rijksuniversiteit groningen

SABRINA REALINI

Kapteyn Astronomical Institute

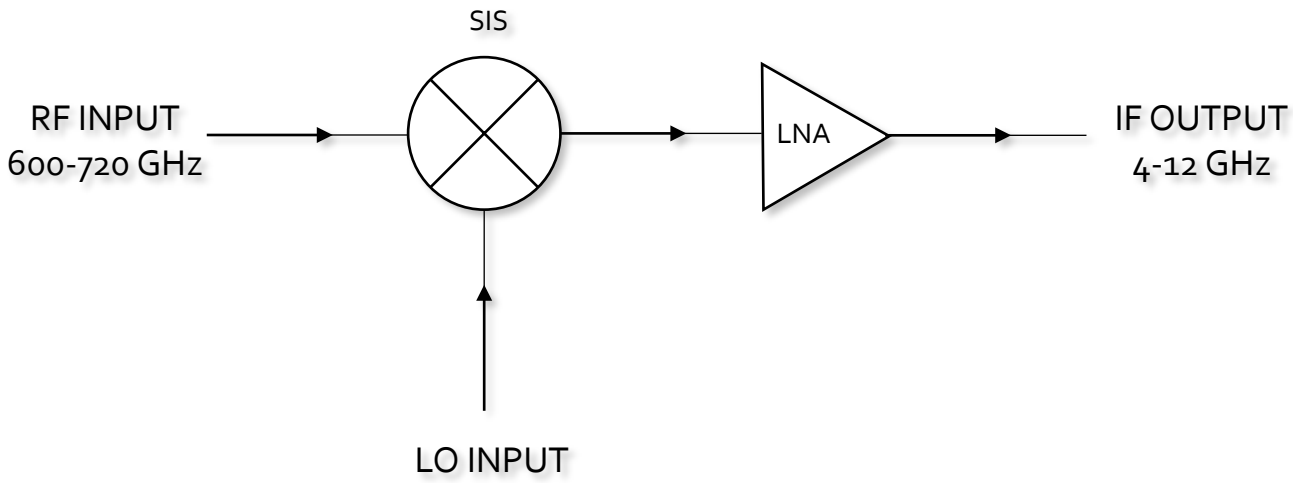
ALMA Band 9 upgrade: a feasibility study

Observing the Universe at millimetre wavelengths

June 26 -30, 2023

BAND 9 RECEIVER

- ALMA Band 9 (600-720 GHz) receiver is a dual channel heterodyne system
  - Detection and down-conversion of two orthogonal linear polarization components



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  - The light entering the front end is refocused with a compact arrangement of mirrors

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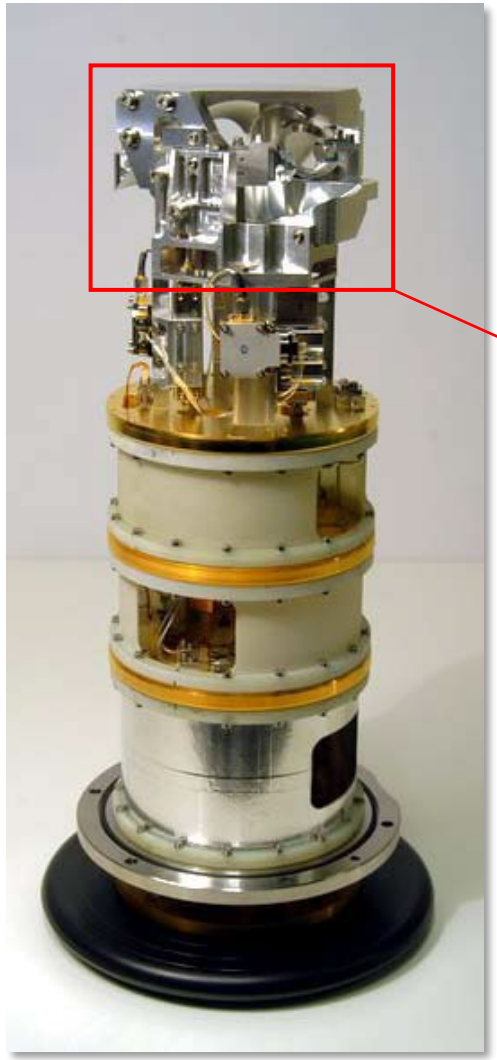

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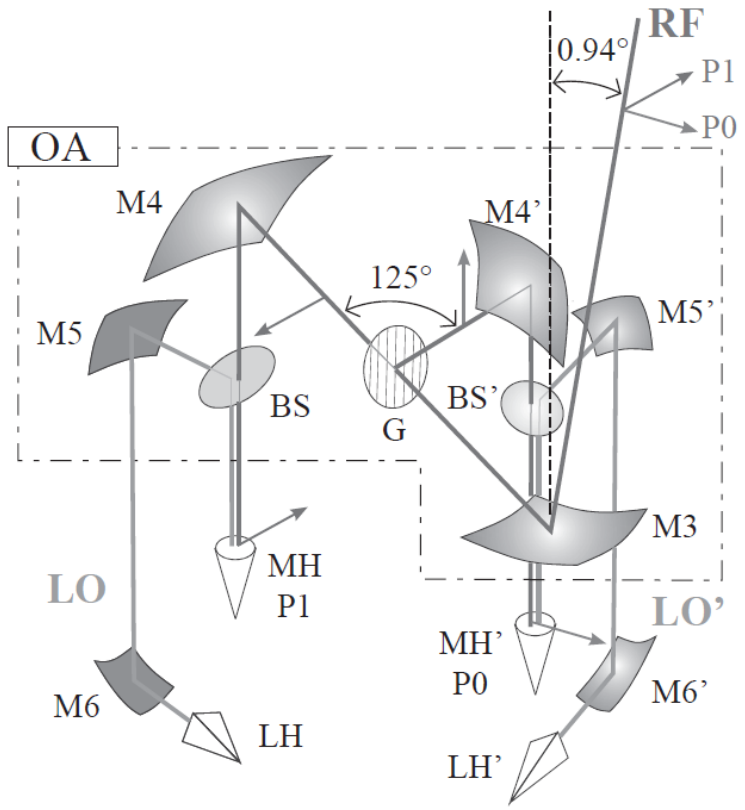

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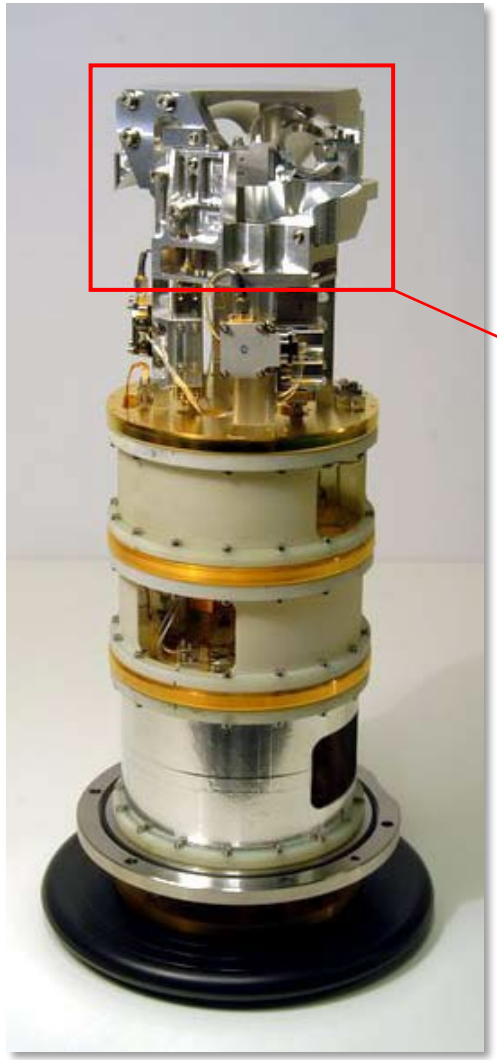

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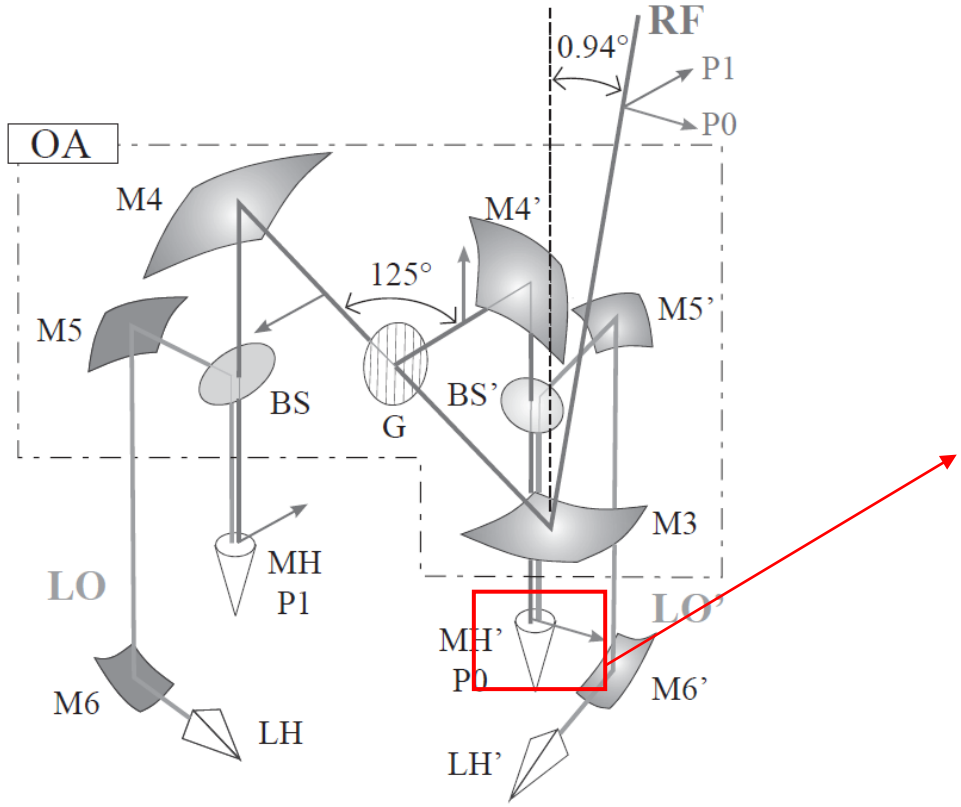
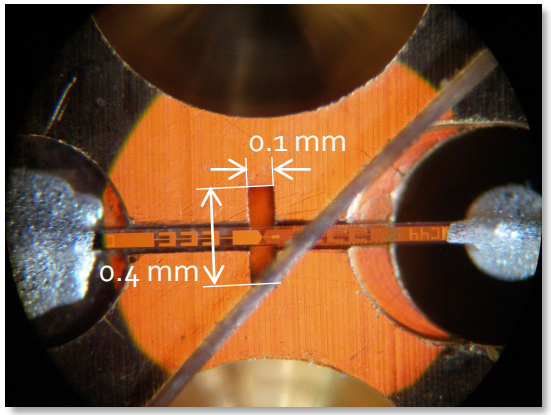
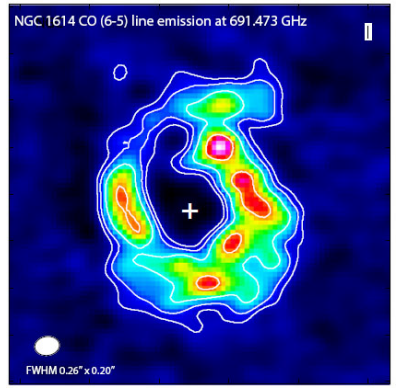




