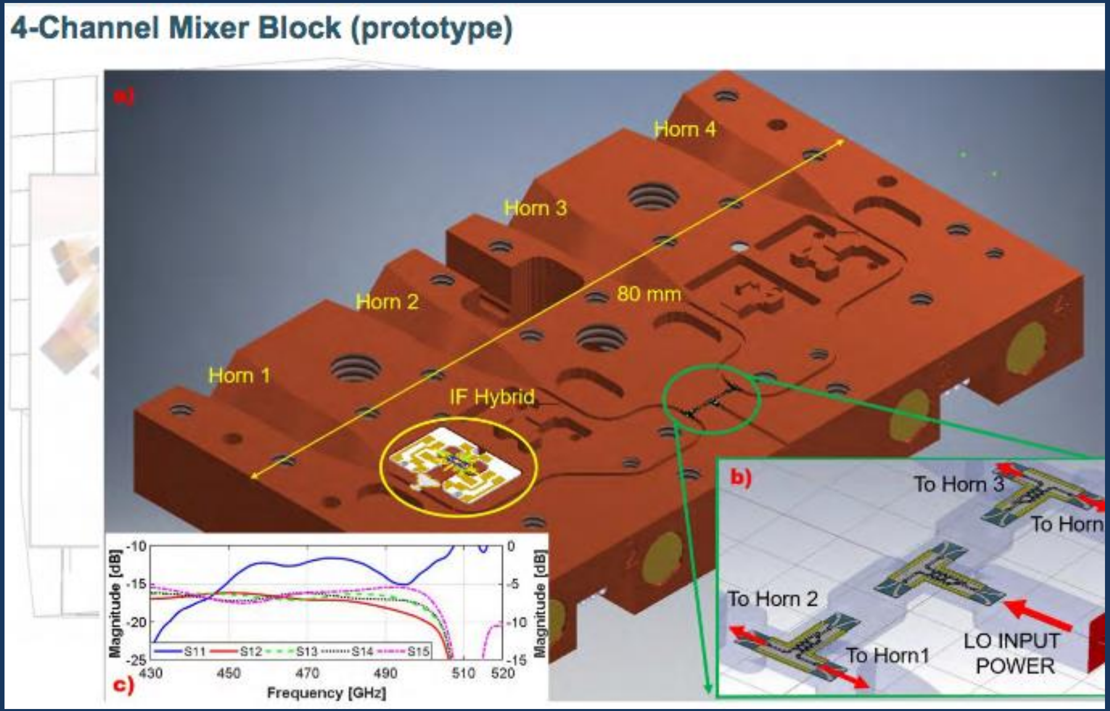


Groppi, Walker et al. U of Arizona

Chai, CCAT - 64 pixels

490, 810 GHz





Graf; Honingh U zu Köln

Chai, CCAT - 64 pixels

