COSMO

(COSmic Monopole Observer)

Silvia Masi for the COSMO collaboration*

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https://cosmo.roma1.infn.it

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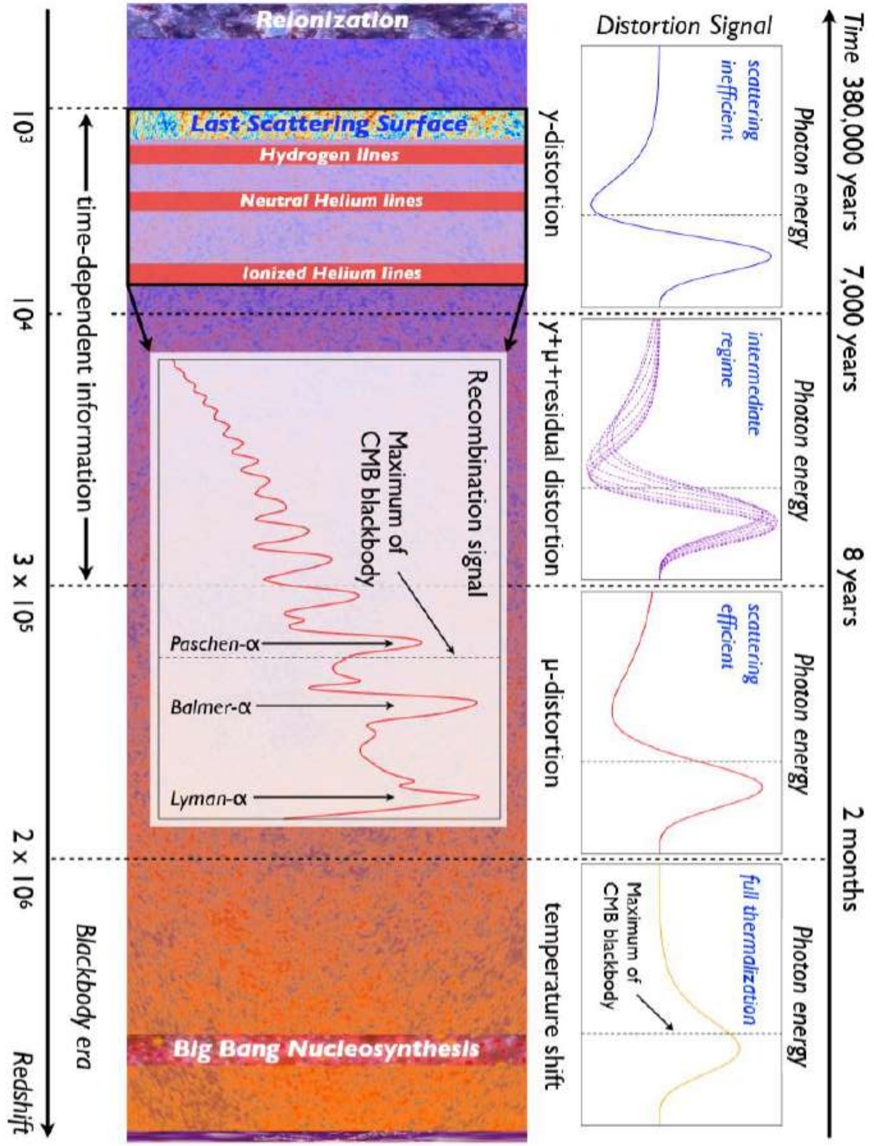
Programmi di Ricerca Scientifica di Rilevante Interesse Nazionale
PROGRAMMA NAZIONALE DI RICERCHE IN ANTARTIDE
ITALIANTARTIDE

Spectral Distortions of the CMB

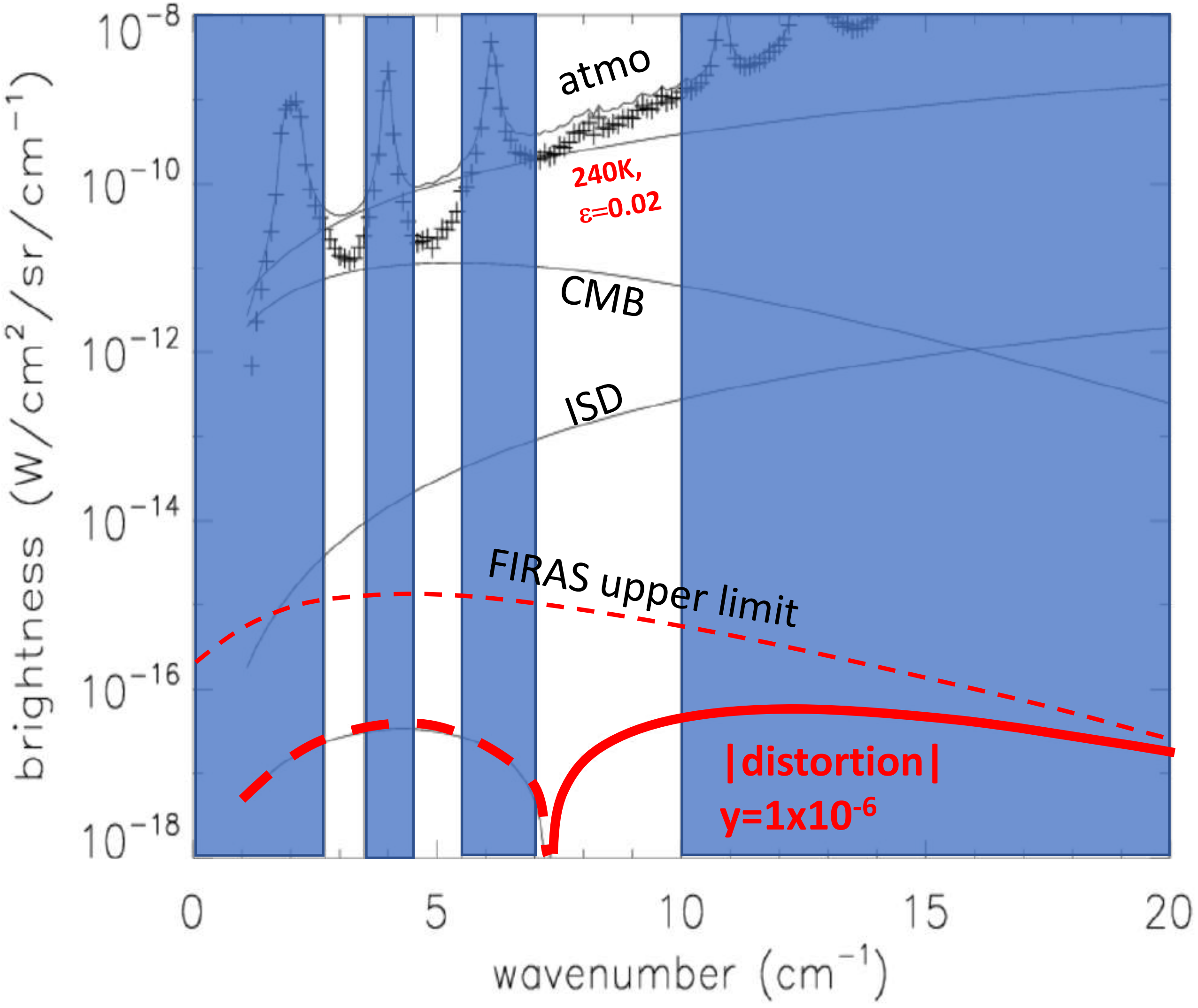
- CMB Spectral Distortions represent a research path orthogonal and synergic to CMB polarization studies.
- Promising to shed light on:
  - Cosmic Reionization
  - Physicws of recombination
  - Dark matter & Energy releases in the primeval fireball
  - Very Early Universe and Cosmic Inflation
  - … much more
- Current upper limits for spectral distortions are at a level of 0.01% of the peak brightness of the CMB [COBE – FIRAS:, Mather et al. (1990) Ap.J.L. **354** 37, Fixsen et al. (1996) Ap.J. **473** 576)] >20 years ago !
- The final measurement must be carried out from space. PIXIE, CORE, PRISTINE proposals not selected yet.
- Meanwhile, ground and near-space efforts are useful to test and refine methods, and possibly to detect the largest distortions.
- Here we focus on ***COSMO***, **a *staged* effort (Dome-C first, then stratospheric balloon) funded by the Italian national programs PRIN and PNRA** .



Chluba et al. 2019

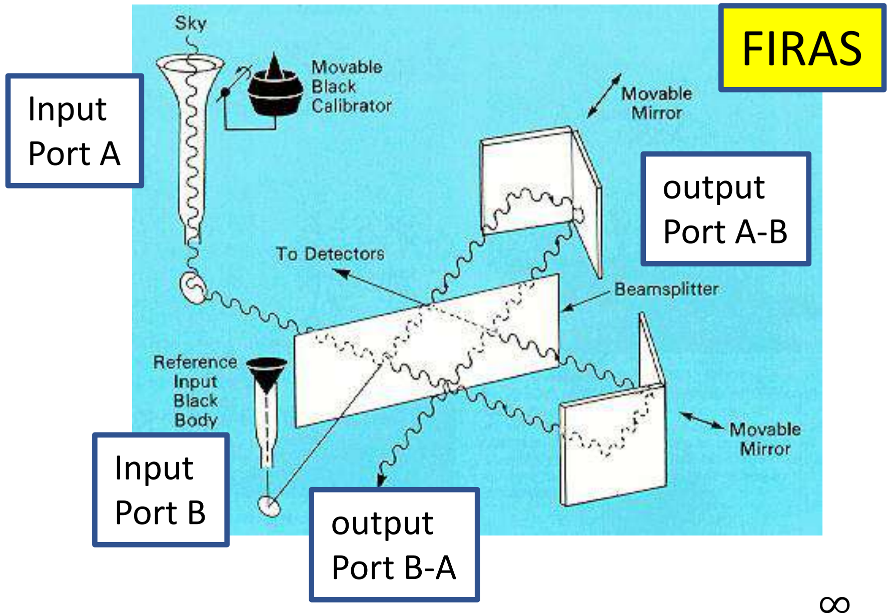
The observable is small, compared to … everything.

- Distortion signals are *guaranteed to exist*, but are *very small* compared to:
  - detector noise,
  - instrument emission,
  - atmospheric emission and its fluctuations,
  - foregrounds,
  - the CMB itself.
- Intelligent measurement methods required, extraxcting a small spectral distortion from an overwhelming common-mode signal.
- Experimentalists are behind theorists here.
- **COSMO** is a pathfinder experiment, ground-based in the first implementation, and balloon-borne in its second step.
- The instrument is a cryogenic **Differential Fourier Transform Spectrometer**, comparing the sky brightness to an accurate internal blackbody.
- Let’s focus on the differences with respect to a space-borne mission, like FIRAS or PIXIE.