Science with ALMA Band 9

» Scientific Case for Band 9

- Map of the dust and gas distribution
- Spectroscopy of warm and dens gas for a range of astrophysical objects
- High-z galaxies, starbursts, black holes in AGN, star-forming regions, proto-planetary disks
- Detection of high excitation lines of CO, HCN, HNC and HCO+ across cosmic time



» Band-9 requires favourable weather conditions

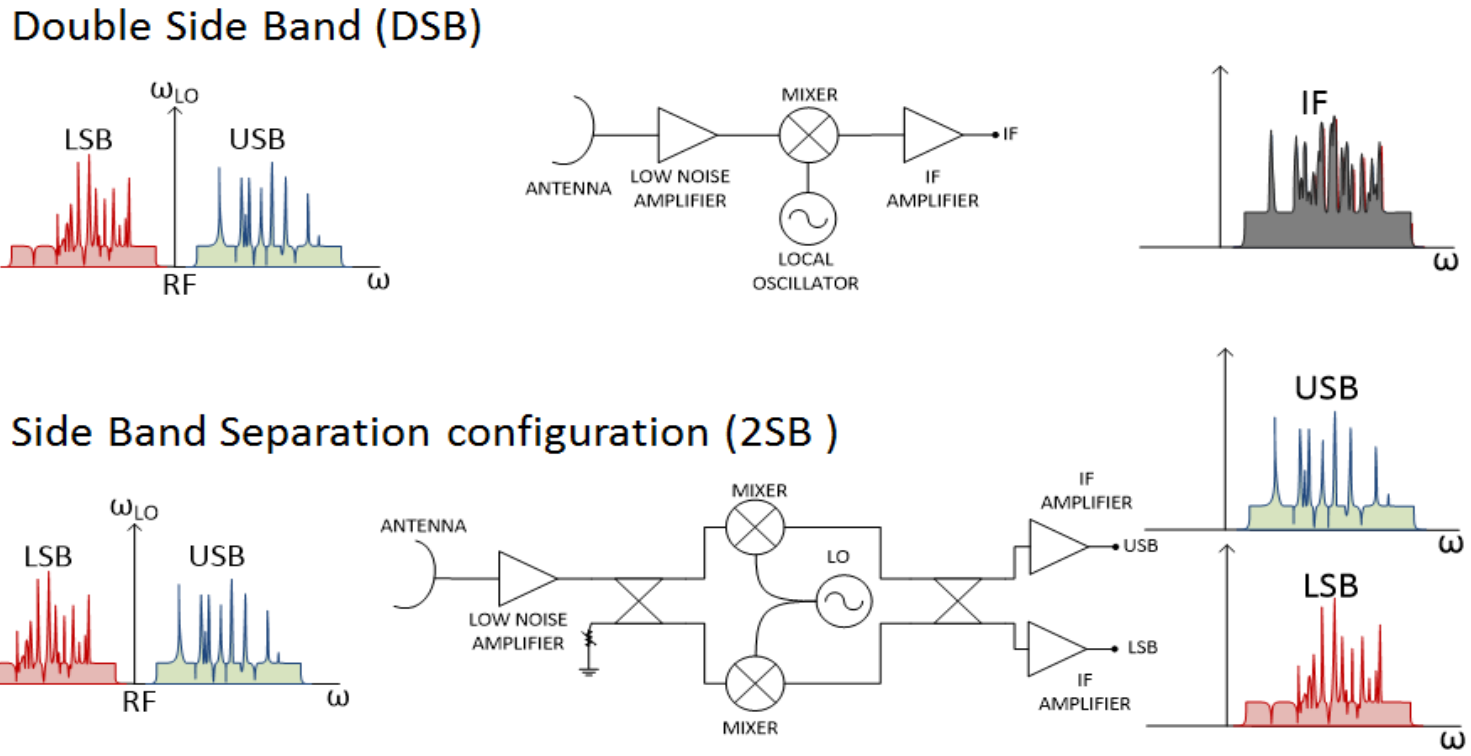
- Improve the scientific throughput of receivers

» Wideband Sensitivity Upgrade in ALMA2030 Development Roadmap

- Increase the instantaneous frequency coverage
- Increase the overall sensitivity

Receiver Sensitivity

» Improvement in spectral line sensitivity upgrading from Double Sideband (DSB) to Sideband Separating (2SB) receiver technology



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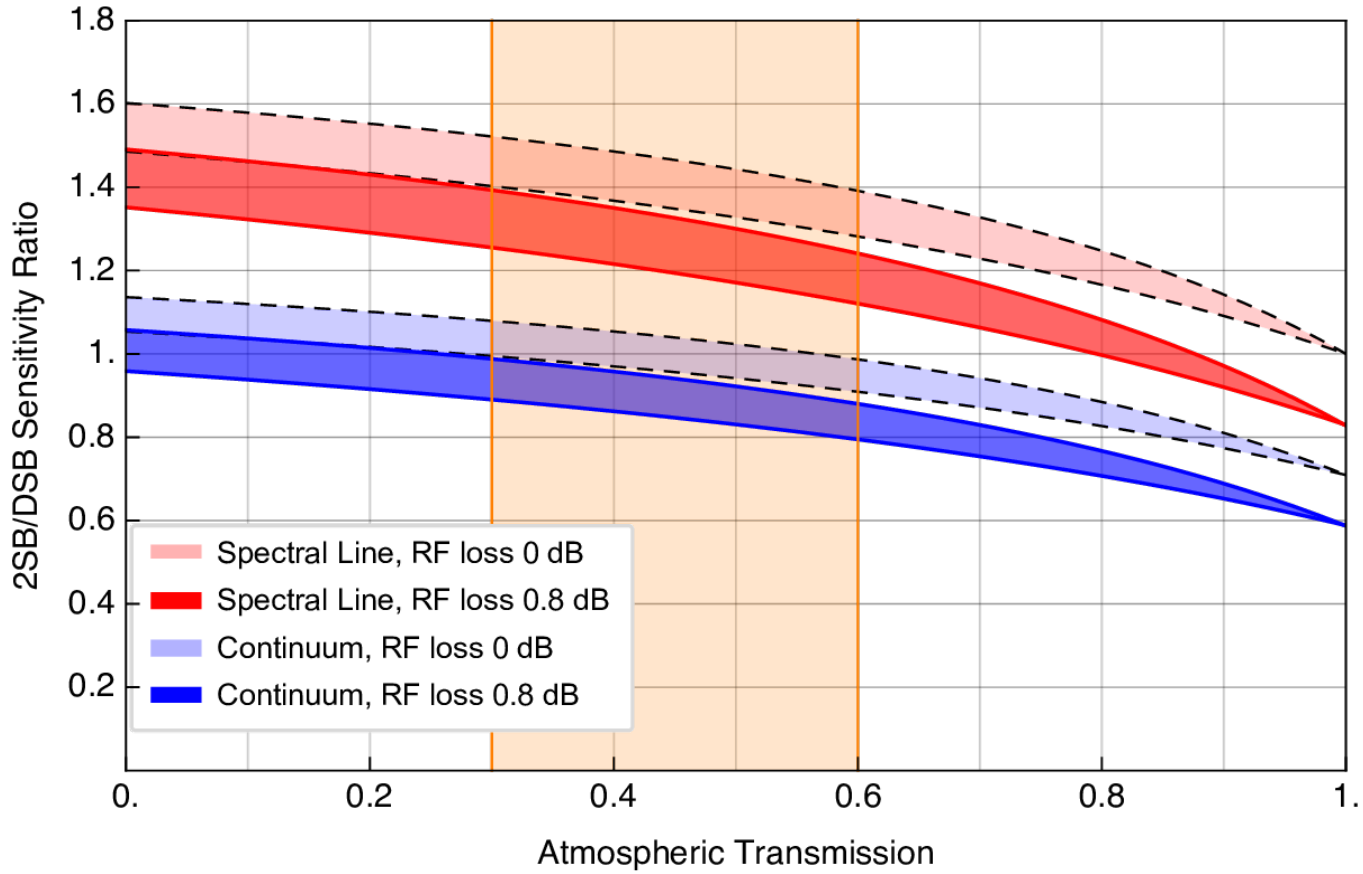

Project Overview

» Full 2SB Receiver Upgrade for ALMA Band 9: Implementation Study

- Study within the framework of the ESO *Advanced Study for Upgrades of the Atacama Large Millimeter/submillimeter Array (ALMA)* (CFP/ESO/16/11115/OSZ)
- Feasibility study performed by the Sub-mm Instrumentation Group at the University of Groningen
  (R.Hesper, A. Barychev, J. Barkhof, S. Realini)

» Main objectives

- Extending the IF bandwidth to at least 12 GHz (2 sidebands & 2 polarizations)
- Extending the RF bandwidth beyond the nominal 602-720 GHz
- Investigate availability of SIS mixer devices for 2SB upgrade of all 73 ALMA Band 9 receivers
- Improving the polarimetric performance