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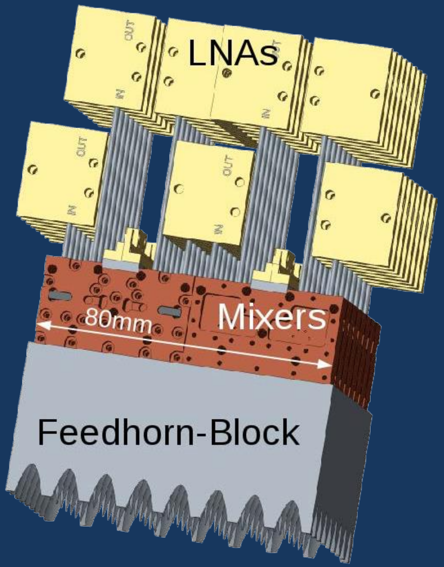
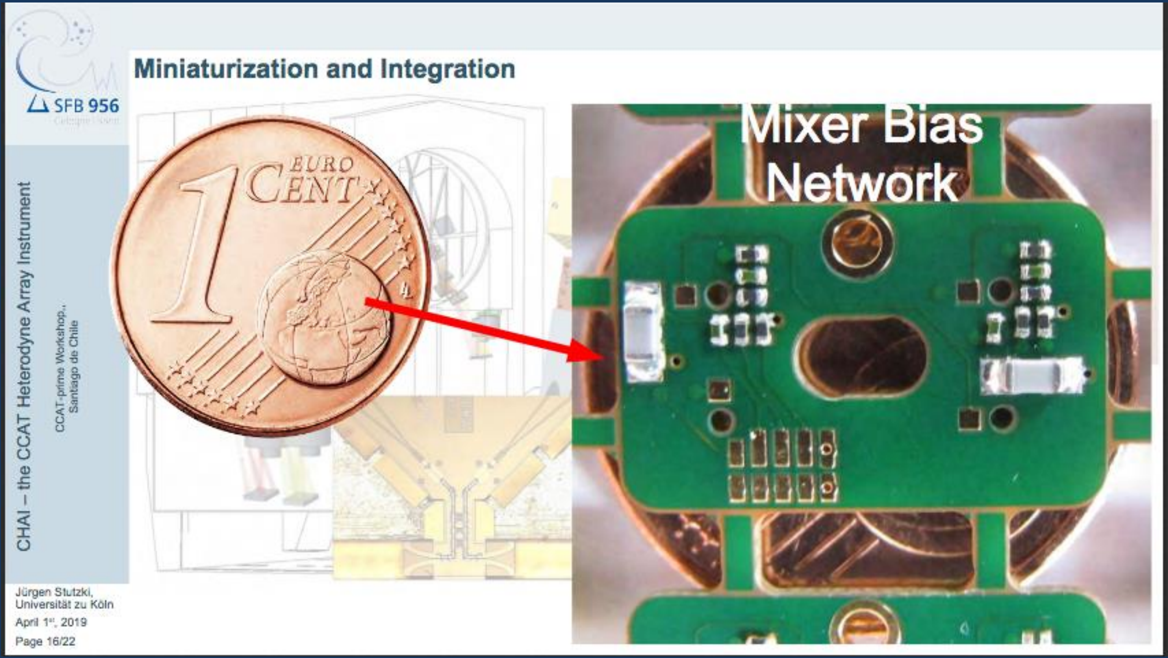
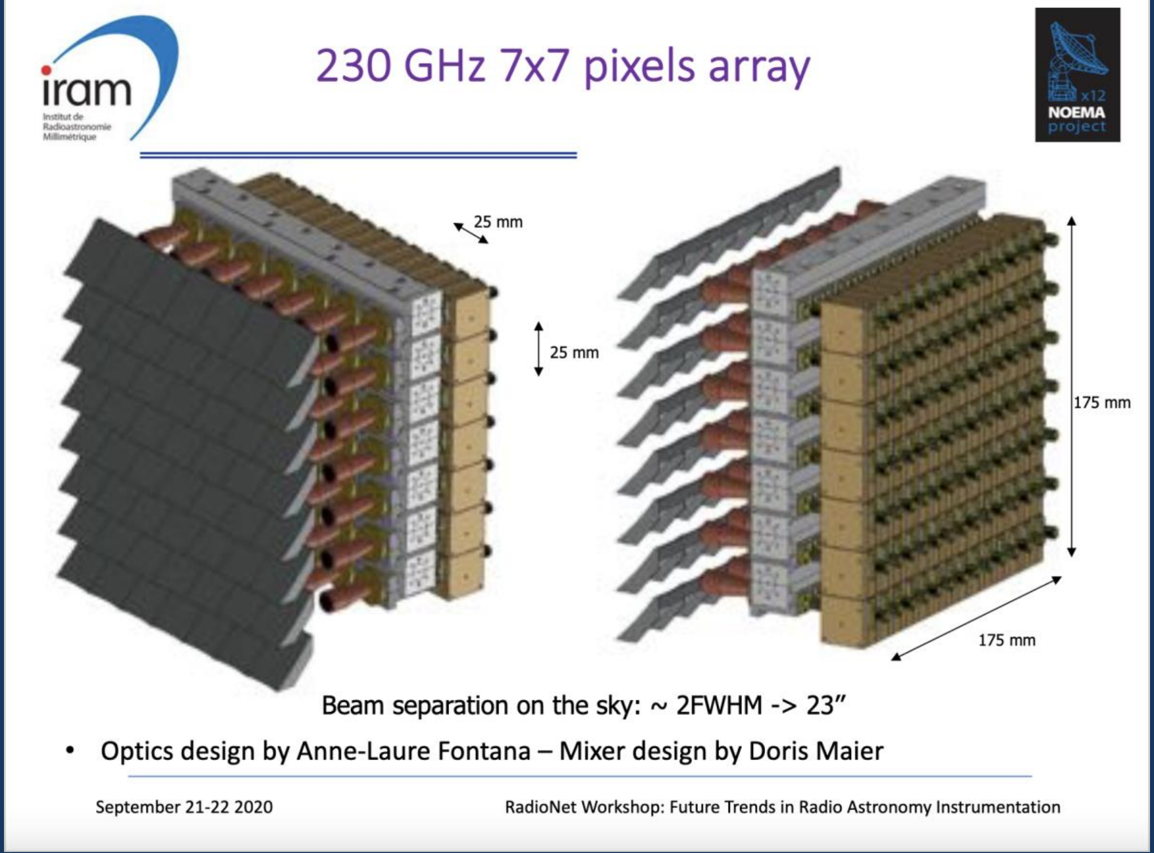




