Development of Conical Calibration Targets for ALMA

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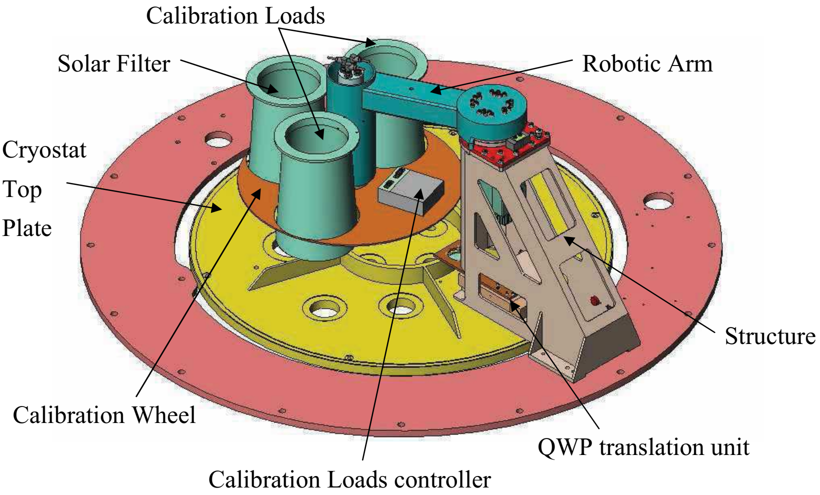
ALMA Calibration Device

Robotic arm with Ambient (ACL) and Hot Calibration Load (HCL)



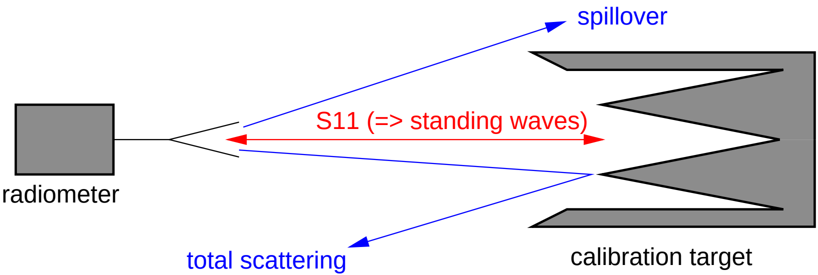
Requirements for ALMA Calibration Loads

	Ambient (ACL)	**Hot (HCL)**
Frequency	31-950 GHz	84-950 GHz
Accuracy	$\pm$0.3 K	$\pm$0.7 K (@70°C)

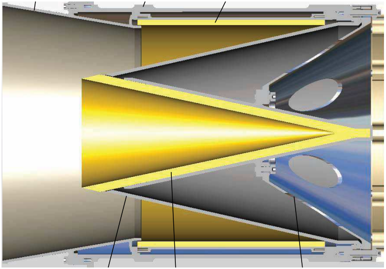
Physical	$\varnothing$200mm, L$<$290mm, mass$<$ 5kg
Emissivity	0.998 (goal 0.999)
Coherent S11	$\leq$ -55 dB (goal)

Radiometric Errors

- Temperature gradients $\Rightarrow$ calibration bias
- Total scattering + spillover $\Rightarrow$ emissivity<1 $\Rightarrow$ calibration bias
- Coherent S11 $\Rightarrow$ standing waves

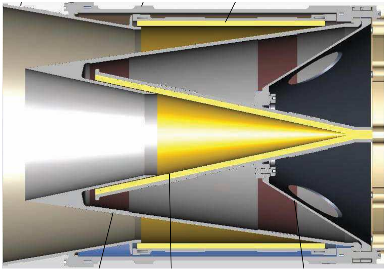


Folded Cone Geometry of ACL and HCL



ACL

- Central absorber cone
- Secondary cylindrical absorber
- Reflecting baffle to reduce spillover