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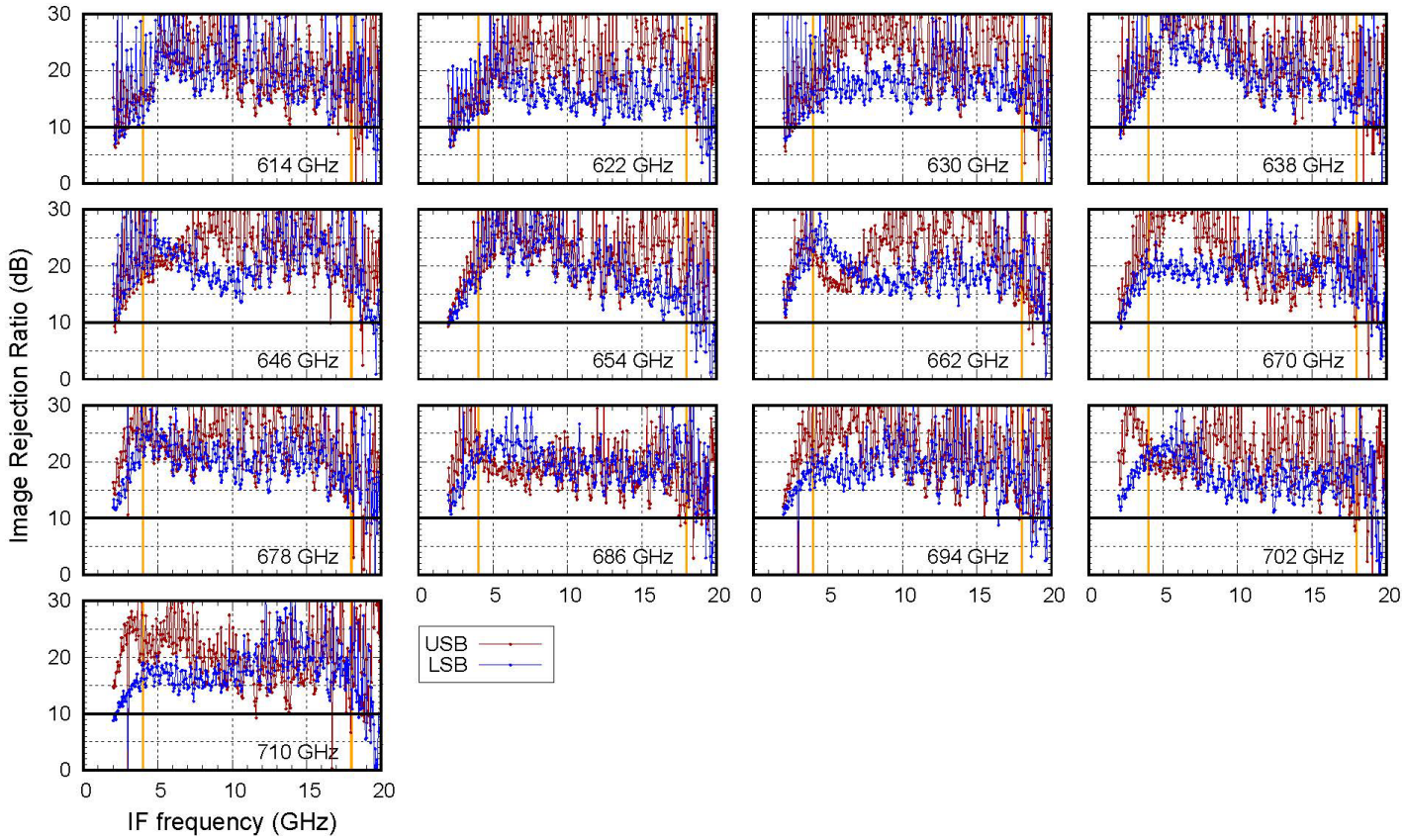
Extension of the IF Bandwidth

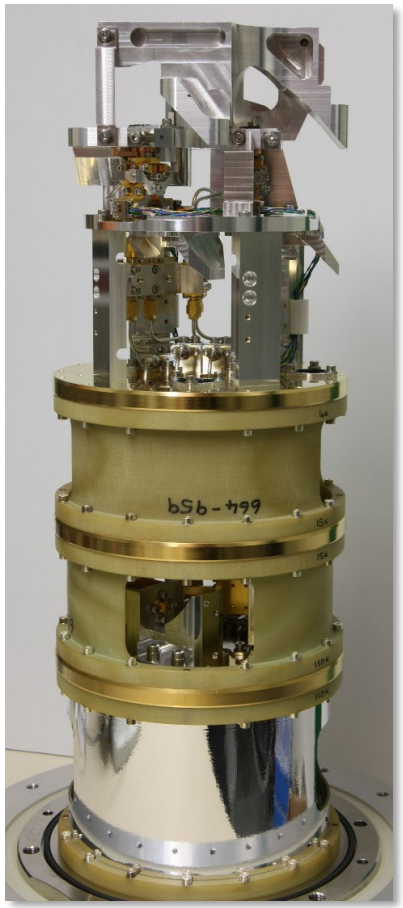
- Technical challenges to go beyond 4-12 GHz:
  - Bandwidth of the mixer devices
  - Cryogenic IF LNAs and hybrid ⟶ Collaboration with Observatorio Astronómico de Yebes, Spain

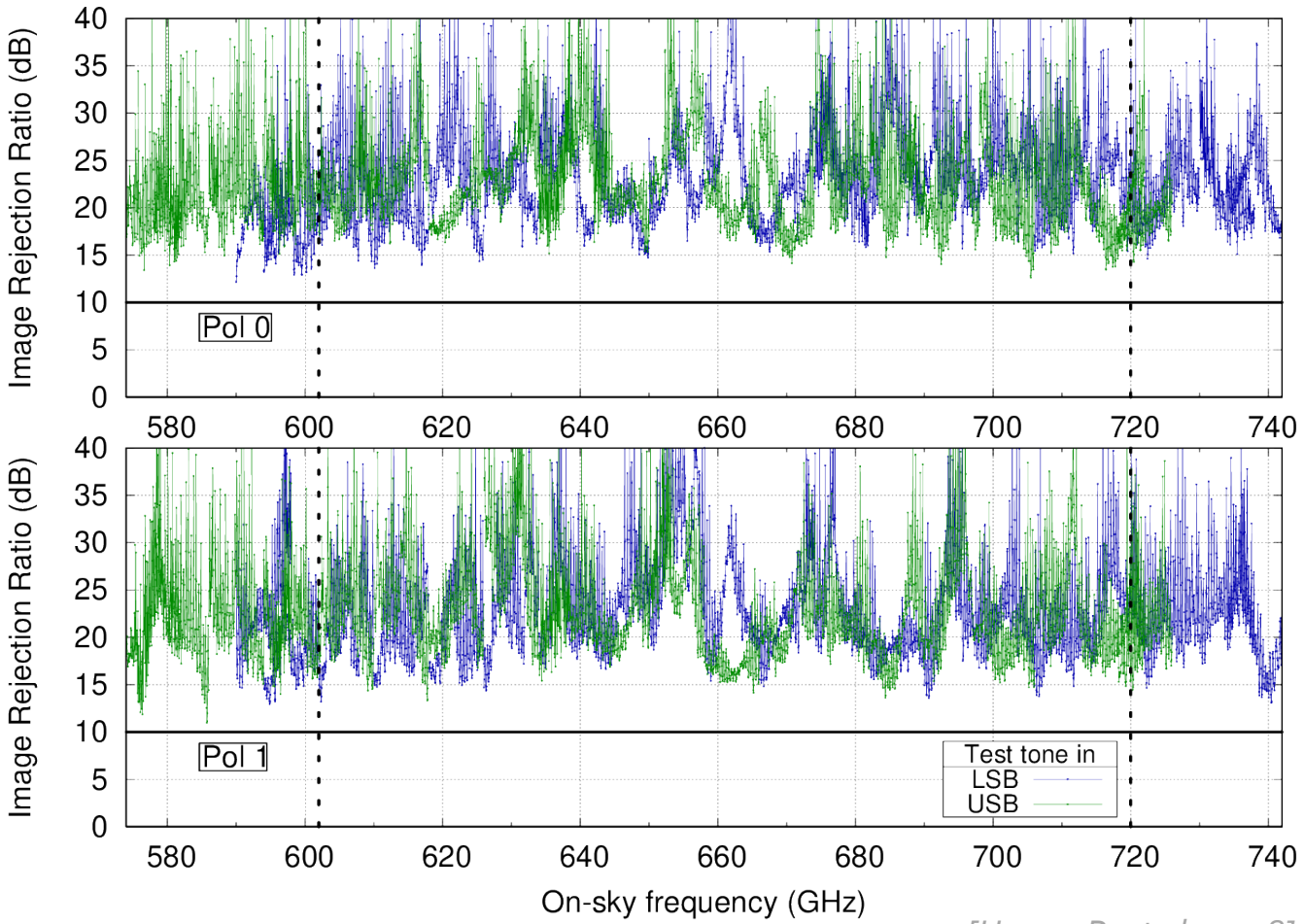


- Test performed over the IF band
  - Image rejection ratio (IRR)
  - Noise temperature.
- Possible extension of the upper limit of the IF band to at least 18 GHz

Extension of the RF Bandwidth

» Demonstrated by the operational SEPIA660 receiver which has an extended RF input band of 580–735 GHz





[Hesper R. et al., 2018]

Polarization Performance

- On-sky performance not optimal for extended-source polarimetry
  - Cross-polarization performance around –17 dB
  - Large beam squint compared to OMT-based bands

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» Science cases
  - Magnetic fields in dense environments of circumstellar envelopes around evolved stars
  - High mass star-forming regions through vibrationally excited water masers at 658 GHz
  - Study dust settling and grain growth in accretion disks around young stellar objects