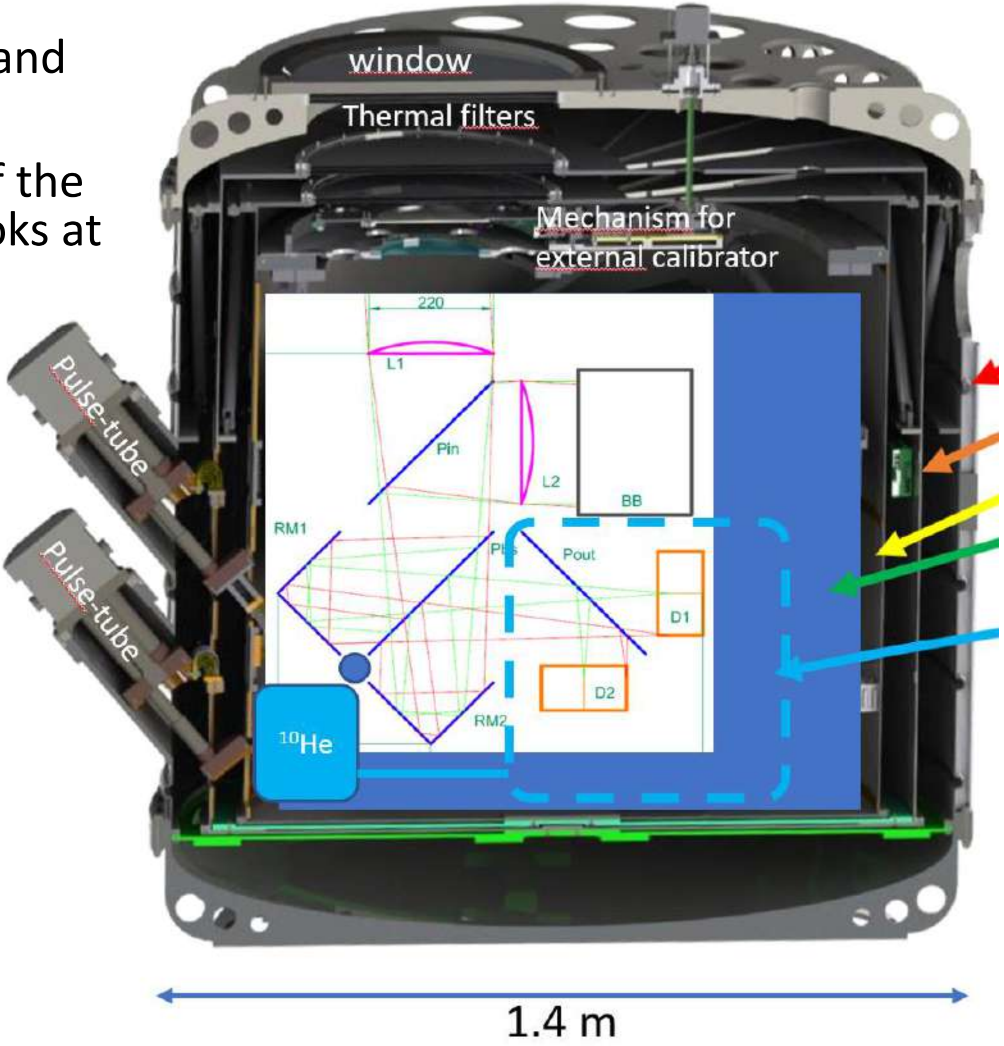


Absolute measurement approach

- The Martin-Pupplett Fourier Transform Spectrometer used un FIRAS and PIXIE has two input ports.
- The instrument is intrinsically differential, measuring the spectrum of the difference in brightness at the two input ports. Normally one port looks at the sky, the other one at an internal reference blackbody.
- For calibration, a movable blackbody fills the sky port.



COSMO



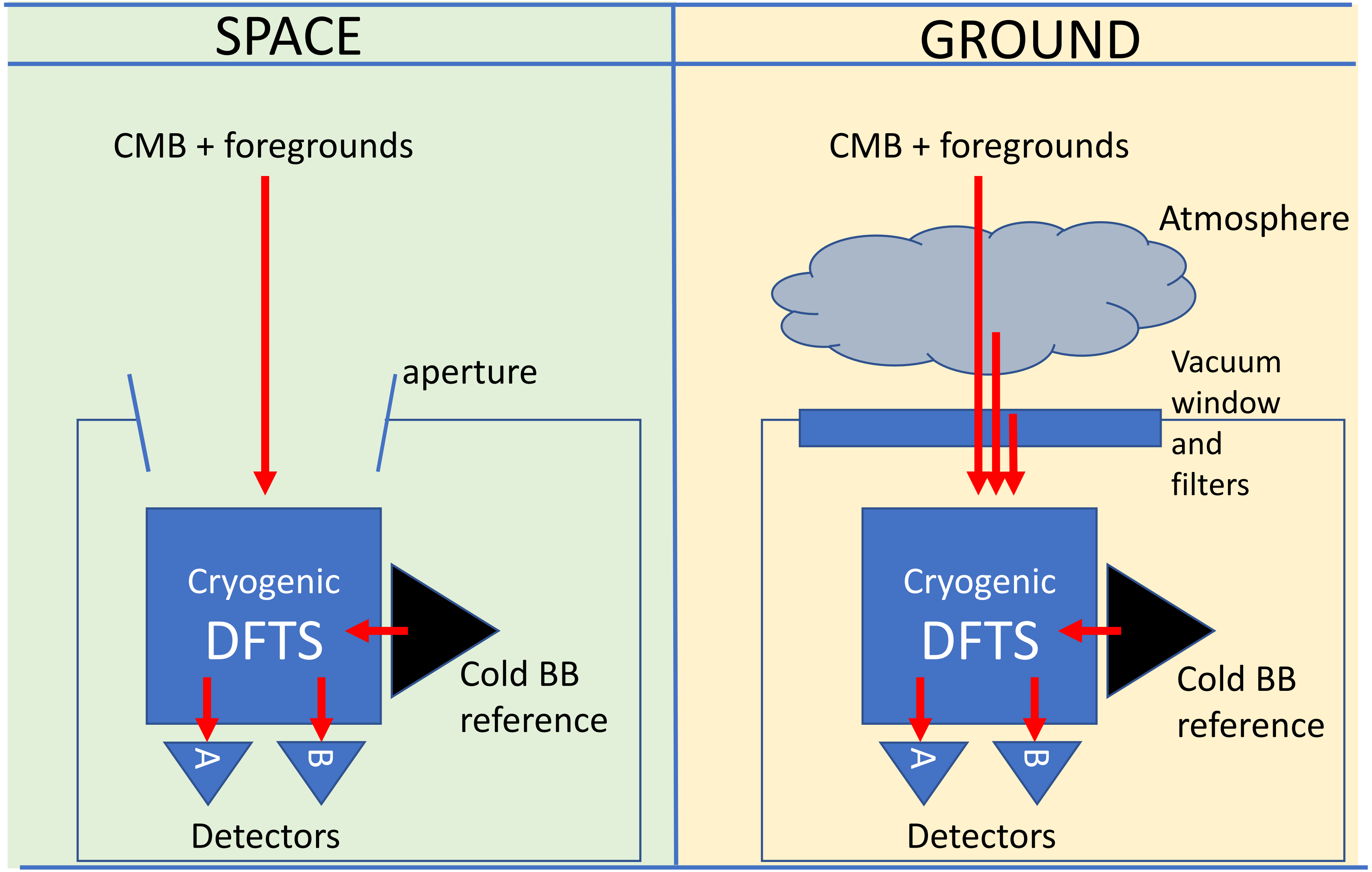
Sky measurement

$$I_{SKY}(x) = C\int_{0}^{\infty}[S_{SKY}(\sigma) - S_{REF}(\sigma)]rt(\sigma)\{1 + \cos[4\pi\sigma x]\}d\sigma$$

Calibration measurement

$$I_{CAL}(x) = C\int_{0}^{\infty}[S_{CAL}(\sigma) - S_{REF}(\sigma)]rt(\sigma)\{1 + \cos[4\pi\sigma x]\}d\sigma$$

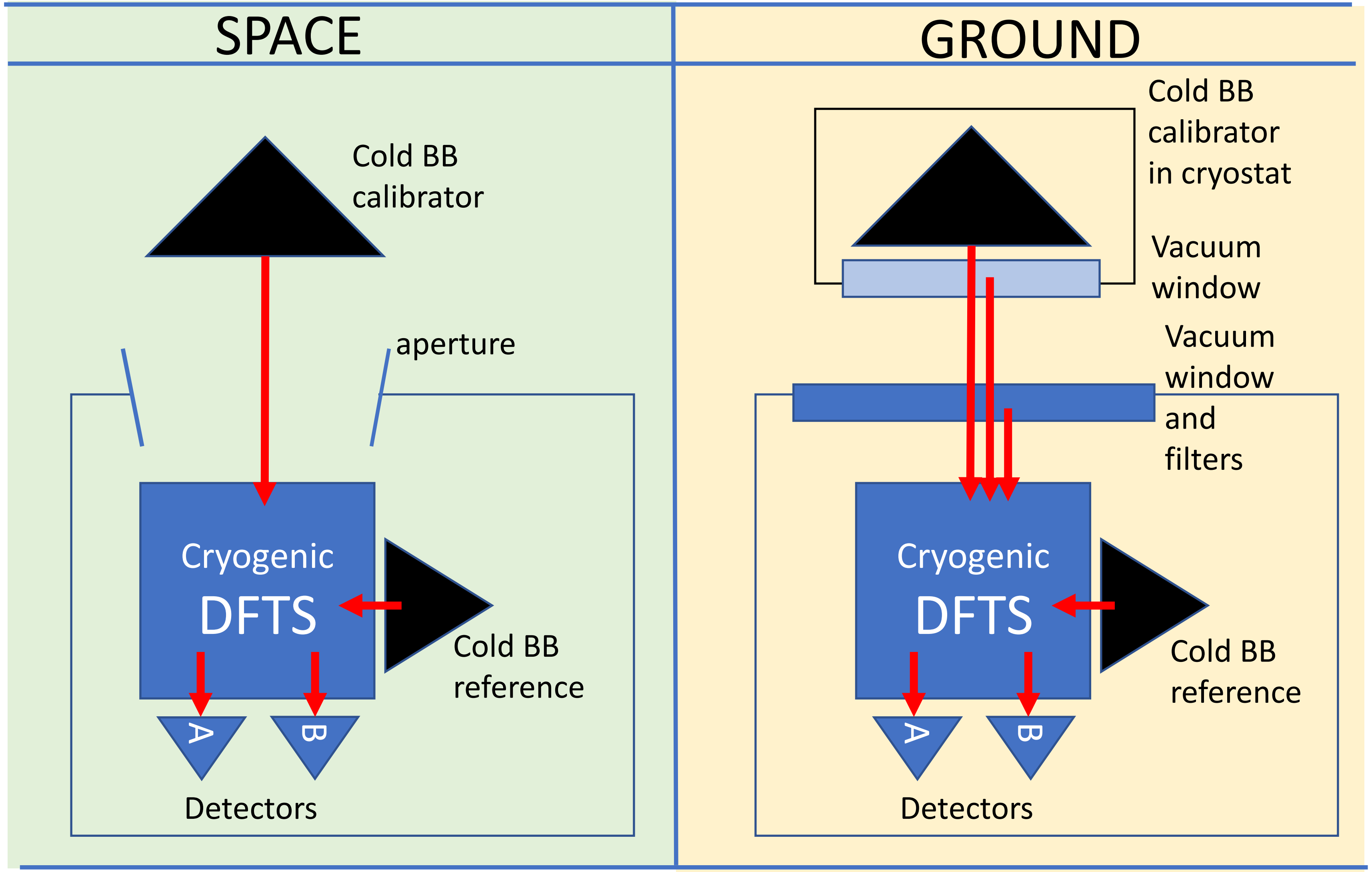
A ground-based measurement ?



In a space-based instrument there is nothing between signal to be measured (CMB + foregrounds) and the DFTS

In a ground-based instrument the signal to be measured (CMB + foregrounds) is dominated by the **emission of the Earth atmosphere and the emission of the warm part of the instrument** (vacuum window & filters). **They must be *minimized* AND *subtracted*.**

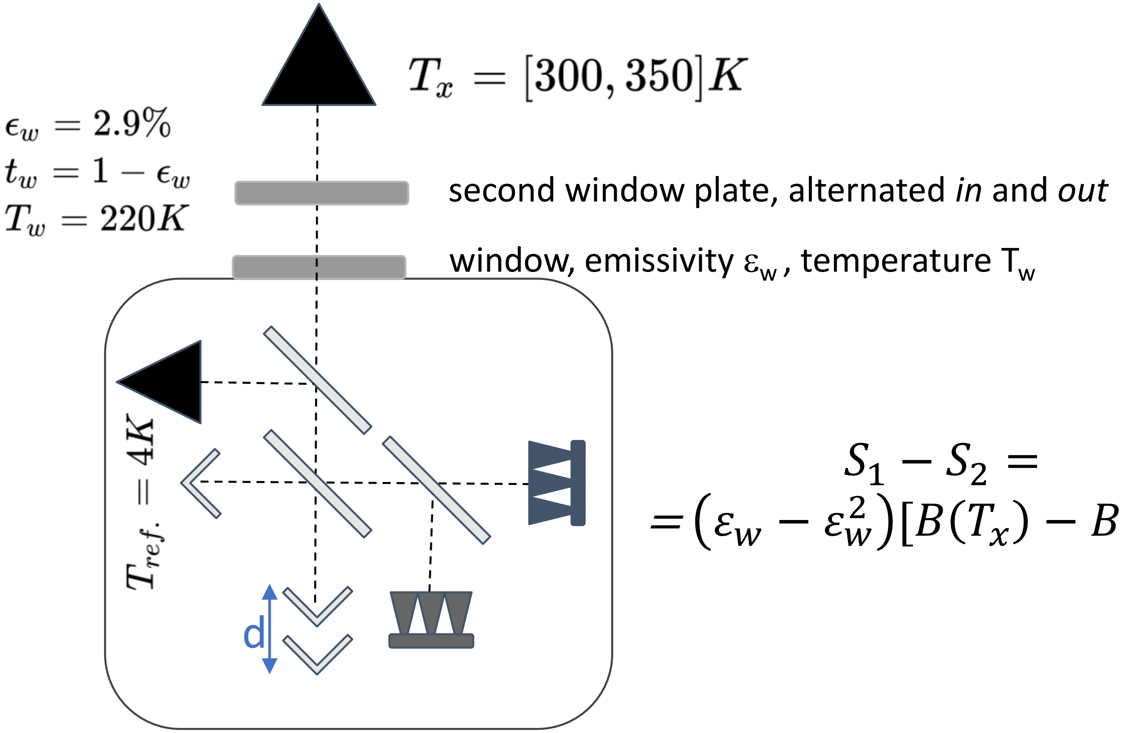
A ground-based measurement ?