Graf; Honingh U zu Köln

IRAM – Alhambra, 49 pixels; 230 GHz



Fontana, Maier et al.; IRAM

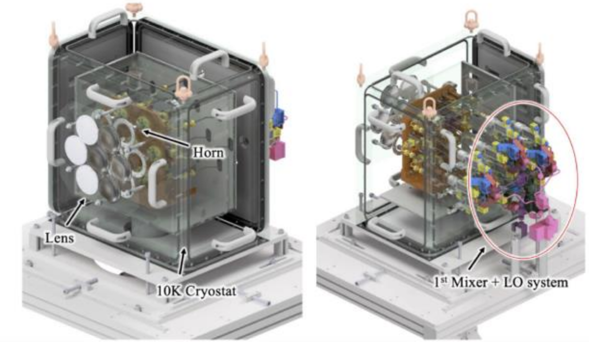
CHAMP+, APEX – 2x7 pixels; 690, 810 GHz

Güsten et al.

Heterodyne array in Nobeyama/NAOJ

7BEE (72-116 GHz)

7-beam dual-polarization 2SB receiver with HEMT
(Yamasaki+2024)

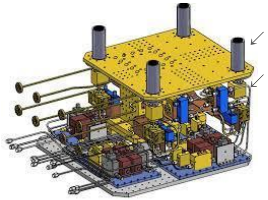


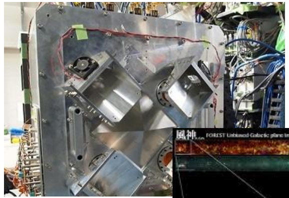
Installed on 45m, commissioning underway.

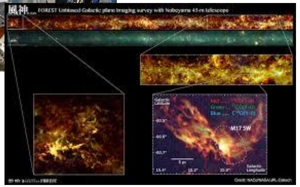
Huge IF chains!

FOREST (80-116 GHz)

4-beam dual-polarization 2SB receiver with SIS
(Minamidani+2016; Nakajima+2019)



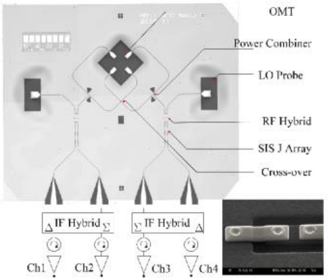


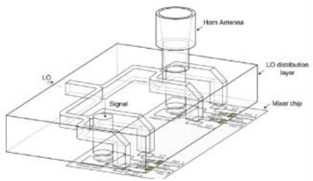


~10 yr operations, gave a lot of results in the Galactic Plane survey "FUGIN"

Integrated circuit (125-160 GHz)

On-chip mixer for future multi-beam receivers under development at NAOJ Advanced Tech. Center
(Shan+2018, 2019)





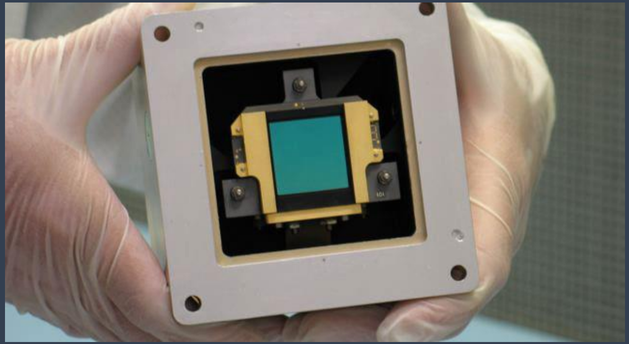
For future large-format heterodyne array, on-chip integrated circuit of SIS mixer is being studied and demonstrated for 2mm band.