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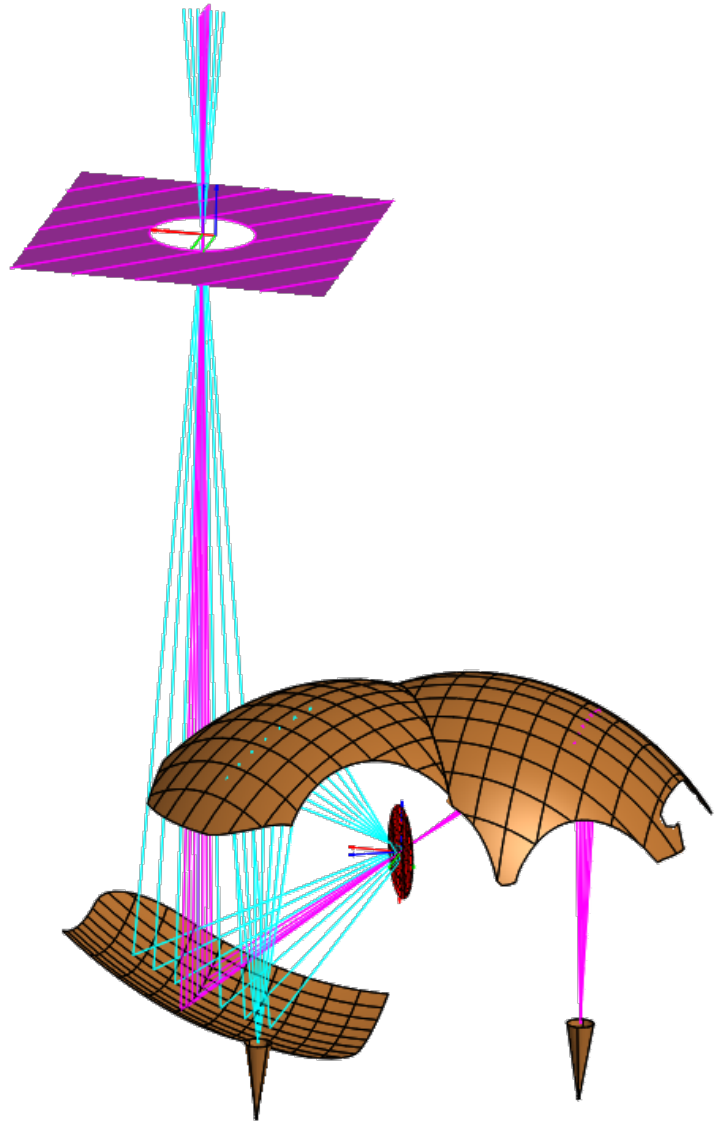
How can we improve polarimetric observations?

- Requires a major re-design
  - Evaluation of the impact of the grid on the x-pol level
  - Investigation of the possibility to use an orthomode transducer (OMT)
- Model of nominal Band 9 optics using GRASP
  - Simulation of the nominal optics
  - Comparison with measurements
  - Simulation of the optics without the grid

The Optics Model

- 2 feedhorns
  - Hybrid-mode horn as best approximation of the corrugated horn



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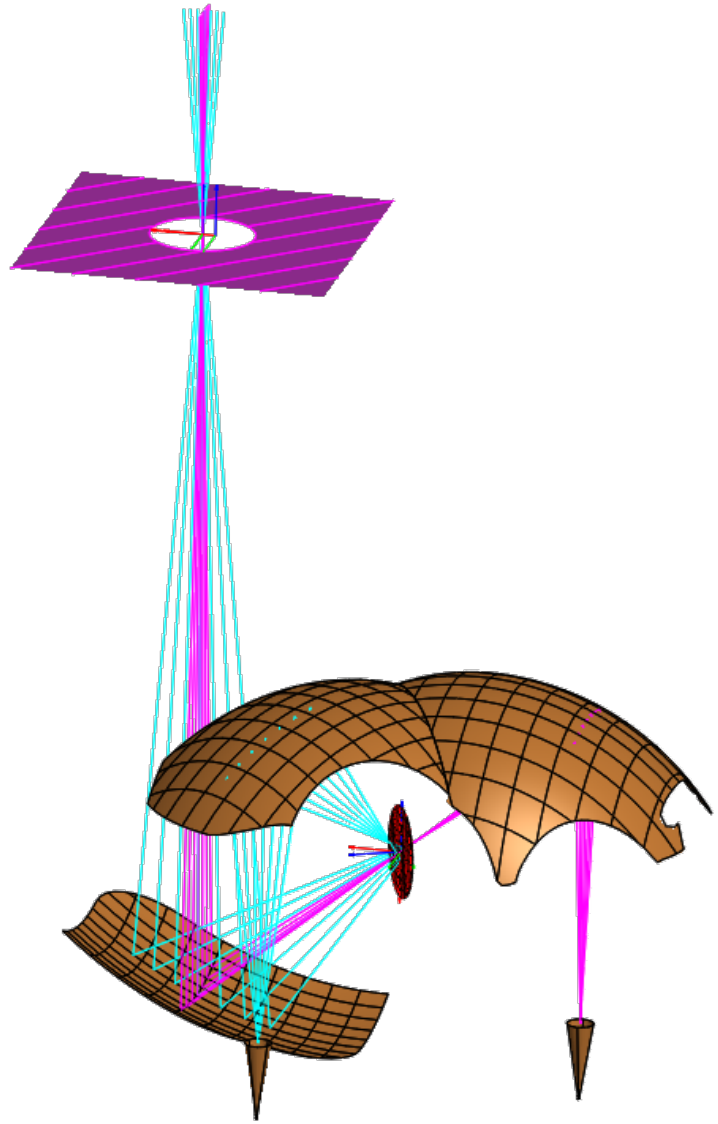

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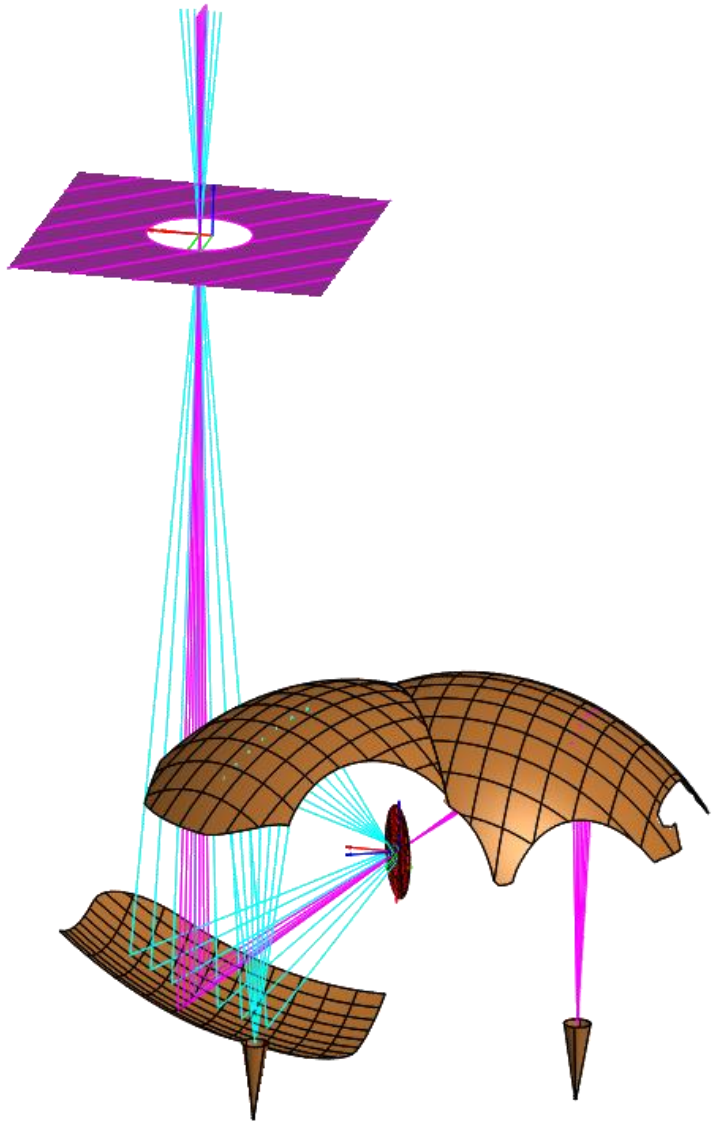
- Polarization grid
  - Grid wires are parallel to the direction of the horn axes
  - Polarization $0P$ is the reflected component (blue)
  - Polarization $1P$ is the component transmitted through the wire grid (pink)