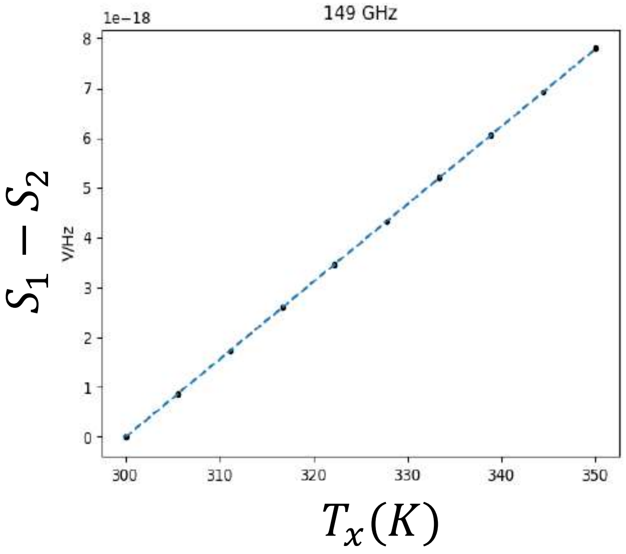
Even the Calibration measurement cannot be carried out on the ground in the same way as is done in space. A **vacuum window** is necessary to keep the calibrator BB cold. **Its emission must be *minimized* AND *subtracted*.**

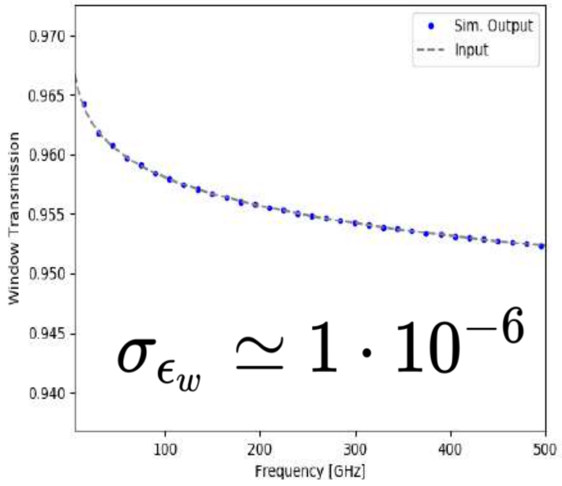
Coping with window emission

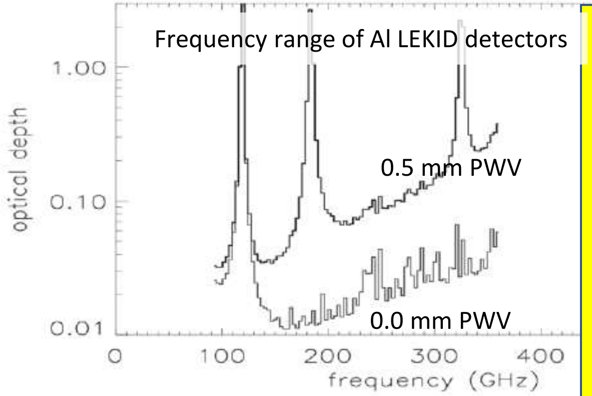
- Window common mode emission must be measured and removed with high accuracy.
- A special subtraction procedure, based on the comparison of the emission from 1 or 2 windows stacked, has been studied (PhD thesis, Lorenzo Mele)
- **Preliminary results:** The window emission can be subtracted, and the expected residual is smaller than the target distortion (assuming *y* ~ 2x10^{-6}).
- This is relevant for the ground based measurement, where the window is HDPE, ~10 mm thick, to withstand 1 bar of atmospheric pressure.
- For the balloon-borne measurement (3 mbar), the window thickness can be reduced to a few tens of microns, and this issue becomes less important.



$$S_1 - S_2 =$$
$$= (\varepsilon_w - \varepsilon_w^2)[B(T_x) - B(T_w)]$$







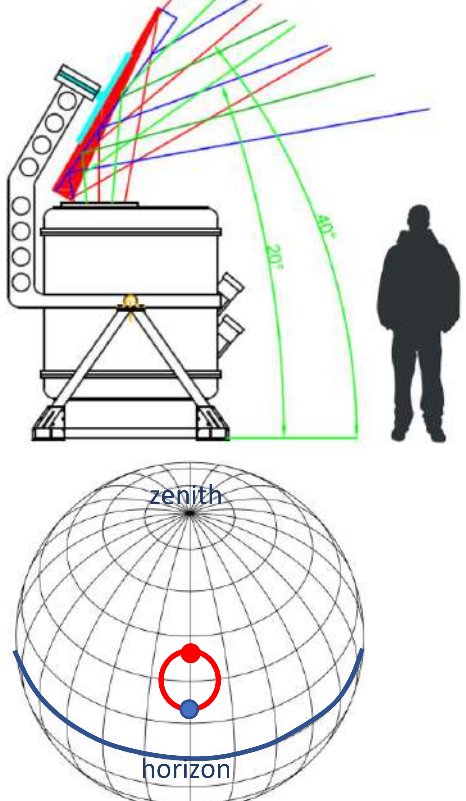
Coping with atmospheric emission

COSMO will operate from the Concordia French-Italian base in Dome-C (Antarctica) … the best site on Earth, extremely cold and dry ! But still has to cope with some atmospheric emission.

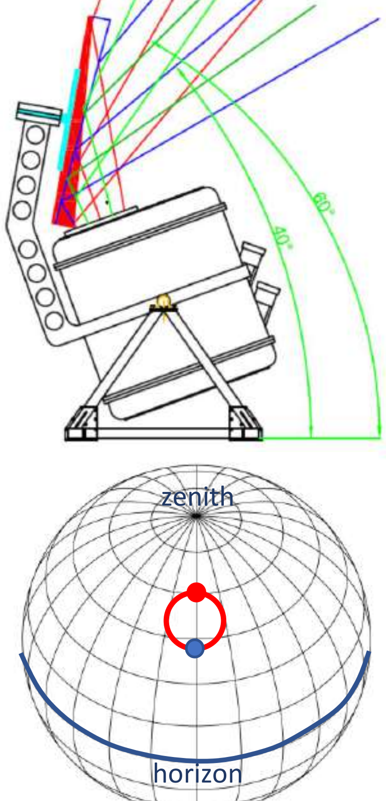
COSMO uses fast detectors (KIDs) and fast elevation scans to separate atmospheric emission and its long-term fluctuations from the monopole of the sky brightness.

A fast spinning wedge mirror (>1000 rpm!) steers the boresight direction on a circle, 20° in diameter, scanning a range of elevations (and corresponding atmospheric optical depths) while the cryogenic interferometer scans the optical path difference.

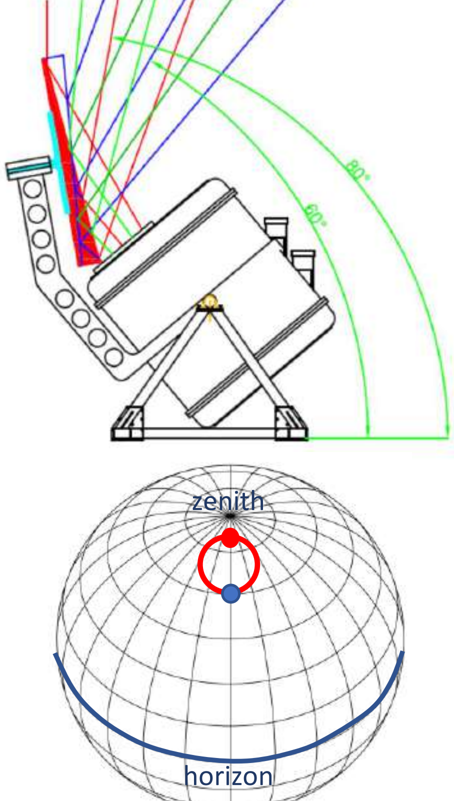
Cryostat tilt = 0°
PT tilt = 40°
Min. elev. = 20°
Max. elev. = 40°



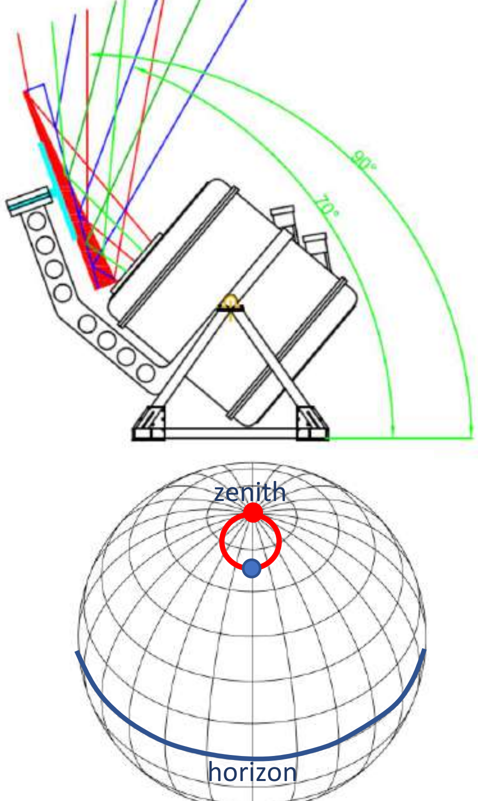
Cryostat tilt = 20°
PT tilt = 20°
Min. elev. = 40°
Max. elev. = 60°