HCL

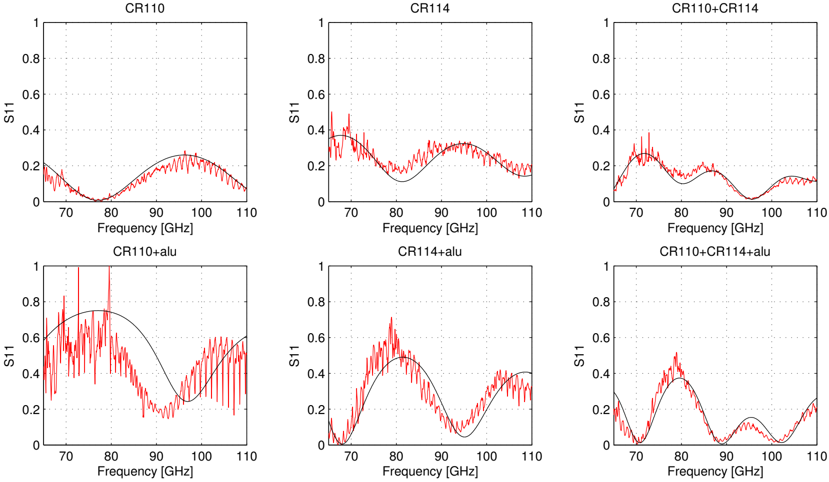
- thinner absorber layers
- additional heated reflecting shroud reduces gradients
- degraded RF performance in Band 1+2

Material Selection

- Multilayer design to improve matching
- Combination of different Emerson&Cuming absorbers: CR110, CR114 (Epoxy resin), CRS117 (Silicone based)
- Material data up to 18GHz, only limited literature data for ALMA frequency bands.
- Transmission and reflection measurements at IAP between 20–150GHz to establish realistic material parameters for target design.
- Retrieval of ε' and ε'' works well for $\nu <$60GHz where $\mu \approx 1$, but difficult at 20–40GHz where $\mu''(\nu)$ dominates the loss.

Material Measurement Examples: S11

S11 from 65-110GHz without (top) and with (bottom) Al backing.



CR110 CR114 CR110+CR114

Thickness of CR110 and CR114 multilayer can be tuned to improve matching and bandwidth

Ray Tracing Model for Conical Target

- Incident plane wave leaves the cone after $N = 180/\alpha$ reflections (α=cone angle)
- Reflectivity $R_n(\theta_n)$ of each reflection is calculated for local incidence angle θ_n using the layered media model.
- Total reflectivity is the product $R_{total} = \prod_{n=1}^{N} R_n(\theta_n)$
- Different for TE and TM polarization (average used)
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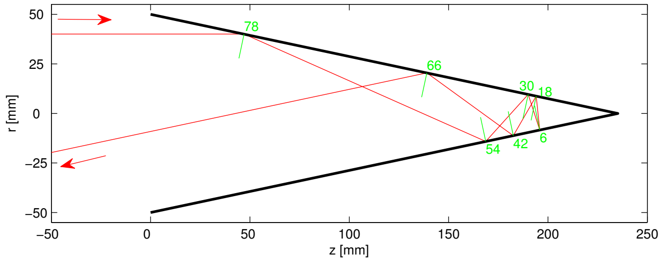

Cone geometry with $\alpha = 12^\circ \Rightarrow N = 7.5$

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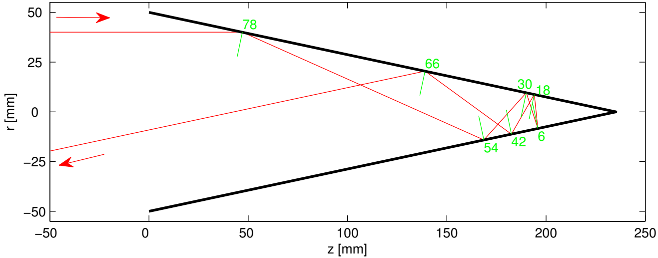
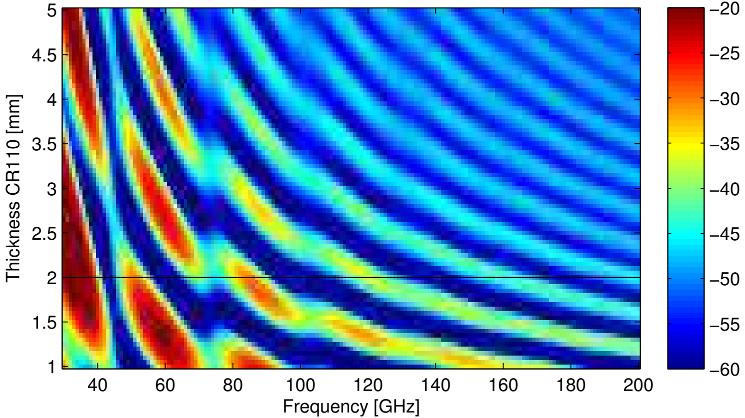
- Total reflectivity is the product $R_{total} = \prod_{n=1}^{N} R_n(\theta_n)$
- Different for TE and TM polarization (average used)
- Effects of the rim and the tip of the cone are neglected!