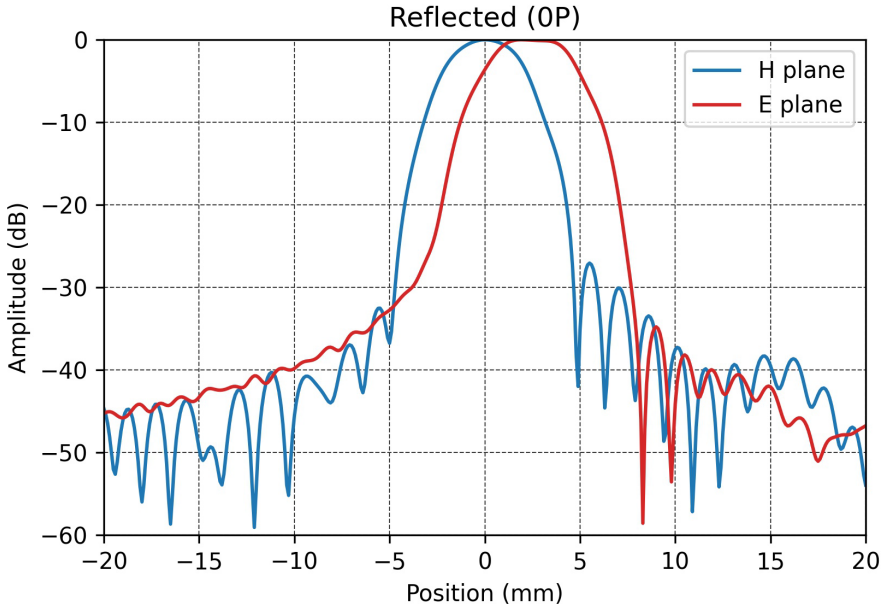
Cross-polarization Level

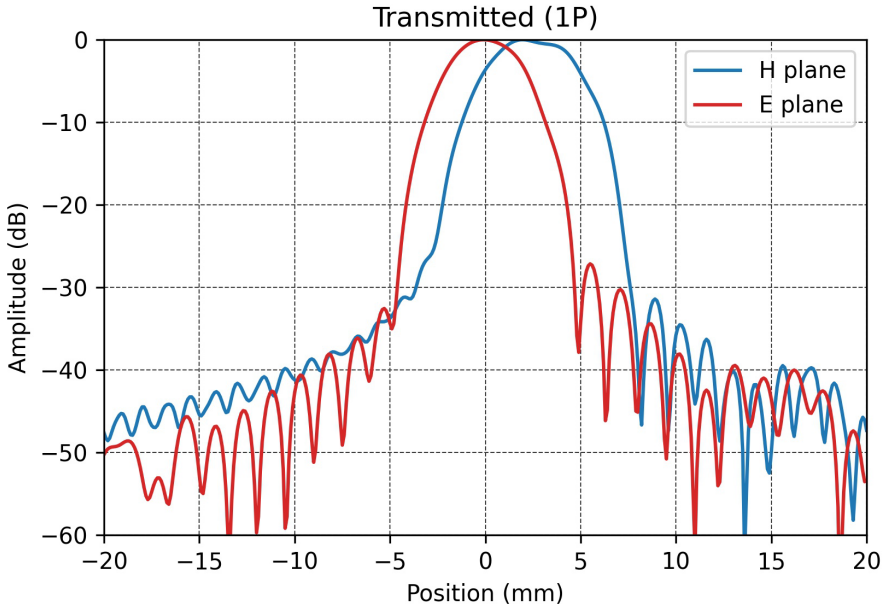
» Simulation technique: Physical Optics

- Computes the induced currents to estimate the total radiated field

» Nominal optics to determine the cross-polarization level

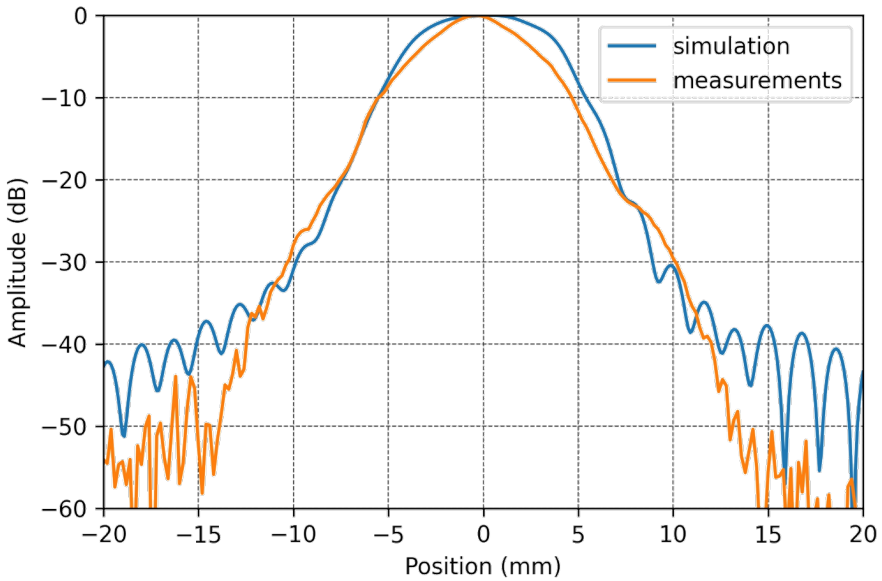
- Co-polar and cross-polar components computed in the focal plane for comparison with measurements
- Orthogonal cuts of the $0P$ (reflected) and $1P$ (transmitted) polarization in the focal plane





Cross-polarization Level

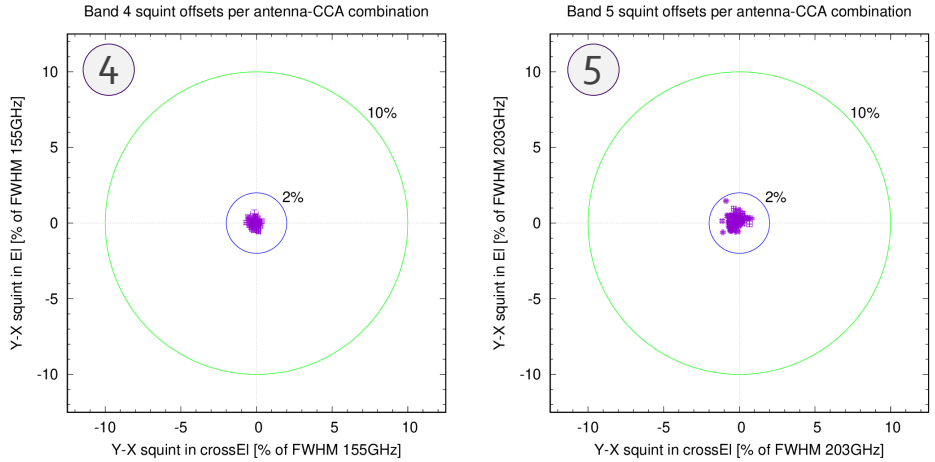
- Comparison of simulations and measurements to verify the model
  - Near field radiation patter @ 690 GHz
  - Distance of scanning plane with respect to the focal plane is not known
  - Effect filters and cryostat window
- Same integrated value of the cross-polarization: **-17 dB**
  - ALMA requirement -21 dB

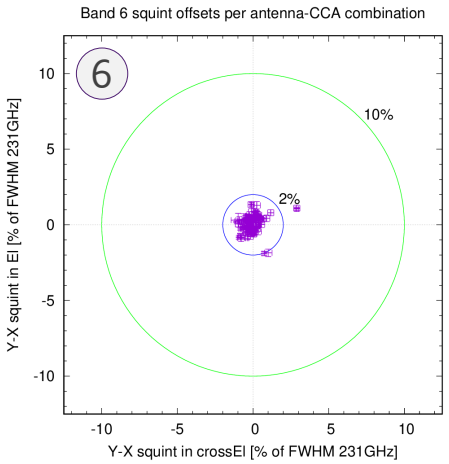


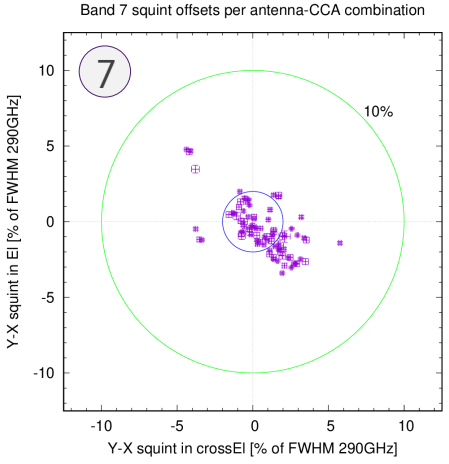
- Simulations removing the grid to get an idea of the best cross-polarization level obtainable with the existing optical assembly when reused in a single-horn configuration: **–23.8 dB**

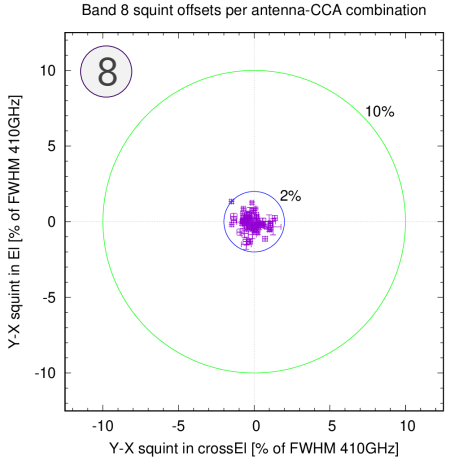
Beam Squint Analysis

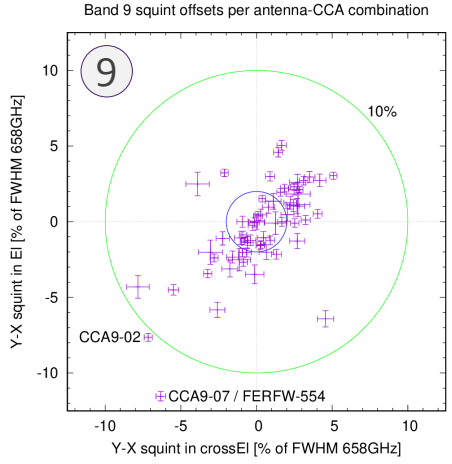
- For polarimetry, the dominating factor in grid-based bands (7, 9, 10) is the beam squint, not X-pol!
  - Misalignment of the two orthogonally polarized beams
  - The two beams follow separate paths from the grid to the feedhorn
  - Specification for ALMA is $< 10\%$ FWHM
- OMT-based (single-horn) bands perform order of magnitude better

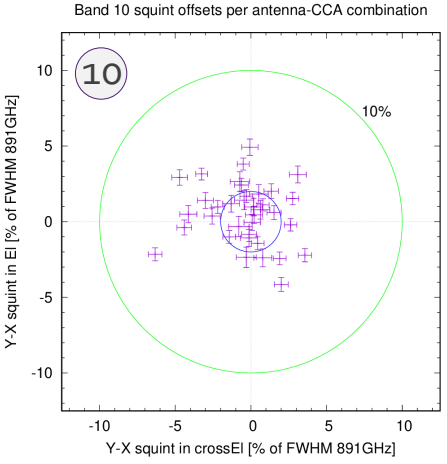








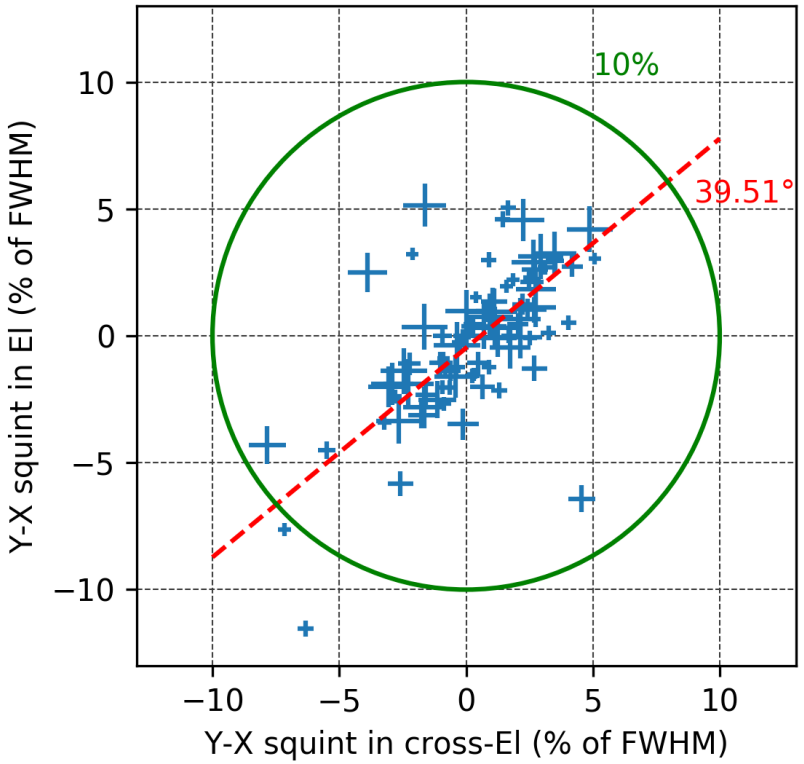




[Phillips N., 2020]