Slide given by Tamura-san

Requirements for Large Heterodyne Array Rx

- Efficient ($t_{int} \sim 1/N$, $t_{int} \sim T_{rx}^{2}$)
- Cost
- Simplified structures for fabrication
- Multiplexing
  - In time – like CCD,
  - In frequency – like MKIDS

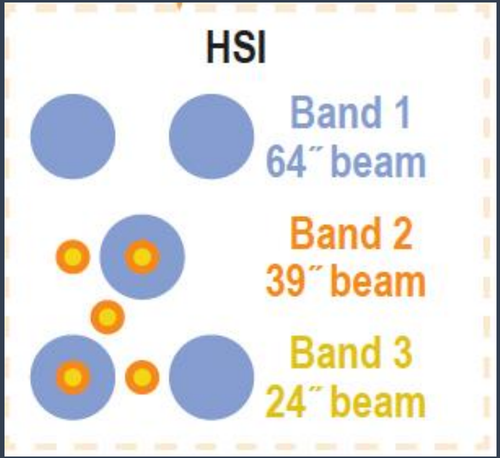
  --> Not possible



JWST/MIRI 1024 × 1024 pixel Si:As detector array – mid-IR (10^6 spexels)

Requirements for Large Heterodyne Array Rx

- Efficient ($t_{int} \sim 1/N$, $t_{int} \sim T_{rx}^{2}$)
- Cost
- Simplified structures for fabrication
- ~~Multiplexing~~
- Dense packaging $2F\lambda$ ok



Optics by Baryshev

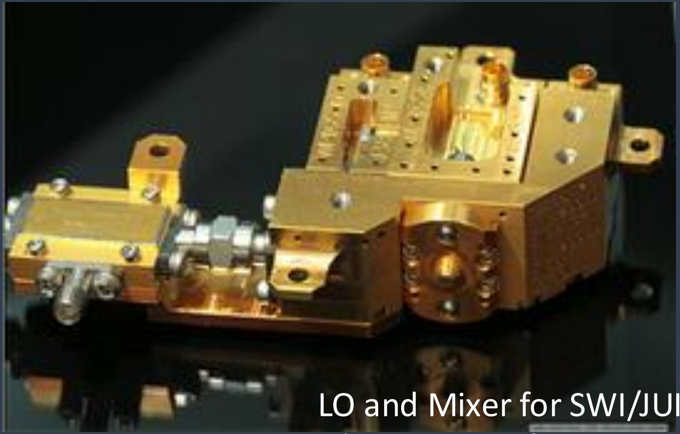
Requirements for Large Heterodyne Array Rx

- Efficient ($t_{int} \sim 1/N$, $t_{int} \sim T_{rx}^{2}$)
- Cost
- Simplified structures for fabrication
- Dense packaging
- low energy consumption,
- low heat dissipation at cryogenic T
- small vol
- Low weight
- Reliability

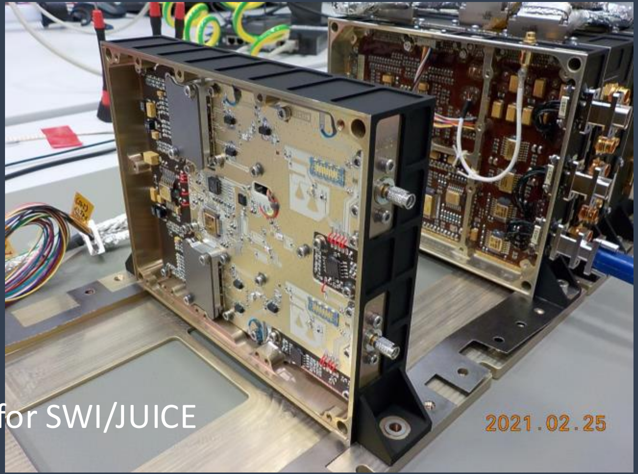
Get inspirqtion from space missions, e.g. Origins, FIRSST

Limit required resources

- low energy consumption:
  - Critical elements:
    - Local oscillator; 2W/pixel with AMC
    - Spectrometers: 7W/4GHz backend