Cone geometry with $\alpha = 12^\circ \Rightarrow N = 7.5$

Multilayer Optimization

- Different composition for ACL and HCL
- Parametric raytracing study to tune the layers
- Example of a 0–5mm CR110 cone on 1.5mm CR114 backing.



Backscatter Test Setup

- S11 measurement with an ABmm VNA
- Directional coupler and ALMA feeds for Band 1+2, quasi-optics above.
- Test object measured at different distances d to calibrate directivity of the test setup
  $\Rightarrow$ phase changes, fit of a circle to the complex data
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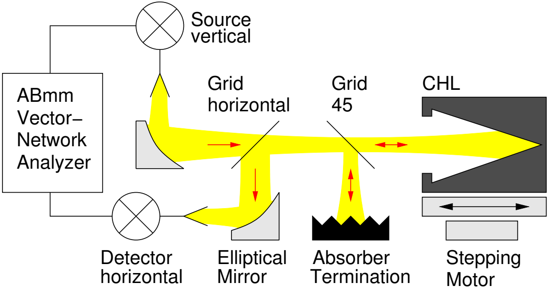

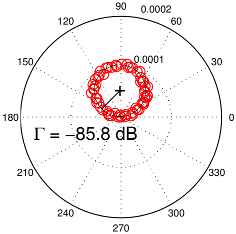

Backscatter Test Setup

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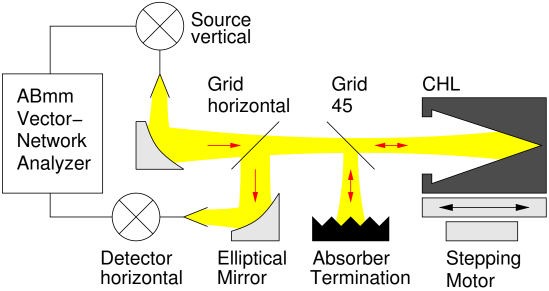
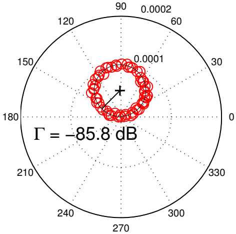
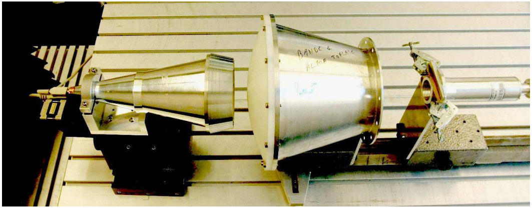
- Directional coupler and ALMA feeds for Band 1+2, quasi-optics above.
- Test object measured at different distances *d* to calibrate directivity of the test setup
  $\Rightarrow$ phase changes, fit of a circle to the complex data
- Determines coherent S11, not total scattering!