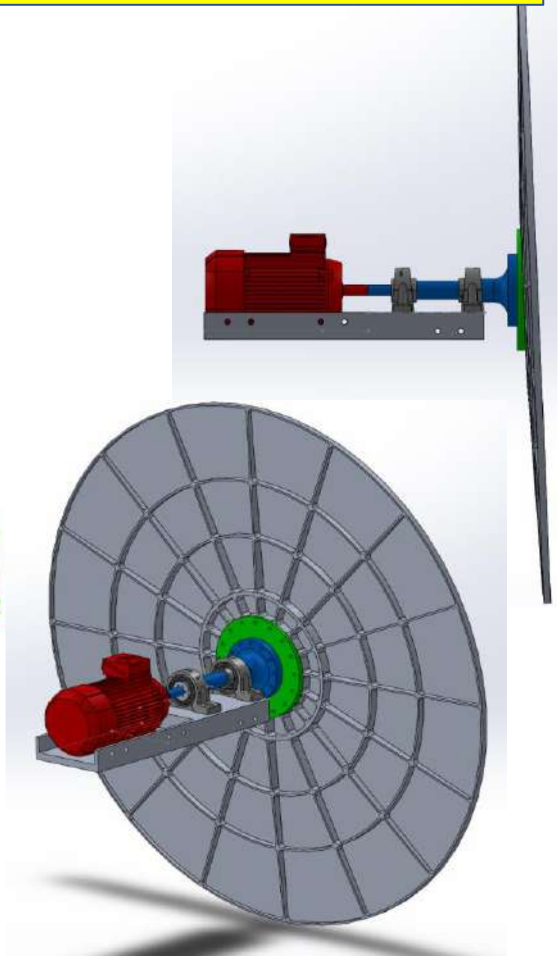


Cryostat tilt = 40°
PT tilt = 0°
Min. elev. = 60°
Max. elev. = 80°

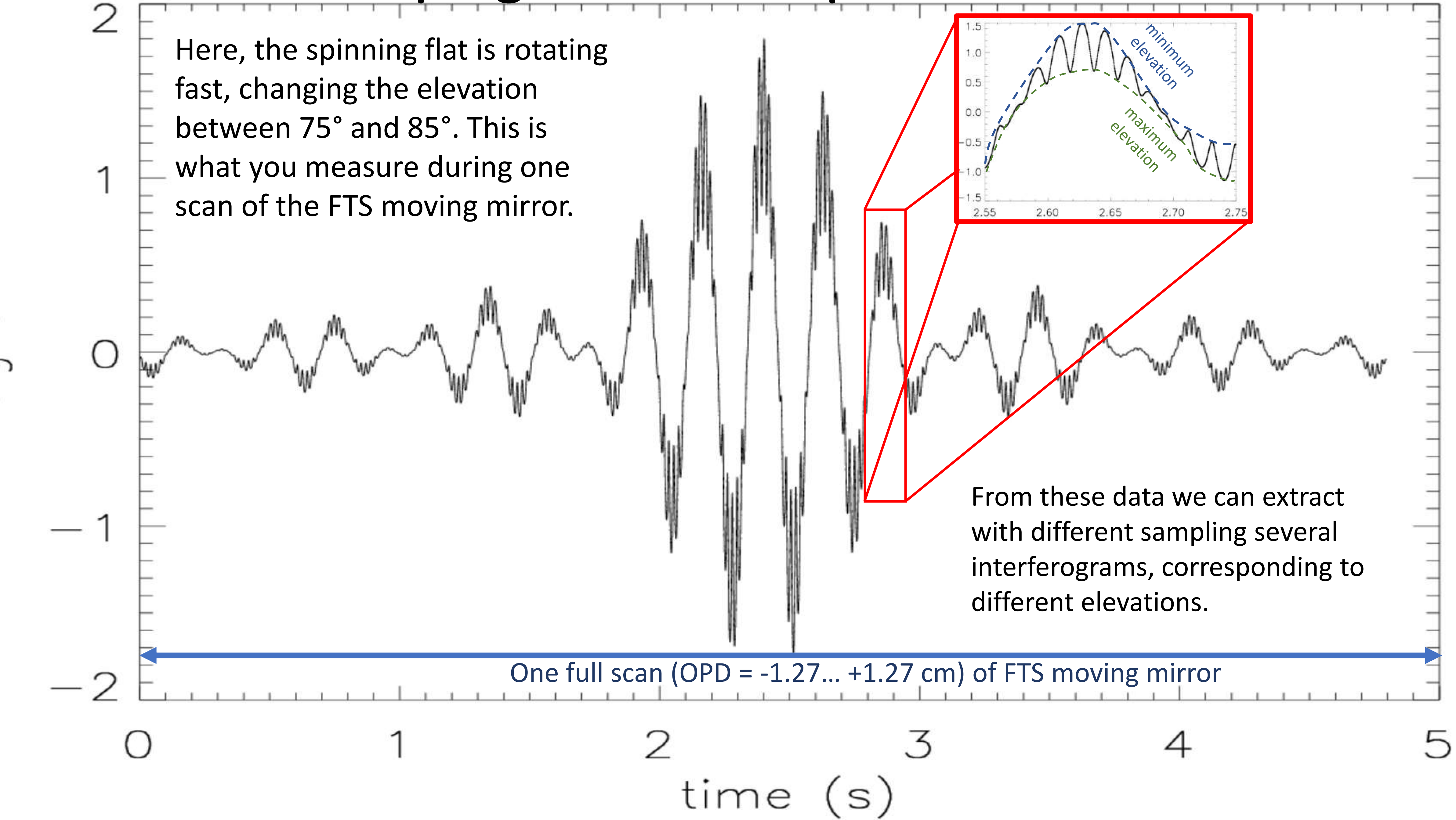


Cryostat tilt = 50°
PT tilt = -10°
Min. elev. = 70°
Max. elev. = 90°





Coping with atmospheric emission



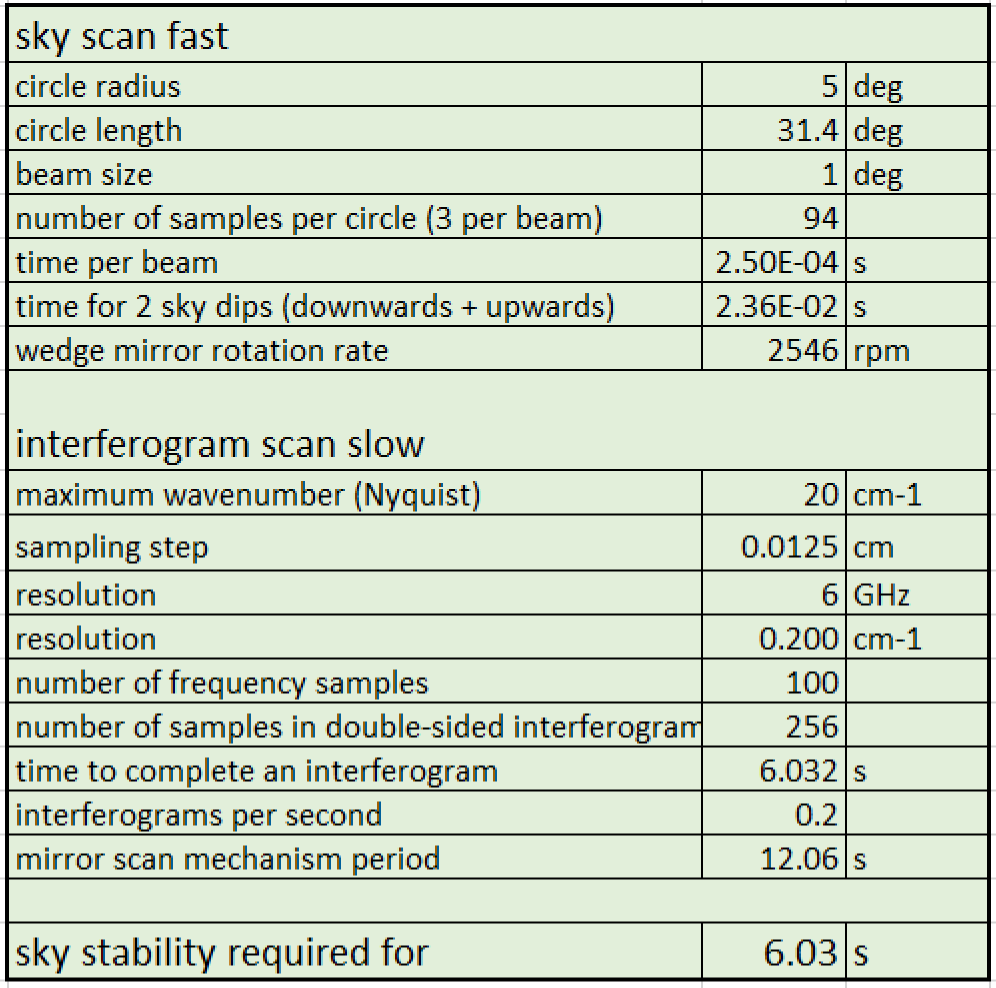
Here, the spinning flat is rotating fast, changing the elevation between 75° and 85°. This is what you measure during one scan of the FTS moving mirror.

From these data we can extract with different sampling several interferograms, corresponding to different elevations.

One full scan (OPD = -1.27… +1.27 cm) of FTS moving mirror

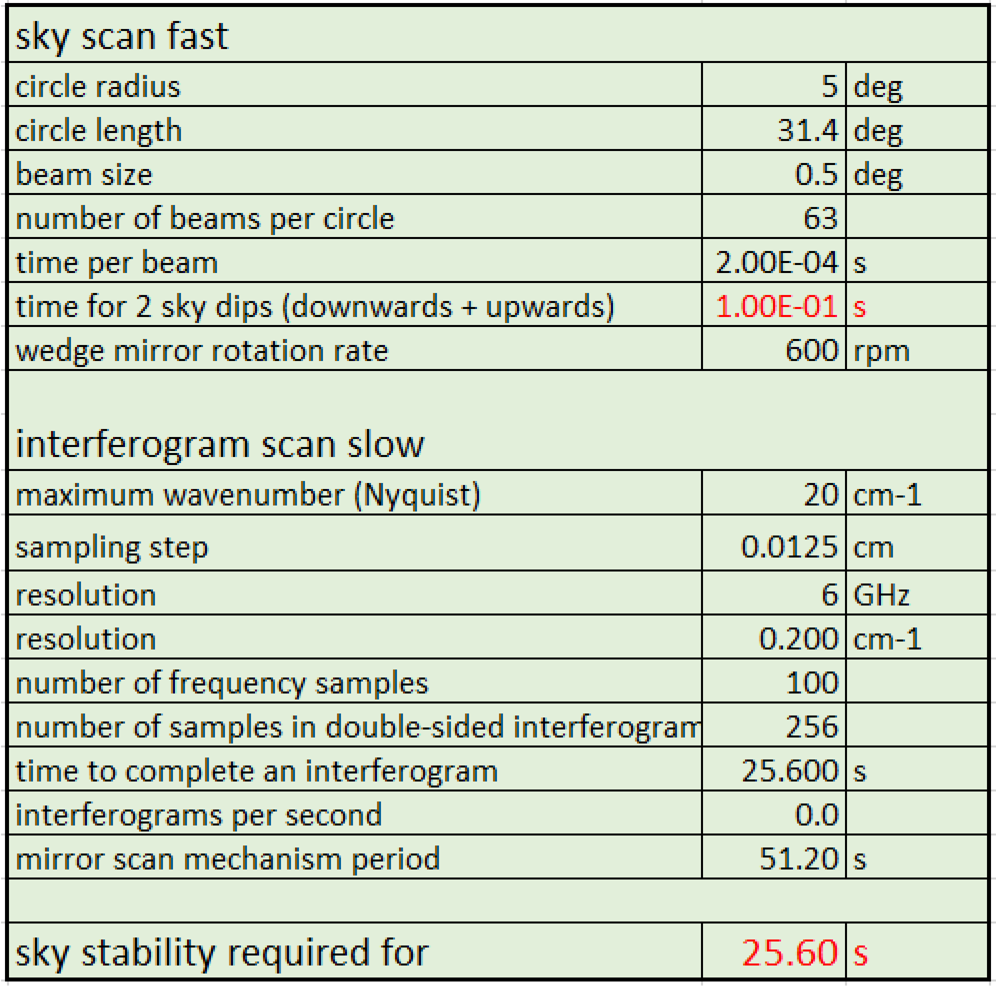
Measurements based on two modulators (slow optical path difference + fast sky scan)