LO and Mixer for SWI/JUICE
Observatory of Paris, C2N

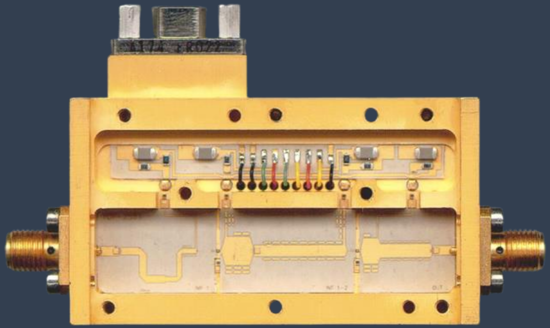


Spectrometers for SWI/JUICE
MPS, Omnisys

Limit required resources

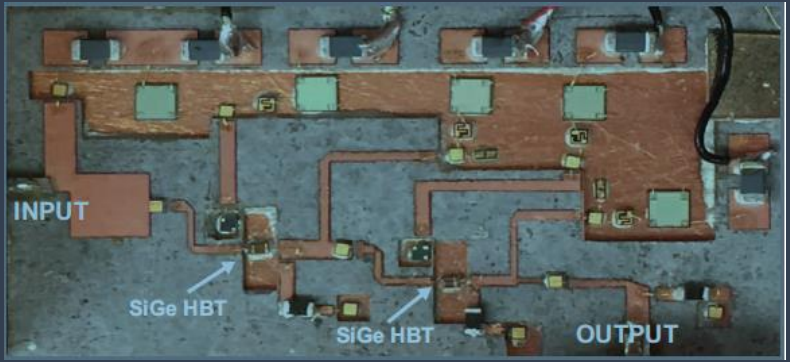
- low heat dissipation at cryogenic temperatures:
  - Critical elements:
    - Low Noise Amplifiers, 1 to 2 mW

InP Amplifiers, Gallego

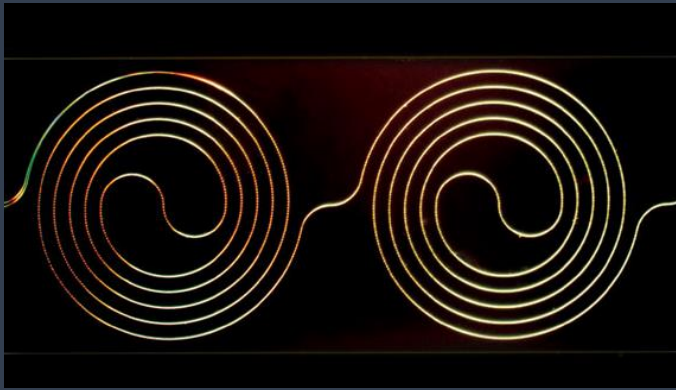


Options:

- InP
- SiGe
- Parametric



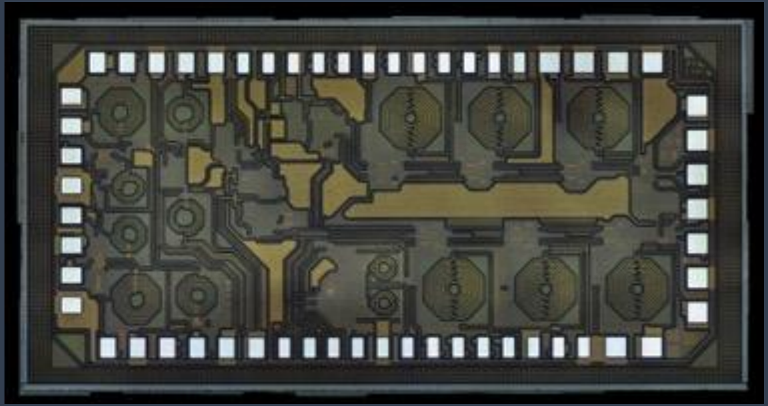
SIGe Amplifiers, Bardin



Parametric Amplifiers

Limit required resources

- Low volume & mass
  - IF chains → miniaturize
  - Few, wide RF frequency bands



R. Plume
U of Calgary

Max-Planck-Institut
für Radioastronomie

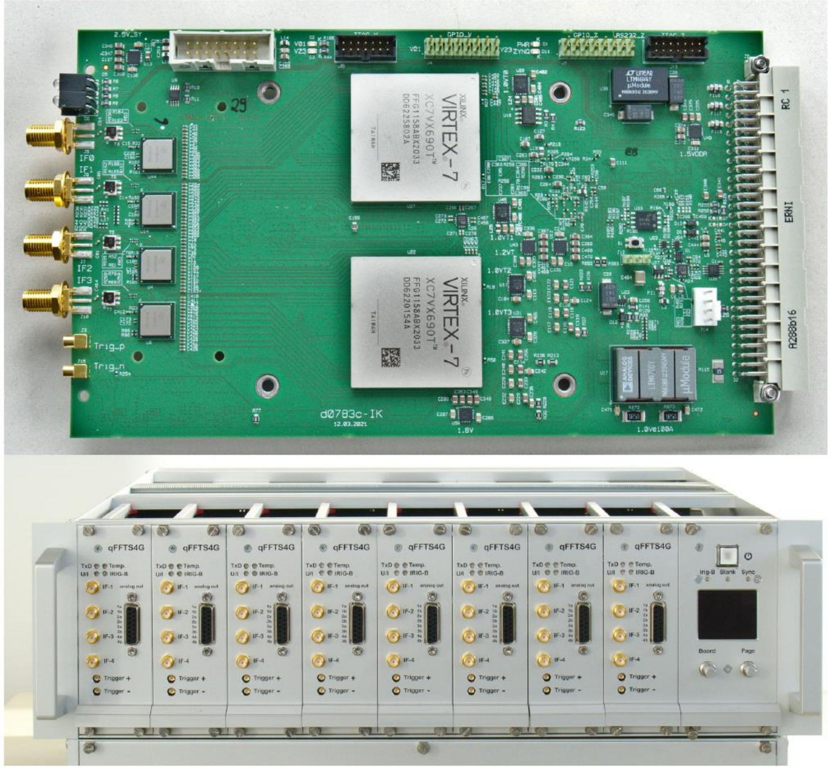
Our latest generation of FFT spectrometer

Technical specifications qFFTS board:

- Input bandwidth: 4 x 4 GHz (0 – 4 GHz and 4 – 8 GHz)
- Spectral channels: 4 x 64k
- Spectral resolution: 71 kHz (ENBW)
- ADC resolution: 12-bit (TI ADC12DJ5200)
- Power consumption: max. 140 W (~9 W / GHz)
- Interface: Gigabit Ethernet

Technical specifications qFFTS crate:

- Total bandwidth: 128 GHz
- Spectral channels: 2 million channels
- Max. dump rate: 20 spectra / second

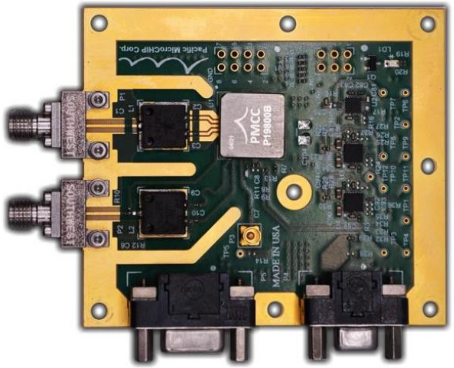
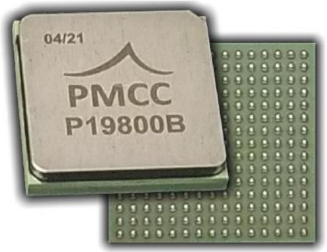


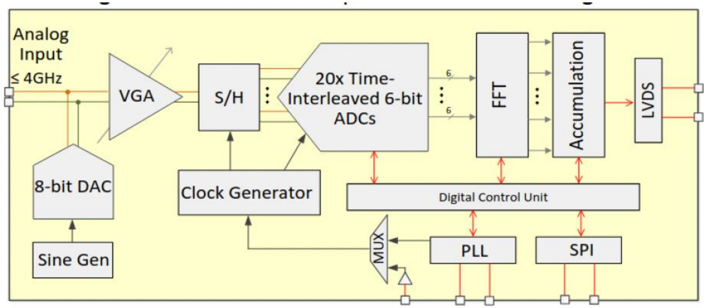
qFFTS spectrometer board and qFFTS spectrometer 19” crate

Spectrometer on a Chip (ASIC)