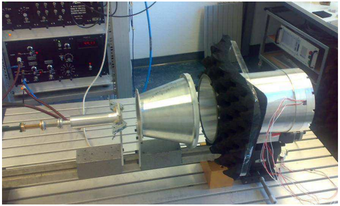


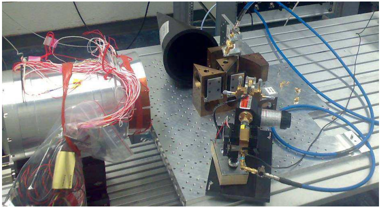


Backscatter Test Setup



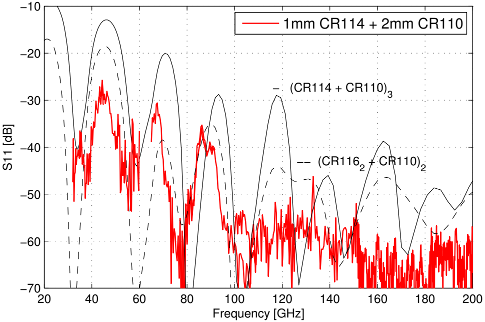
Experimental setup for isolated cone prototypes
⇒ no interferences from secondary absorber or reflector.



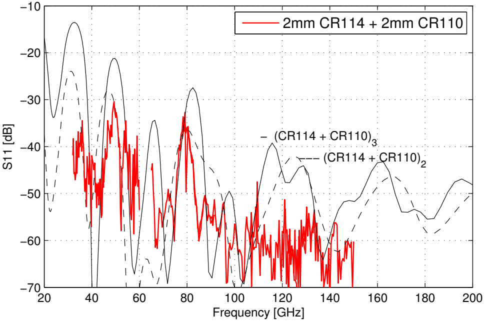


Experimental setup with ACL and HCL in Band 1 and 4

S11 Measurement Results



1mm CR114 +
2mm CR110

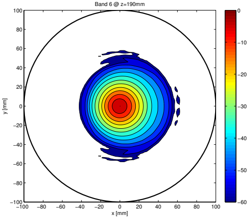


2mm CR114 +
2mm CR110

GRASP Spillover Analysis

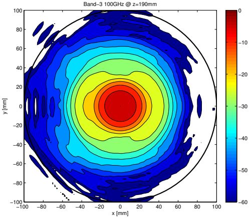
- GRASP model of all ALMA receivers provided by Ticra
- Simulation of the near field at the apertures of the target and the central cone ⇒ estimate of the coupling efficiency η_c into central cone
- GRASP simulation of S11 requires MoM addon from Ticra