Optimal



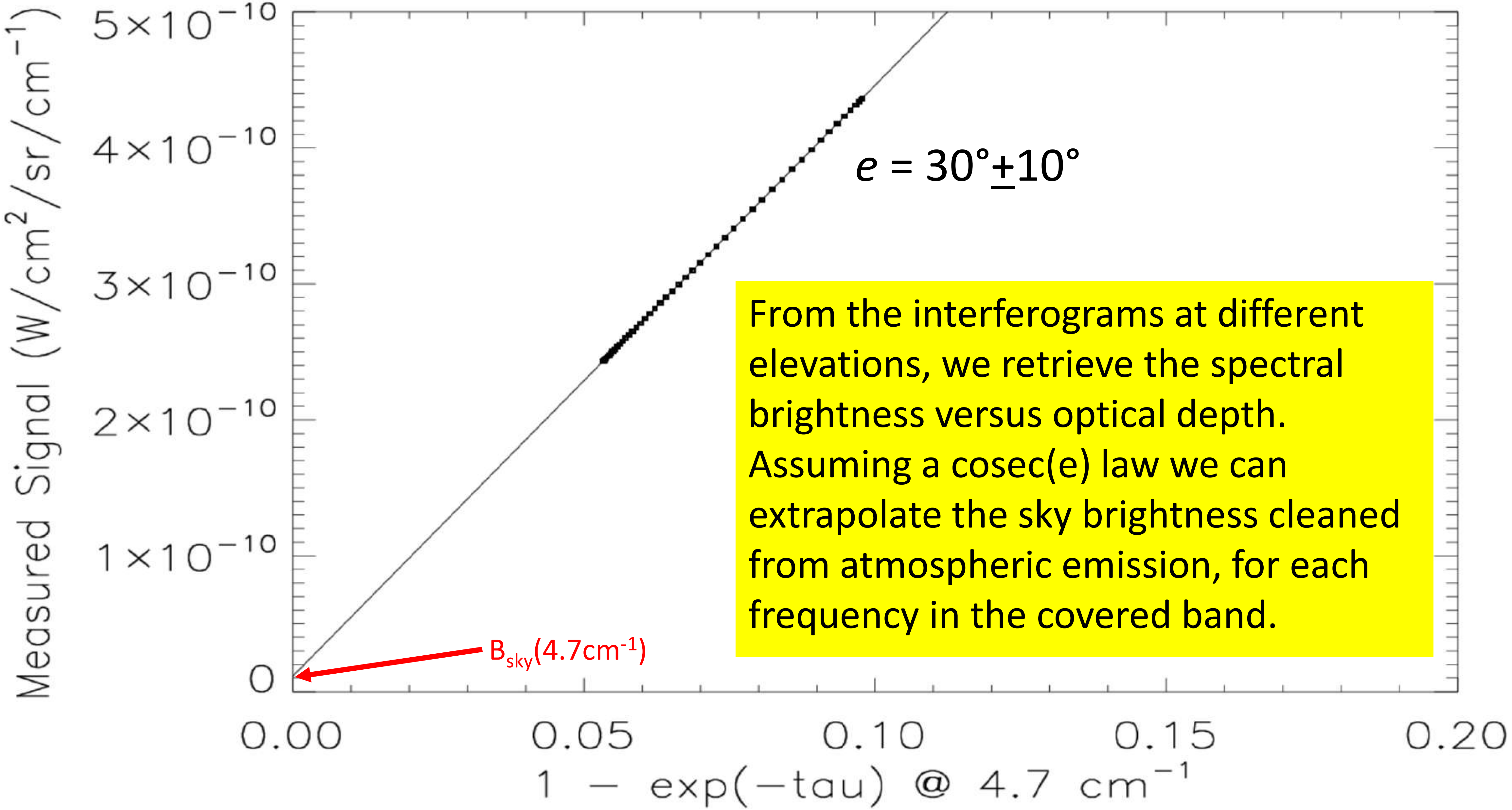
sky scan fast		
circle radius	5	deg
circle length	31.4	deg
beam size	1	deg
number of samples per circle (3 per beam)	94	
time per beam	2.50E-04	s
time for 2 sky dips (downwards + upwards)	2.36E-02	s
wedge mirror rotation rate	2546	rpm
interferogram scan slow		
maximum wavenumber (Nyquist)	20	cm-1
sampling step	0.0125	cm
resolution	6	GHz
resolution	0.200	cm-1
number of frequency samples	100	
number of samples in double-sided interferogram	256	
time to complete an interferogram	6.032	s
interferograms per second	0.2	
mirror scan mechanism period	12.06	s
sky stability required for	6.03	s

Certainly Feasible



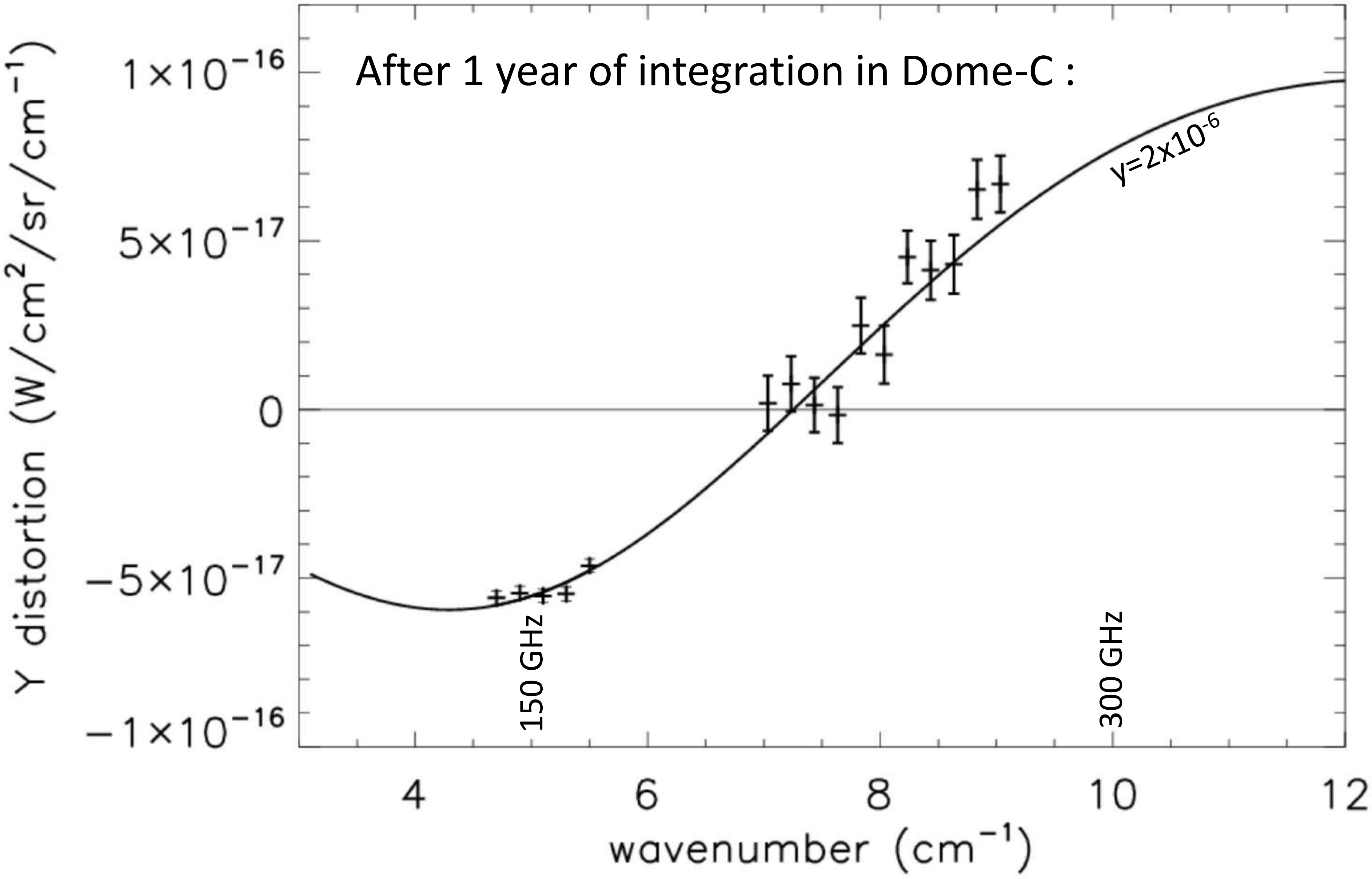
sky scan fast		
circle radius	5	deg
circle length	31.4	deg
beam size	0.5	deg
number of beams per circle	63	
time per beam	2.00E-04	s
time for 2 sky dips (downwards + upwards)	1.00E-01	s
wedge mirror rotation rate	600	rpm
interferogram scan slow		
maximum wavenumber (Nyquist)	20	cm-1
sampling step	0.0125	cm
resolution	6	GHz
resolution	0.200	cm-1
number of frequency samples	100	
number of samples in double-sided interferogram	256	
time to complete an interferogram	25.600	s
interferograms per second	0.0	
mirror scan mechanism period	51.20	s
sky stability required for	25.60	s

Coping with atmospheric emission



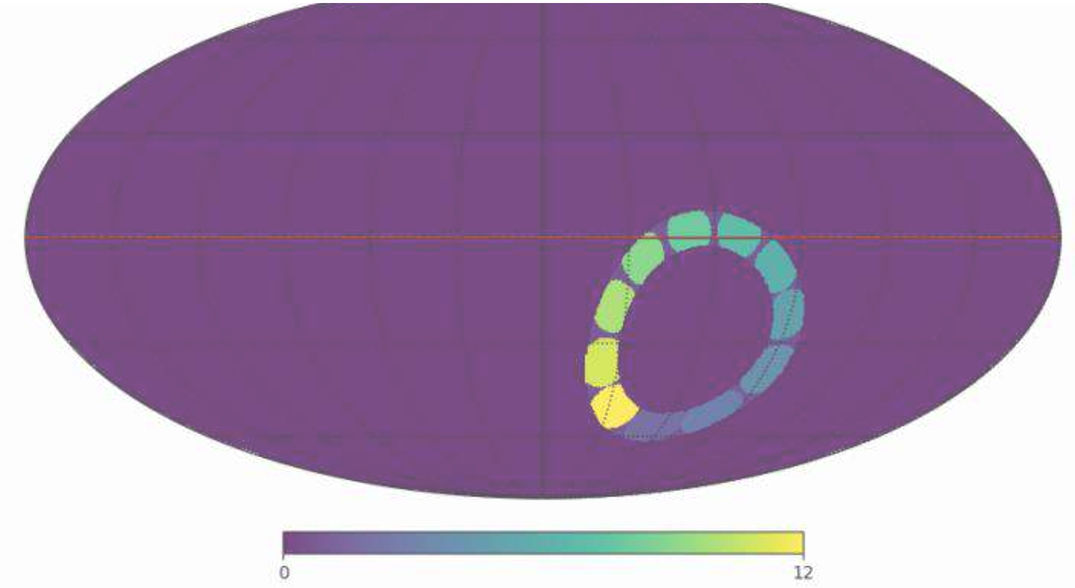
From the interferograms at different elevations, we retrieve the spectral brightness versus optical depth. Assuming a cosec(e) law we can extrapolate the sky brightness cleaned from atmospheric emission, for each frequency in the covered band.