Beam Squint Analysis

» On-sky beam squint for Band 9 shows a preferred direction with an angle of ~39.5°



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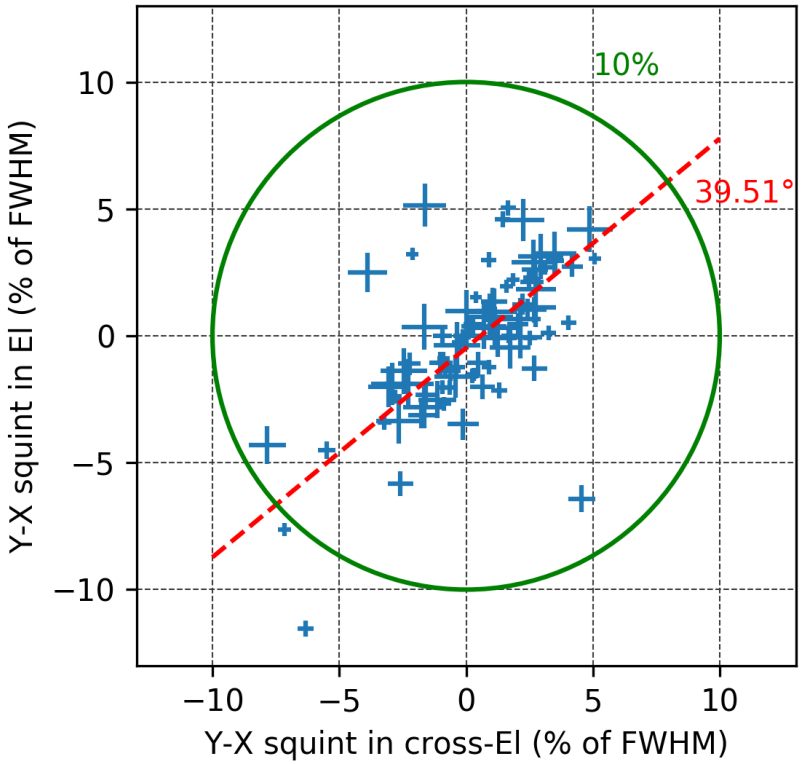

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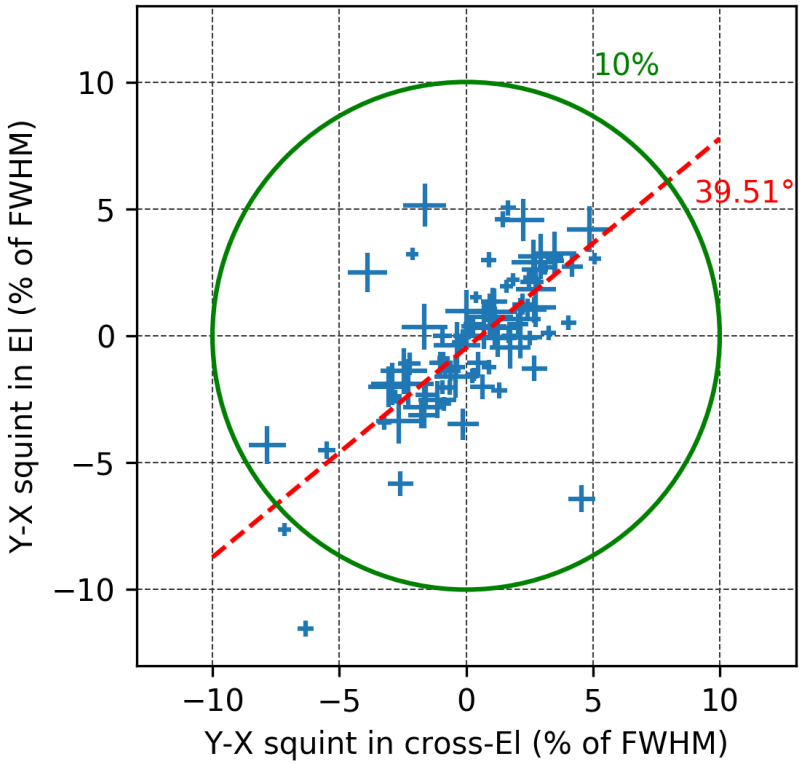

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- Reproduce the effect considering a random tilt of the grid around its x and y axes
- Two independent gaussian distributions for the tilt in the two perpendicular directions
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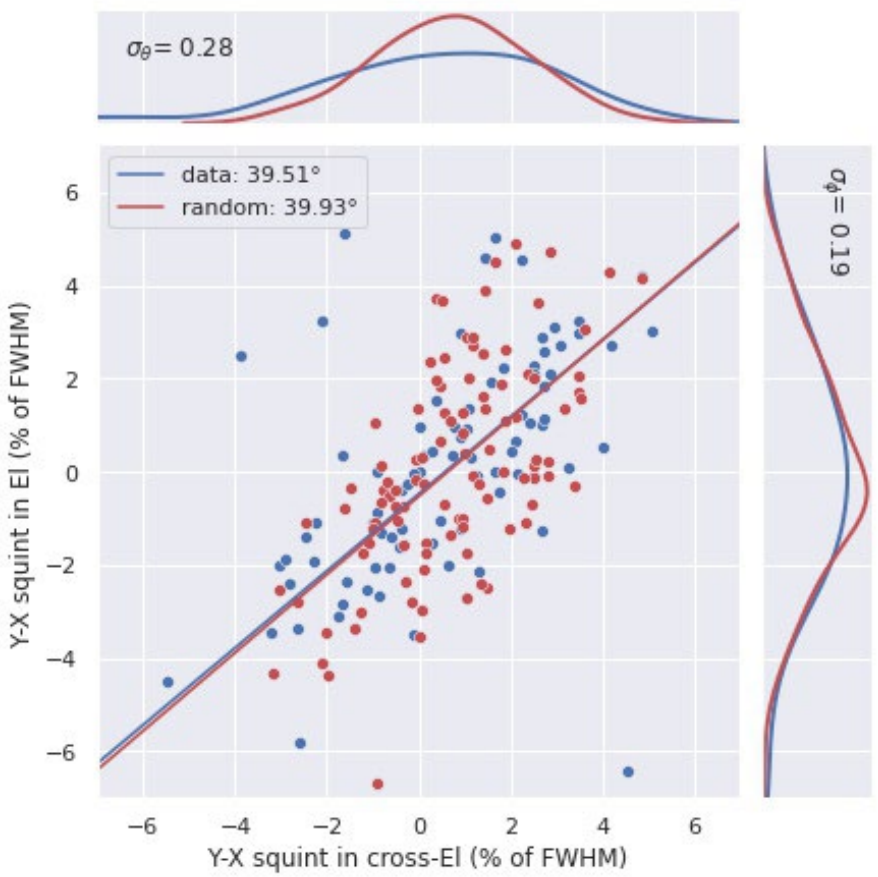

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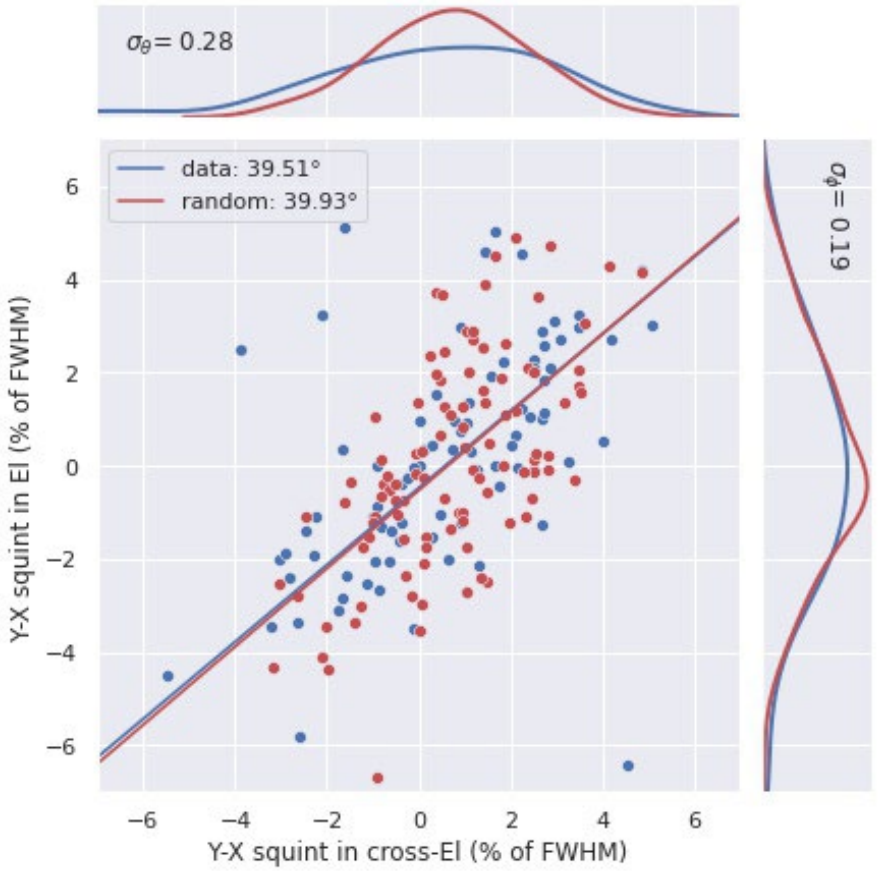

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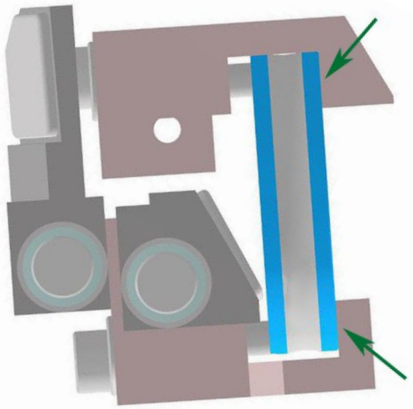
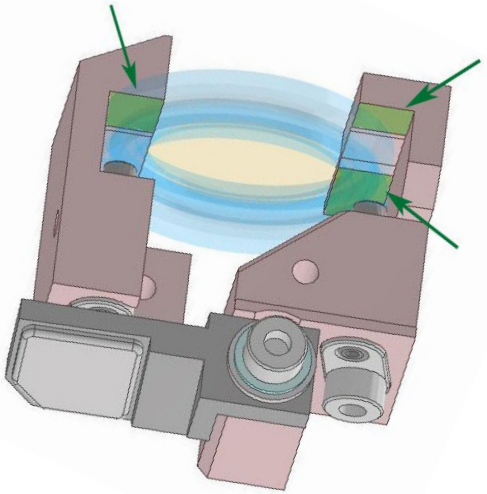
» Uncertainty in the grid foil mounting angle in its frame