Max-Planck-Institut
für Radioastronomie

Pacific MicroCHIP Corp.
IC/ASIC Design Services

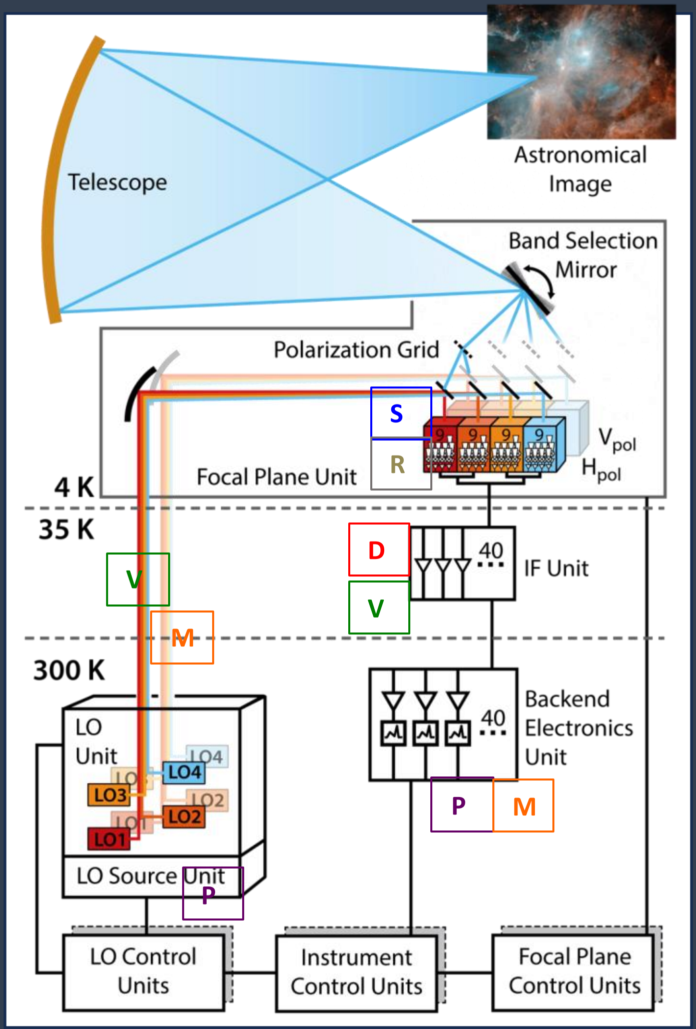





ASIC Operational Capabilities

The ASIC digitizes the RF signal and splits the spectrum into 8192 frequency bins. The power or magnitude is computed for each bin and the result accumulated.

- Input signal bandwidth up to 5.5GHz
- Sampling rate up to 8GS/s
- Input signal FSR programmable from 66mV to 400mV pp differential
- Digitizer ENOB > 4.5-bit to 4GHz
- Power consumption < 1.6W (full functionality)
- Power consumption < 1.2W (4MHz bin resolution)
- Up to 8192 Frequency bins within 0 to 4GHz
- Accumulation time programmable from 2us to 34s
- An integrated 16GHz PLL with selectable Fref
- An SPI interface for control, diagnostics and readout
- Temperature range -40°C to 110°C
- 15 x 15 BGA package (12.8mm x 12.8 mm)
- Fabrication technology 28nm CMOS



HERO/Origins

Improve on:

- D – Dissipation
- P – Power
- S – Simplification
- V – volume
- M – mass
- R - reliability

Wiedner et al.

Requirements for Large Heterodyne Array Rx

- Efficient ($t_{int} \sim 1/N$, $t_{int} \sim T_{rx}^2$)
- Cost
- Simplified structures for fabrication
- Dense packaging
- low energy consumption,
- low heat dissipation at cryogenic temperatures
- small vol and
- Low weight
- Reliability
- Uniformity
- Research Groups

Other aspects not discussed
as they apply equally to single pixel heterodyne receivers

- (line) polarimetry
- IF bandwidth, e.g. ALMA upgrades, SMA wideband upgrade
- Receiver sensitivity, e.g. ALMA, NOEMA, APEX
- Calibration (accuracy)
- Multifrequency: dyplexed

- Observing modes, e.g. for mapping

Conclusion

100 pixels: today

1000 pixels: cooling, power, size, mass starting to become acceptable

largest challenges: time, cost (>25 M€)

FoV 0.03 deg; power >125 kW

>1000 pixels: need breakthrough or lots of resources

Technological developments for larger arrays are ongoing