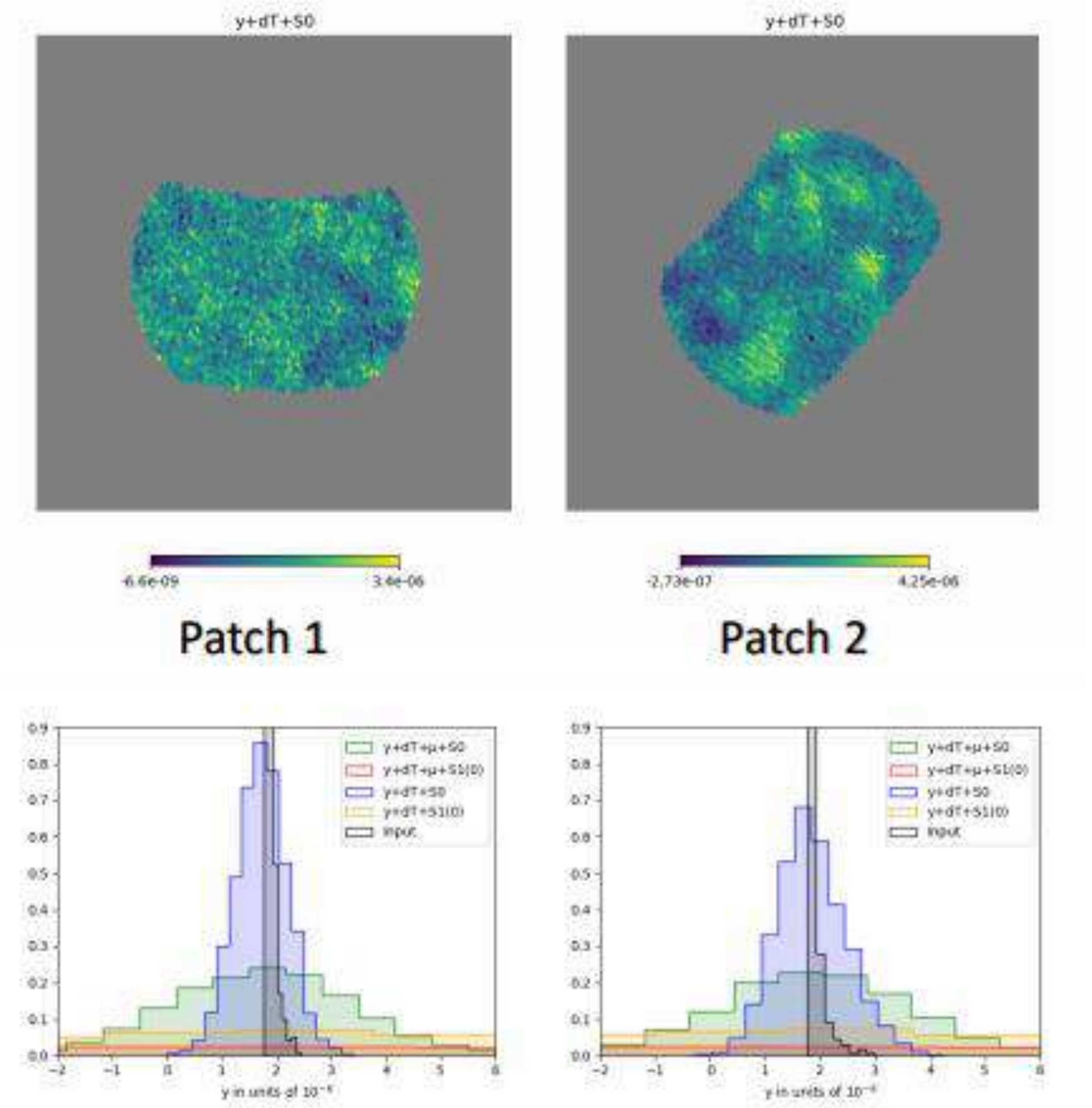
Simplistic Forecast



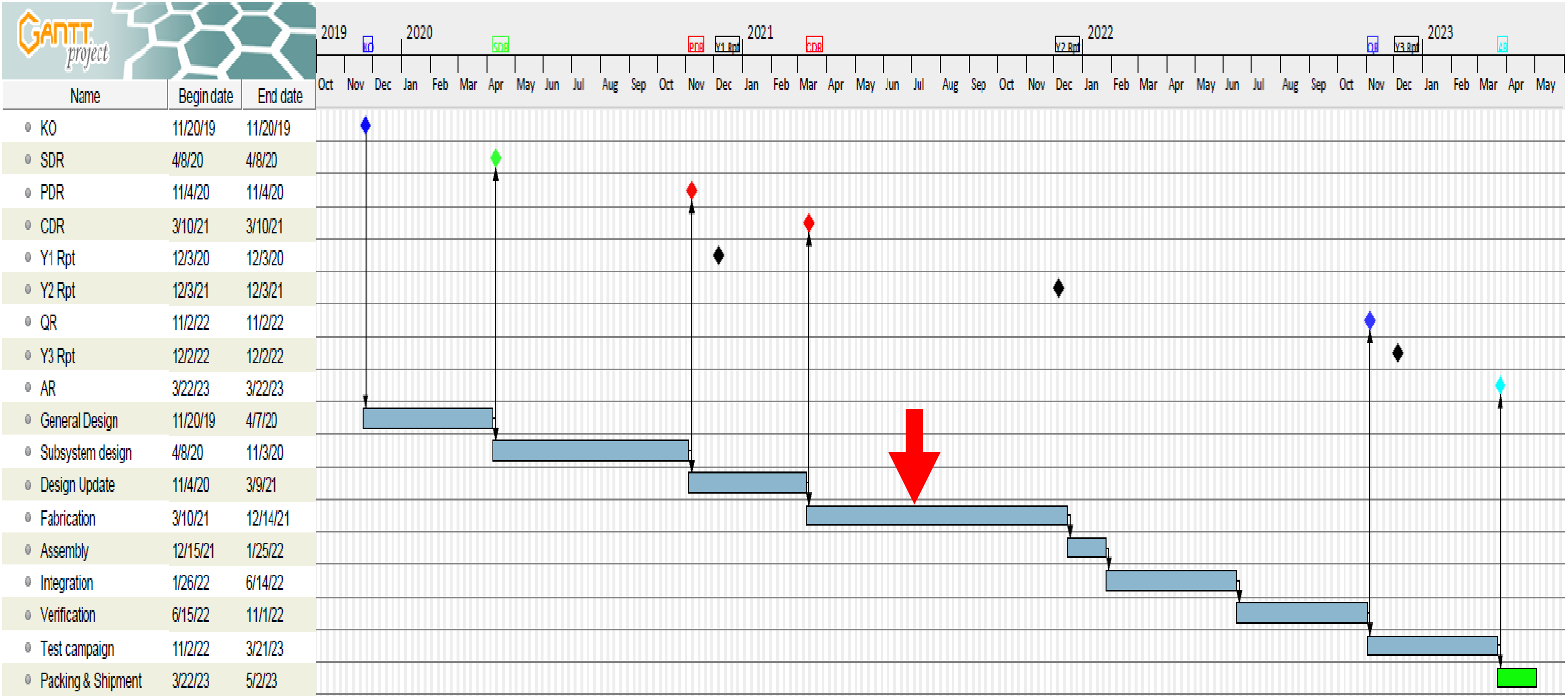
Performance Forecast

- Assuming photon noise limited performance, dominated by the atmospheric emission (AM model) and cryostat window (with $\varepsilon = 1\%$)
- Observing site: Dome-C. Daily coverage of 11 sky patches at high elevation, 1 year of integration.
- ILC-based simulations: COSMO can extract the isotropic comptonization parameter (assumed to be $y = 1.77 \cdot 10^{-6}$) as $y = (1.76 \pm 0.26) \cdot 10^{-6}$ in the presence of the main Galactic foreground (thermal dust) and of CMB anisotropy, and assuming perfect atmospheric emission removal (L. Mele)





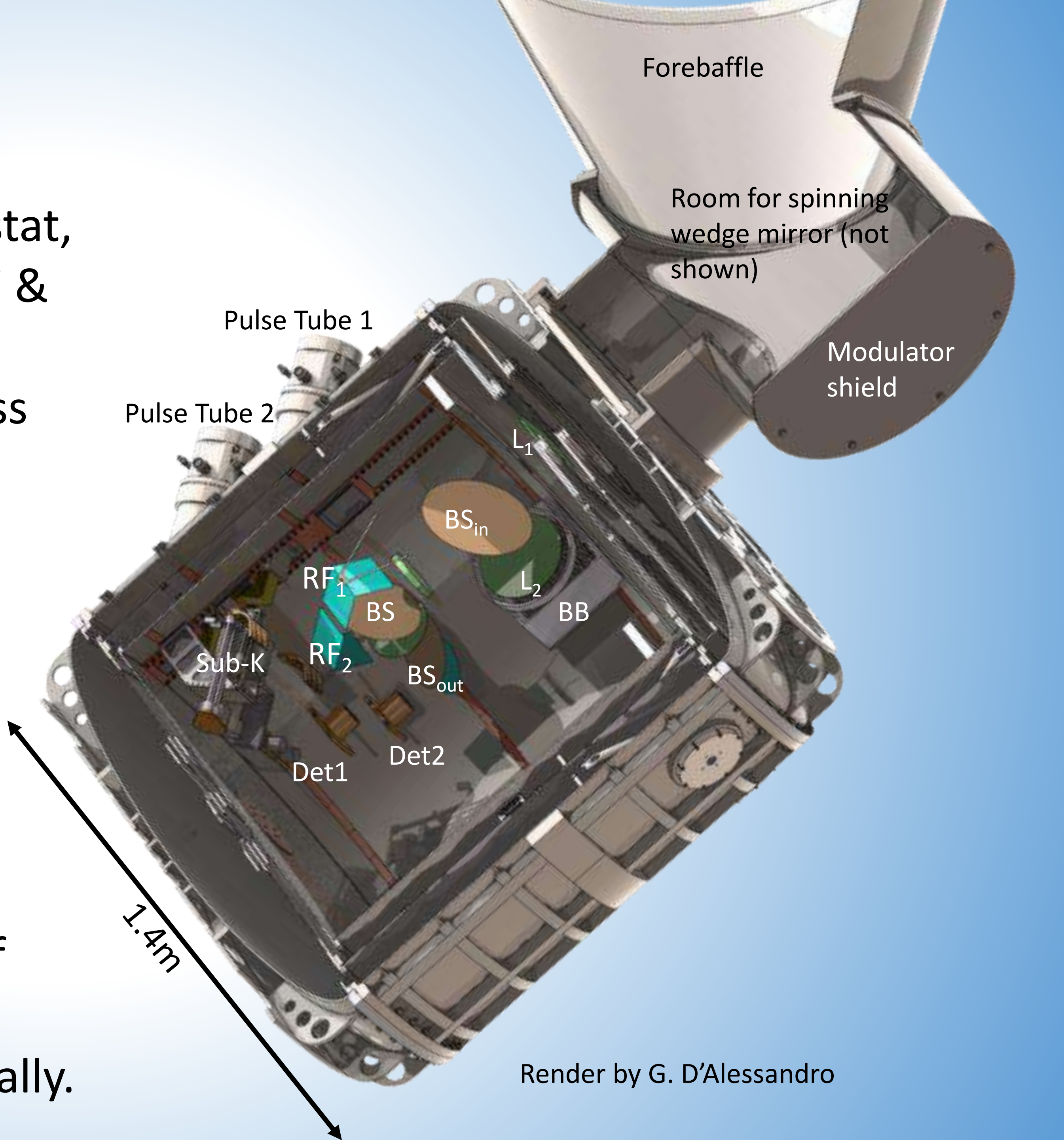
Gantt Chart



Name	Begin date	End date
KO	11/20/19	11/20/19
SDR	4/8/20	4/8/20
PDR	11/4/20	11/4/20
CDR	3/10/21	3/10/21
Y1 Rpt	12/3/20	12/3/20
Y2 Rpt	12/3/21	12/3/21
QR	11/2/22	11/2/22
Y3 Rpt	12/2/22	12/2/22
AR	3/22/23	3/22/23
General Design	11/20/19	4/7/20
Subsystem design	4/8/20	11/3/20
Design Update	11/4/20	3/9/21
Fabrication	3/10/21	12/14/21
Assembly	12/15/21	1/25/22
Integration	1/26/22	6/14/22
Verification	6/15/22	11/1/22
Test campaign	11/2/22	3/21/23
Packing & Shipment	3/22/23	5/2/23