» Rotation of the upper and lower mirrors blocks with respect to each other

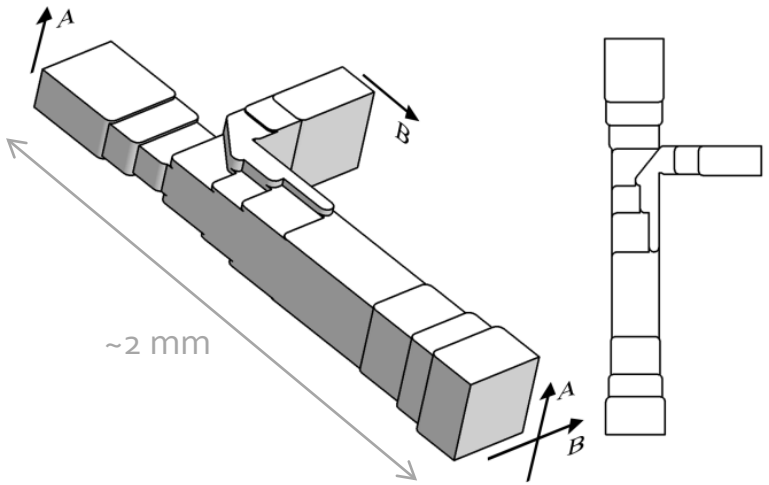
Improving Polarization Performance

» Improve alignment/flatness of the grid
  - Shimming the grid holder to achieve the beam coalignment
  - No extra losses





» Change the way in which polarization separation is performed
  - Convert the current dual-horn architecture to a single-horn one using an orthomode transducer (OMT)
  - More loss (0.4-0.5 dB ⟶ 9-13 K)
  - OMT for Band 9 is non-trivial
  - Redesign of the optics with slower mirrors and smaller bending angles



[Dunning A. et al., 2009]

Conclusion

- The Band 9 SIS mixers allow an extension of the upper limit of the IF band to at least 18 GHz
- We demonstrated 2SB operation for 4-18 GHz IF band
- Widening of the RF bandwidth to 580 – 735 GHz has already been demonstrated by SEPIA660
- A sufficient number of SIS devices for a 2SB upgrade with comparable noise performance are available
- The polarimetric performance could be improved by shimming the grids or employing an OMT-based architecture

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Proposal "Study Towards a Producible ALMA2030-Ready Band 9 CCA" just approved by ESO

Thank You

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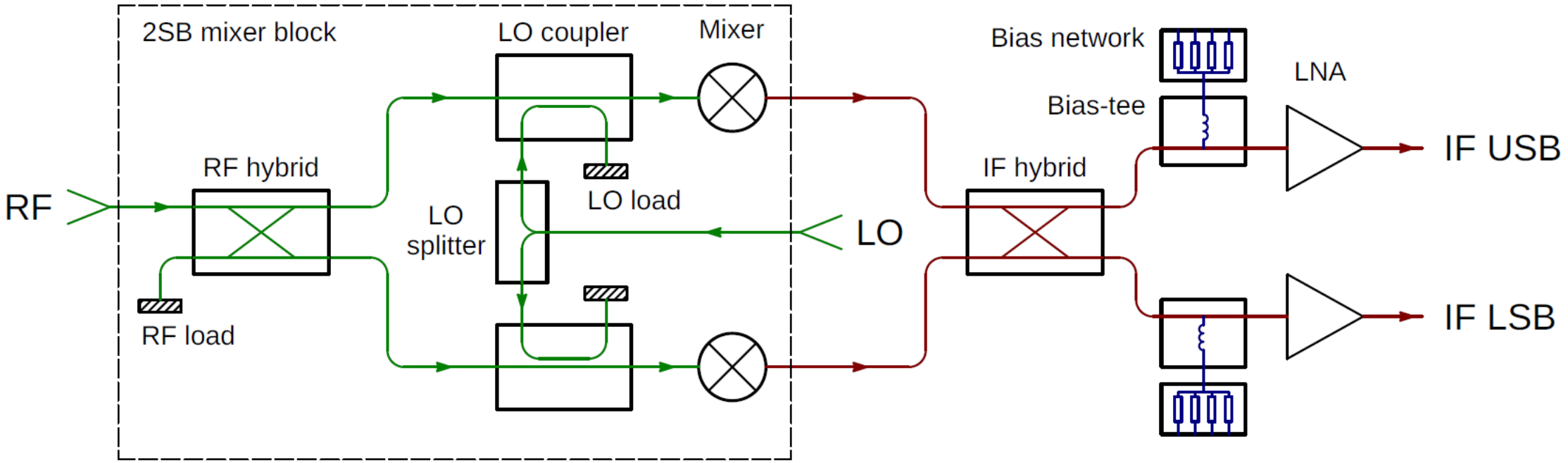
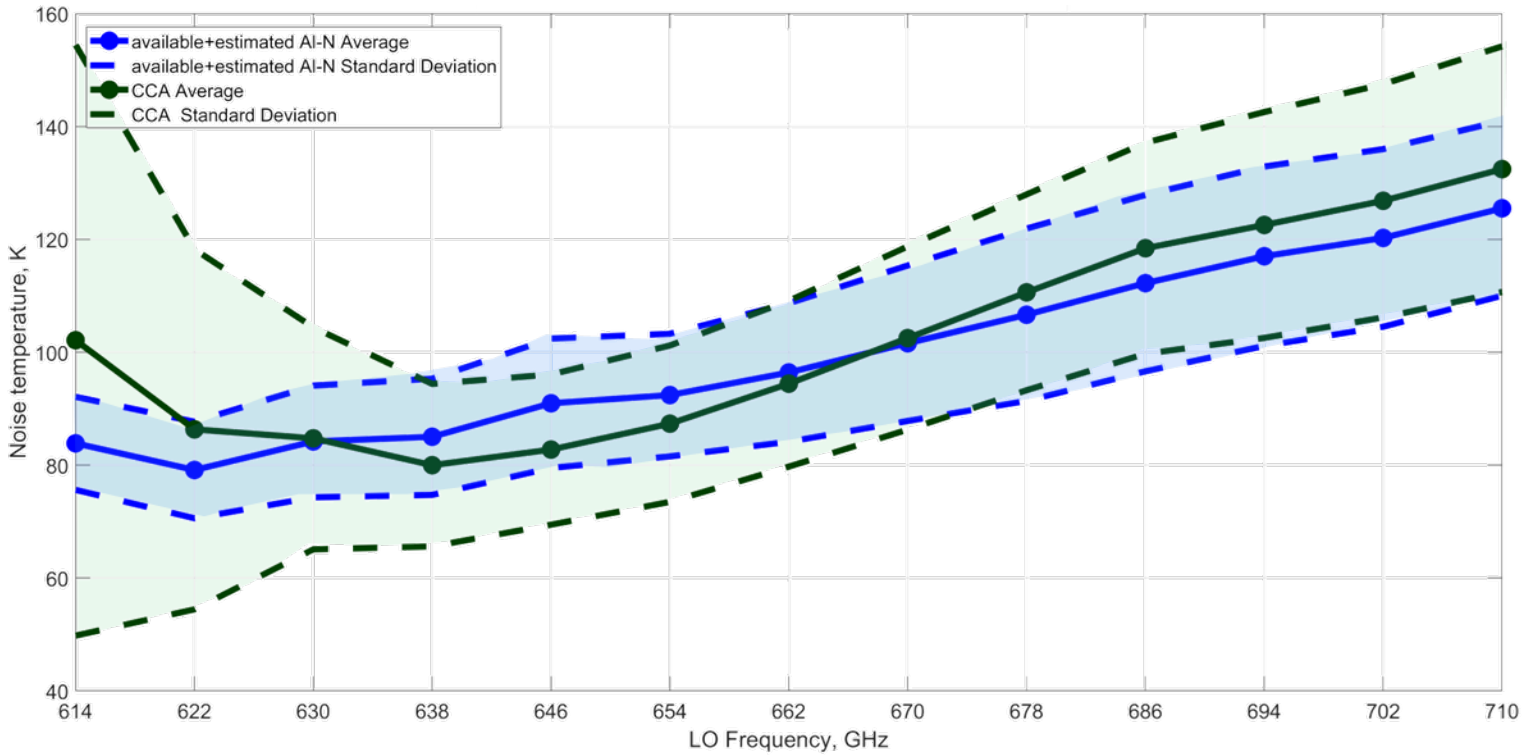
2SB Mixer Architecture