Band 6



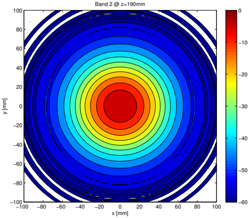
$\eta_c > 99.9\%$

Band 3



$\eta_c > 99\%$

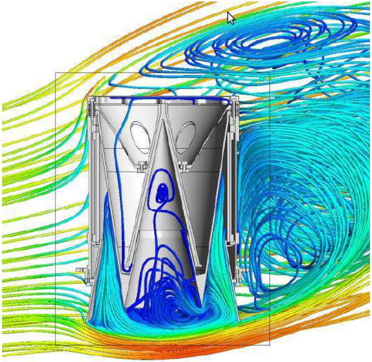
Band 2

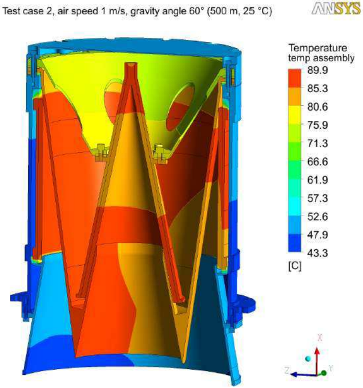


$\eta_c > 97\%$

Thermal Simulations

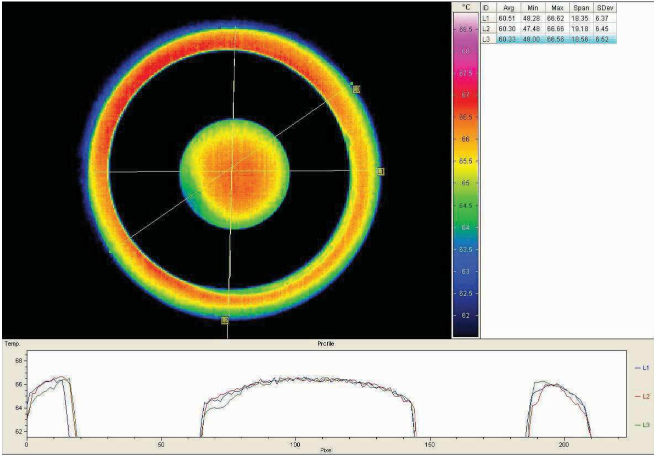
- Finite Elements and Computational Fluid Dynamics simulations by CADFEM Gmbh
- Thermal gradients simulated for different conditions: wind speed, orientation, temperatures, air pressure, ...





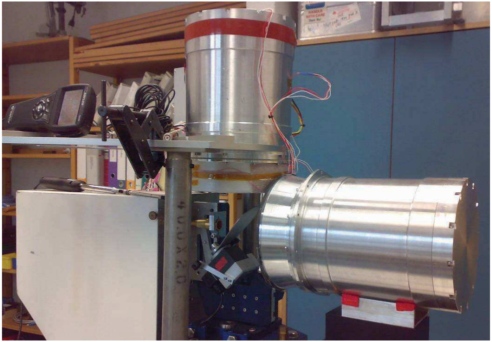
Measured Temperature Gradients

- HCL temperature gradients observed with IR Camera
- Example at 70°C set temperature 60° elevation ⇒ ∼1K surface temperature gradient across the aperture
- Additional PT100 sensors to verify thermal simulations



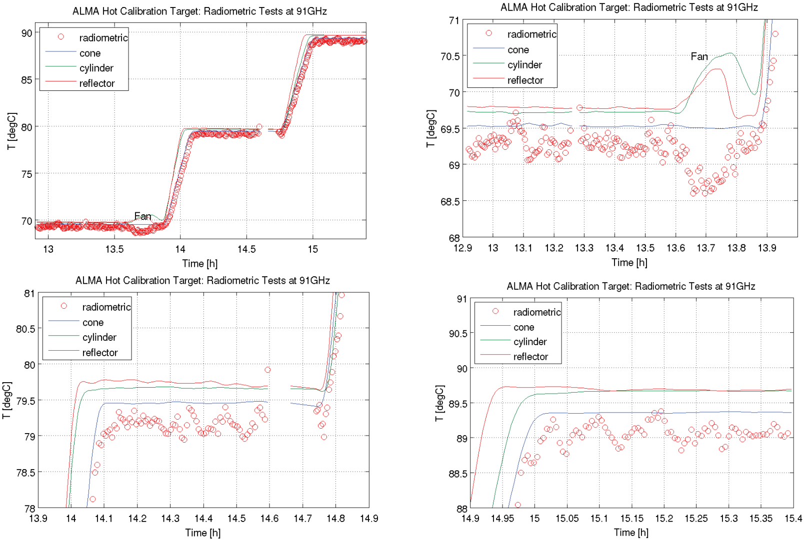
Radiometric Test with 91GHz Radiometer

- Calibration with external switching mirror between HCL (vertical) and ACL (horizontal).
- Internal noise diodes as additional calibration standards (calibrated against external LN2 target)



Radiometric Test Results

- Comparison HCL radiometric and physical temperature



Radiometric Test Results

- Radiometric bias between -0.3K and -0.5 to -0.7K
- Additional -0.5 K cooling by 1 m/s forced airflow
- Some uncertainty from ACL, LN2 errors and noise diode drift
- Higher HCL bias expected for:
  - different orientation ($\Rightarrow$ higher convective cooling)
  - higher frequencies ($\Rightarrow$ shorter penetration depth)
- Tests with ALMA receivers at RAL FEIC are currently ongoing

Conclusions

- Conical design with multilayer absorber coating results in very low S11 and high emissivity over wide bandwidth.
- Accurate knowledge of the material parameters needed to tune the layer thickness
- Reflection measurements show good S11 performance consistent with raytracing model, issues remain from HCL shroud in Bands 1+2.
- Extensive thermal simulations and tests have been done, temperature gradients are the dominant error source for HCL.