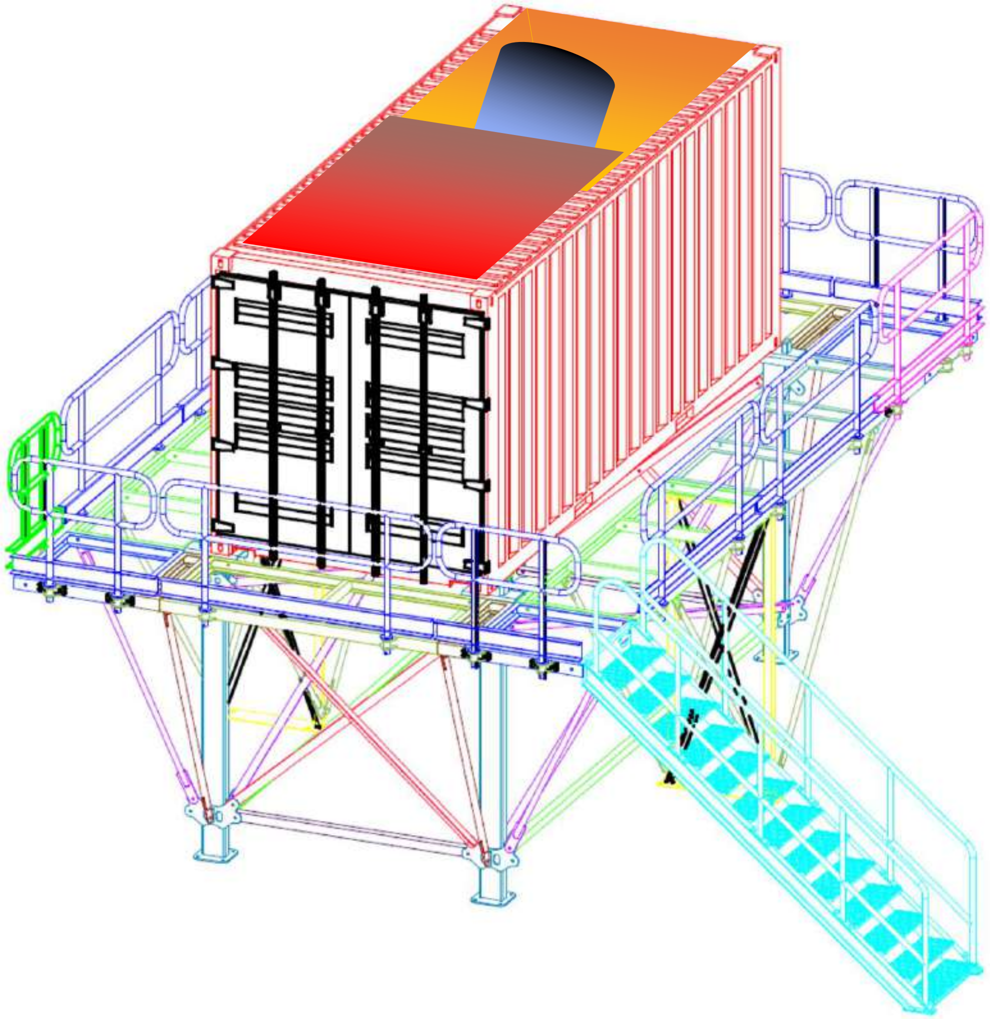
Instrument Implementation

- Instrument inside a pulse-tube based cryostat, twin of the one developed for QUBIC (Masi & JCAP 2021)
- Cryostat height 1.54m, diameter 1.4m, mass 350kg.
- The spinning wedge mirror for sky scans is mounted on top of the vacuum window.
- A large, absorbing forebaffle protects the spinning wedge from straylight.
- The interferometer operates at cryogenic temperature (close to 2.7K)
- The optical path difference modulation is obtained by translating one of the two roof mirrors by means of a frictionless cryomechanism, actuated electromagnetically.

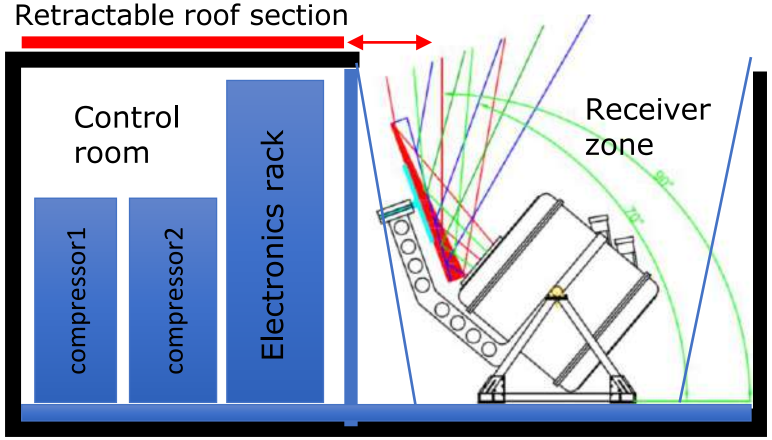


Render by G. D'Alessandro

On-site Implementation

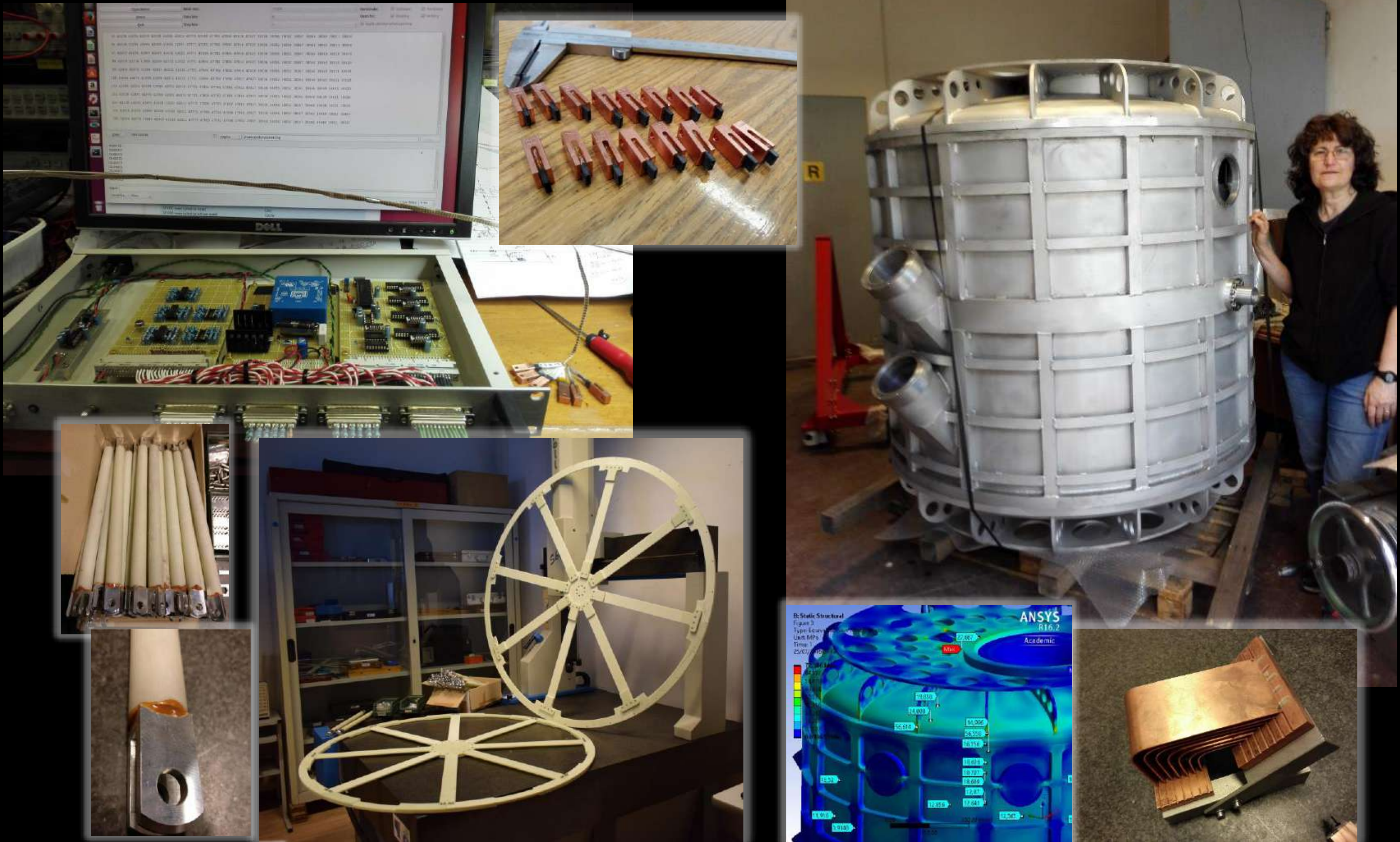


Thanks to Gianluca Bianchi-Fasani for palafitte dwg.



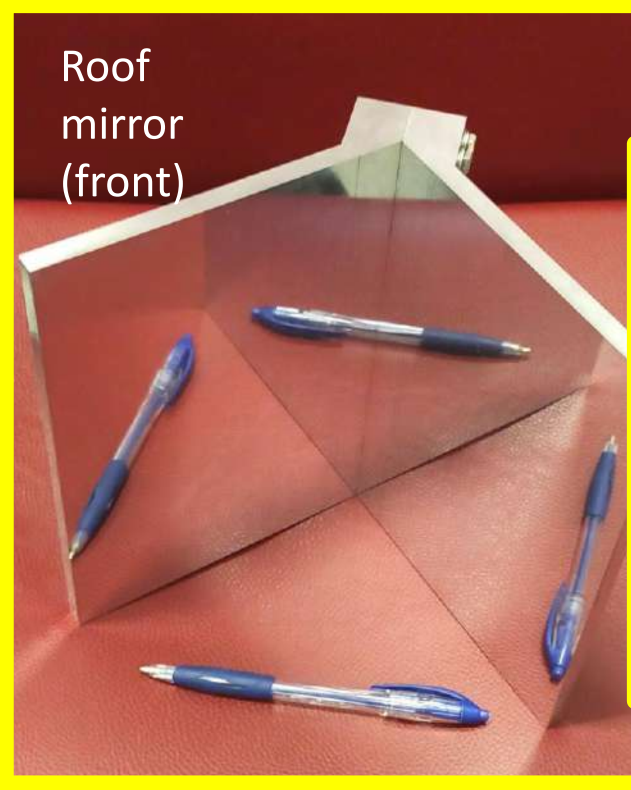
- Experiment in a thermally insulated container
- Warm section with electronics and compressors.
- Cold section with receiver. No window. Shields.
- The same container used for tests and shipment
- Palafitte as usual in Dome-C (e.g. superDARN)
- Installation site: near astronomy lab
- Energy needed: 20 kW for 100 days (feedback from program is necessary)

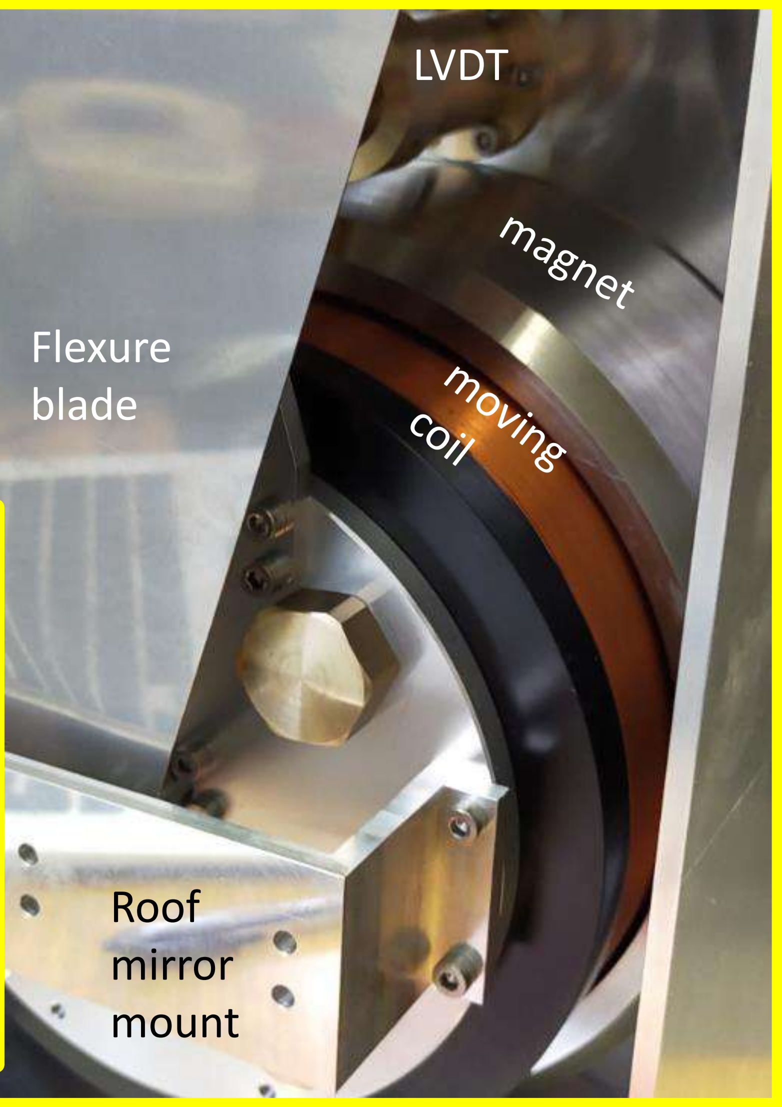
COSMO hardware



Variable Delay Line for the FTS

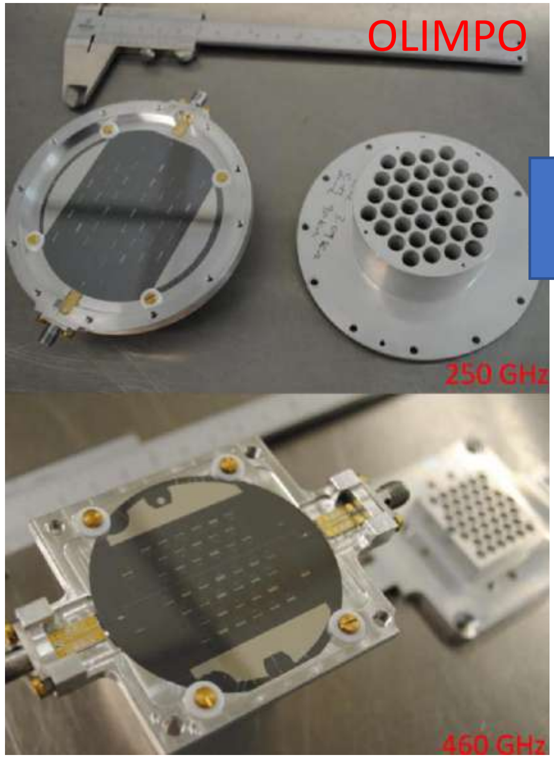
- Cryogenic operation – frictionless design to minimize heat load
- Based on a powerful voice coil with steel flexure blades support, to move one roof mirror. up to 0.2 cm/s.
- Voice coil delivered, assembly built.
- Eddy currents in moving coil support minimized by means of a dielectric coil support.
- Electronics being developed (E. Marchitelli)