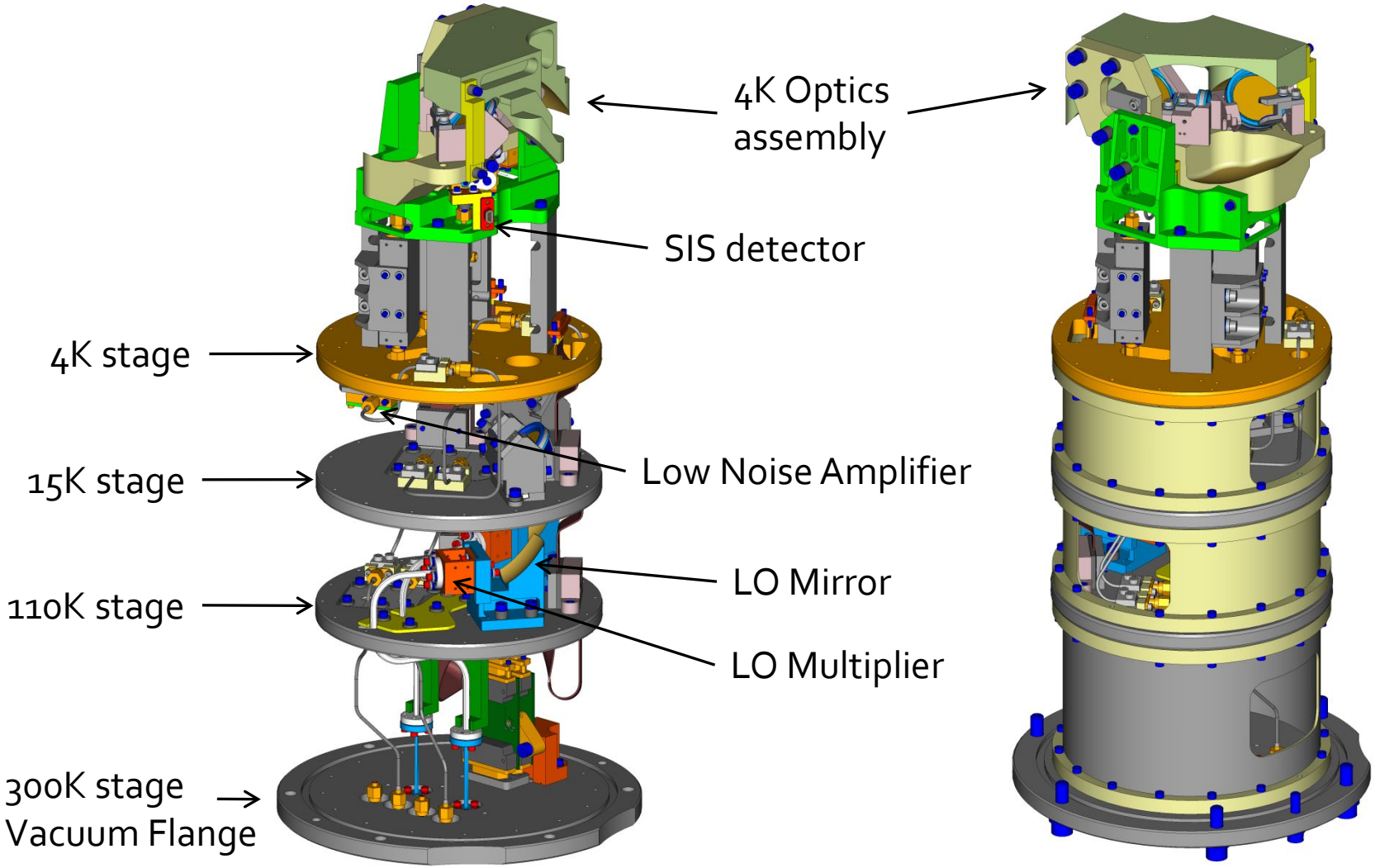
Availability of SIS Devices

» Measurement campaign & statistical survey of all existing Band 9 SIS devices (deployed, spare & left-over) to estimate number of available in-spec devices



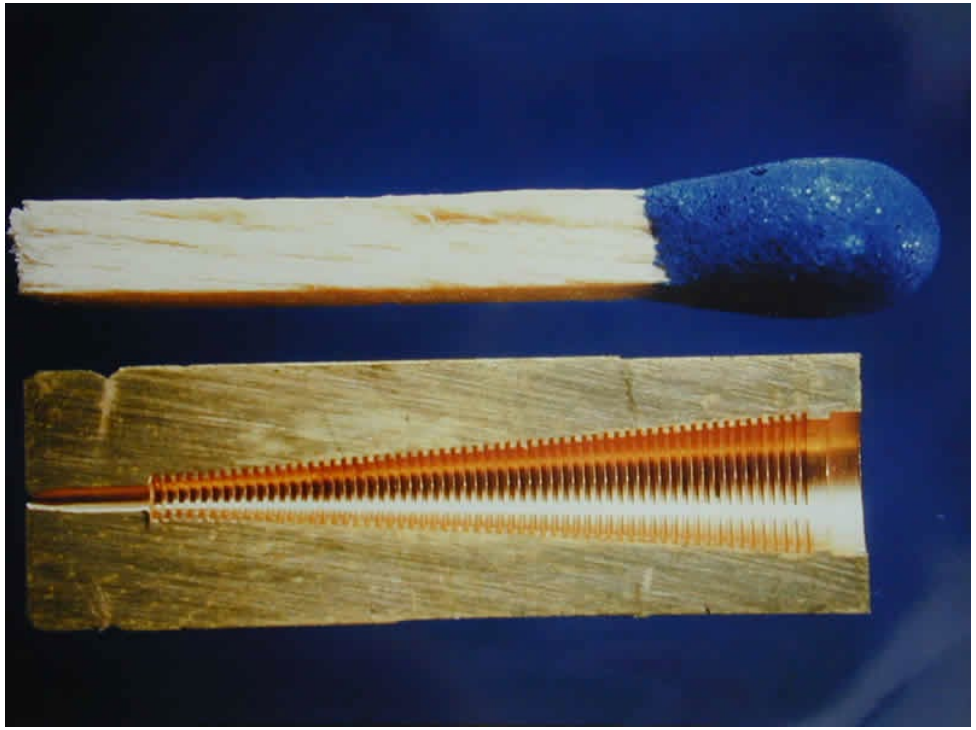
» A sufficient number of good devices is available, even for a small overall improvement of the array's sensitivity

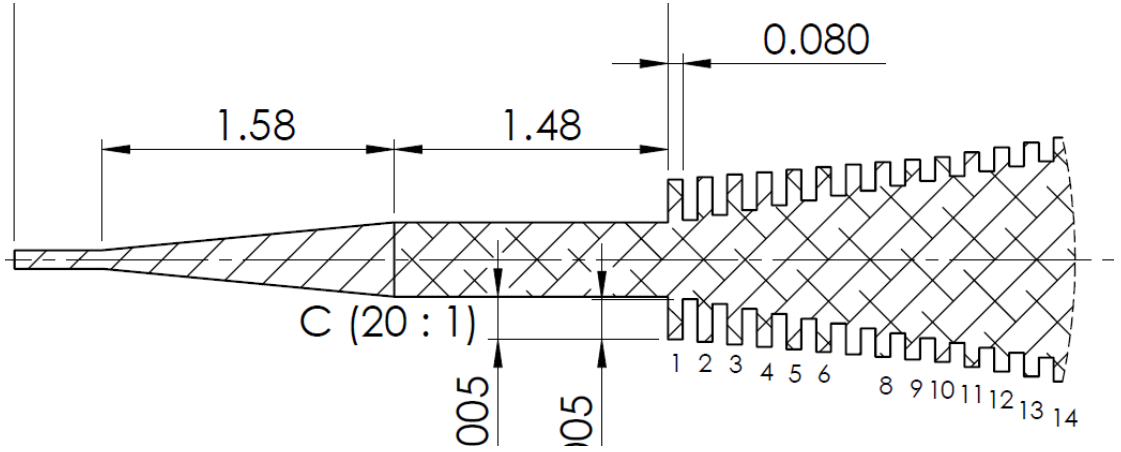
Cartridge Components



Corrugated Horn

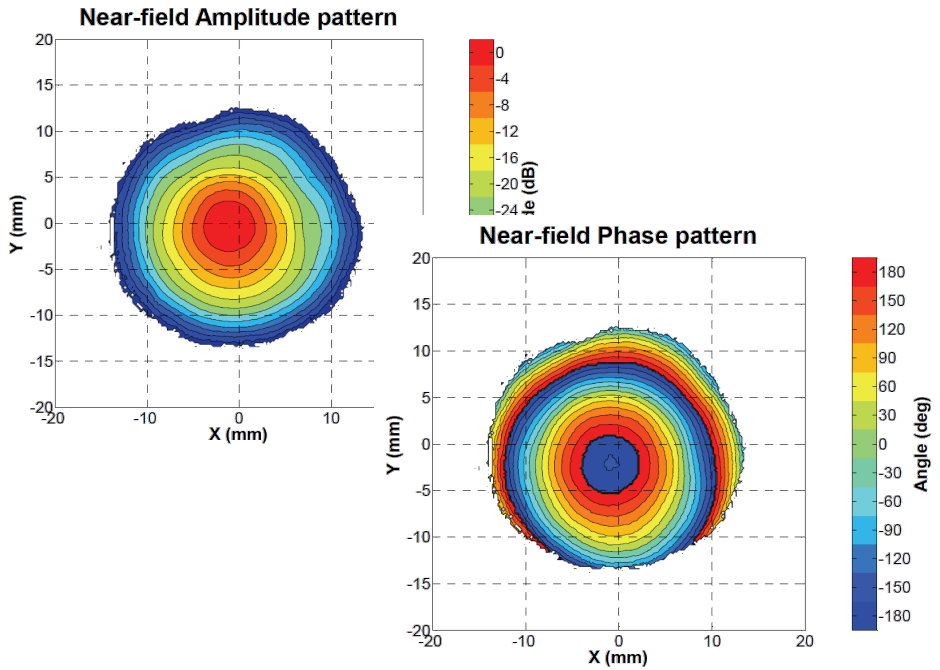
» 90 corrugations with 0.08 mm thickness

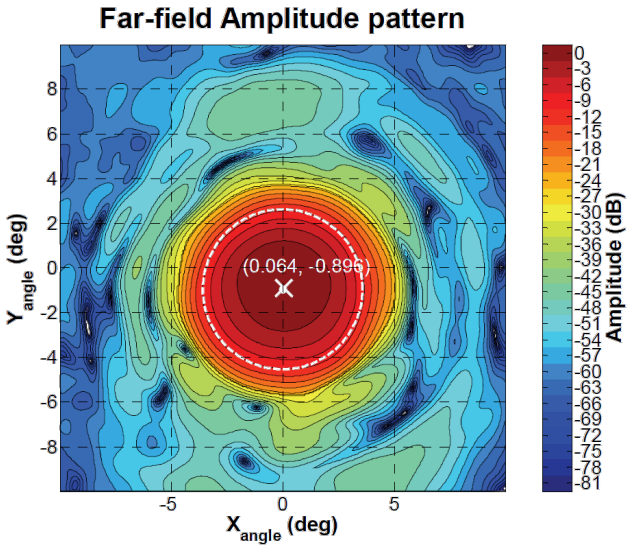




The Receiver: Testing

- Every fabricated receiver tested by the NOVA group at the University of Groningen
- Heterodyne sensitivity, gain compression, output power and signal path phase stability, aperture and polarization efficiency and antenna beam pattern





[Barkhof J., 2009]

The Optics Model

- 2 feedhorns
  - Hybrid-mode feedhorn as best approximation of the corrugated feedhorn