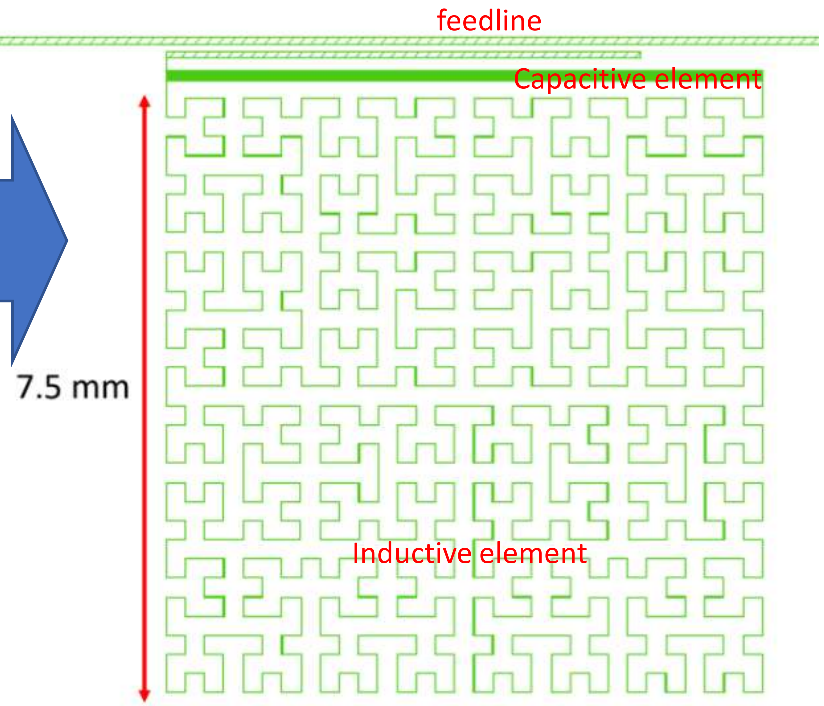


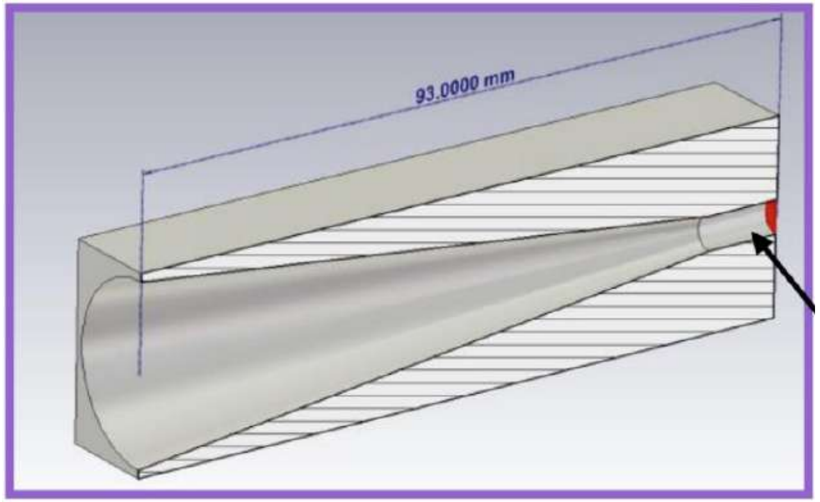


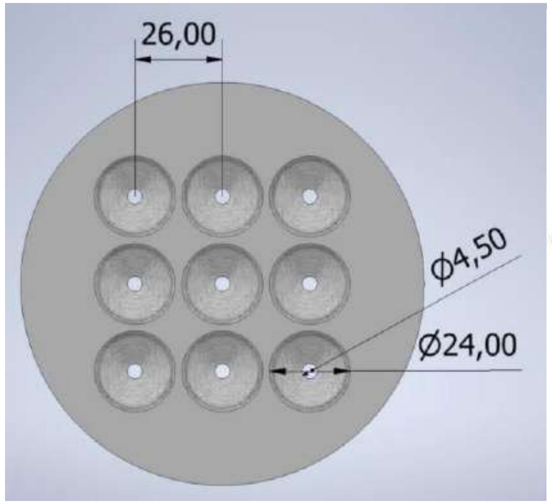
Detectors & Feedhorns

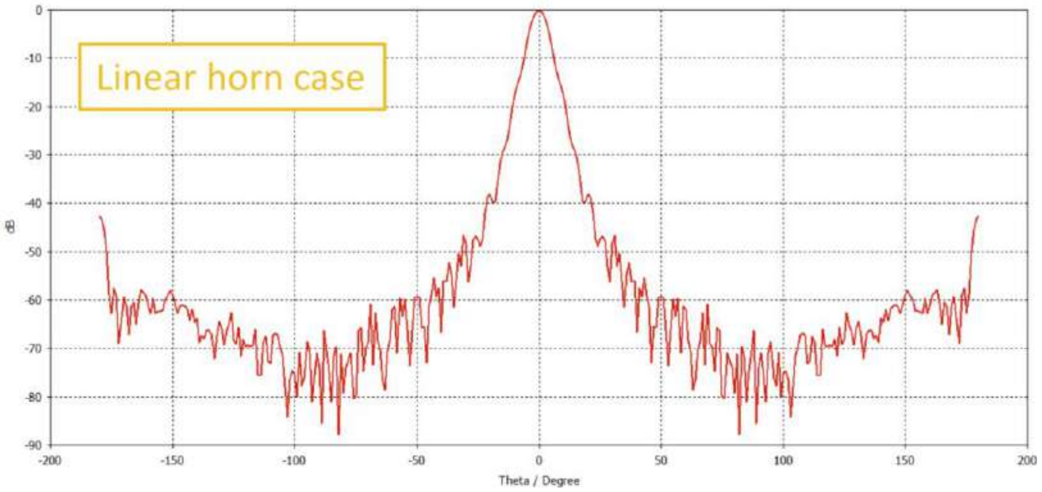
- COSMO uses two small arrays of multi-moded Al Kinetic Inductance Detectors, fabricated with the same process developed for the OLIMPO ones (Paiella et al. 2019, Masi et al. 2019).
- The two arrays cover the 130-160 GHz and the 200-300 GHz bands.
- Optimization in progress (A. Paiella).
- The KIDs are coupled to Al multi-mode feedhorns. Optimization in progress (E. Manzan).





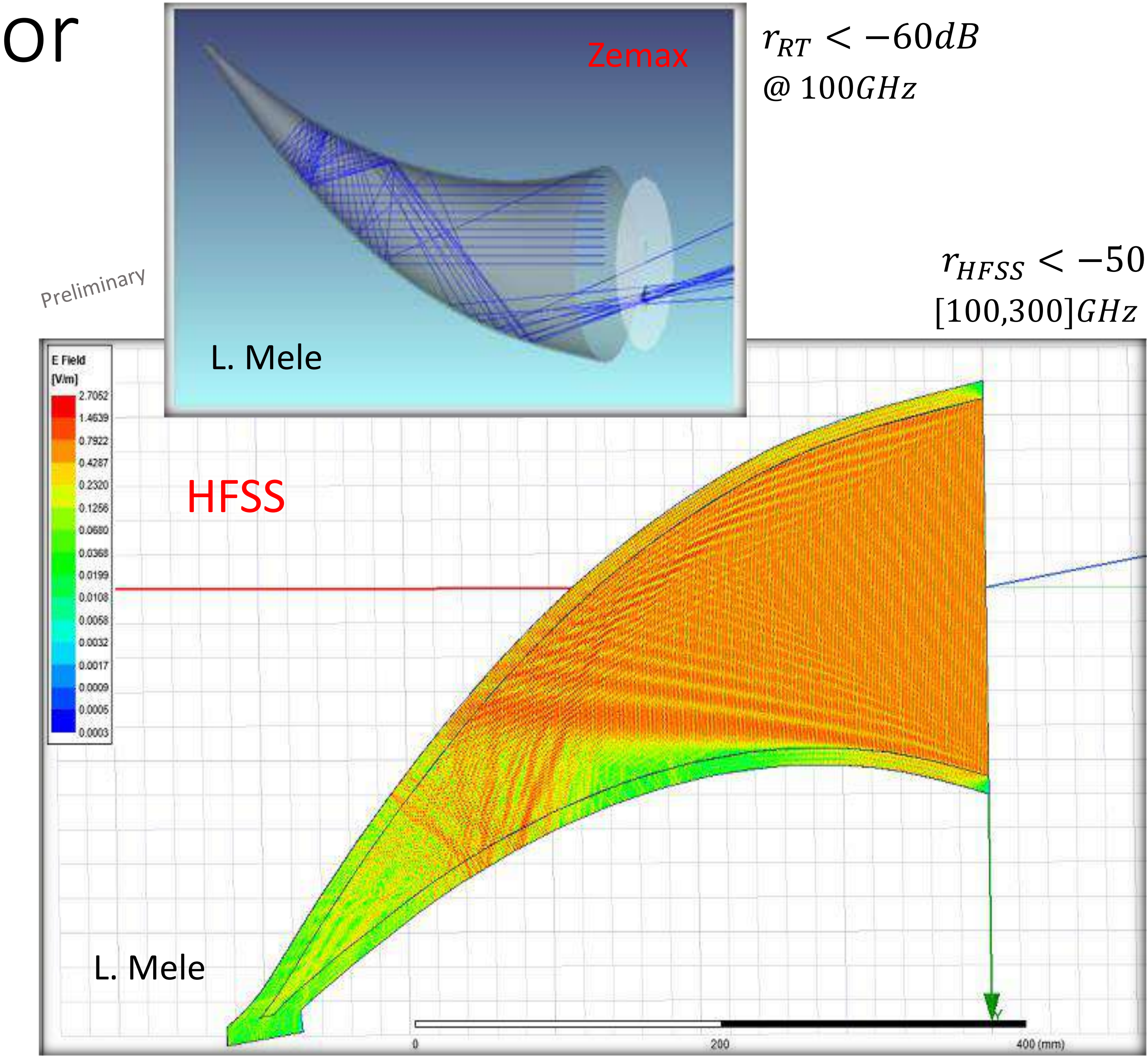






Blackbody calibrator

- Emissivity ->1
- Low thermal gradients (single compact element)
- Ray Tracing approach (RT): Maximization of the # of reflections with the absorbing coating (cr-110, Emerson & Cuming)
- EM approach with HFSS modelling.
- Reflectivity lower than 1 ppm, to be better evaluated experimentally.
- Fabrication of Cu support for validation prototype started recently.

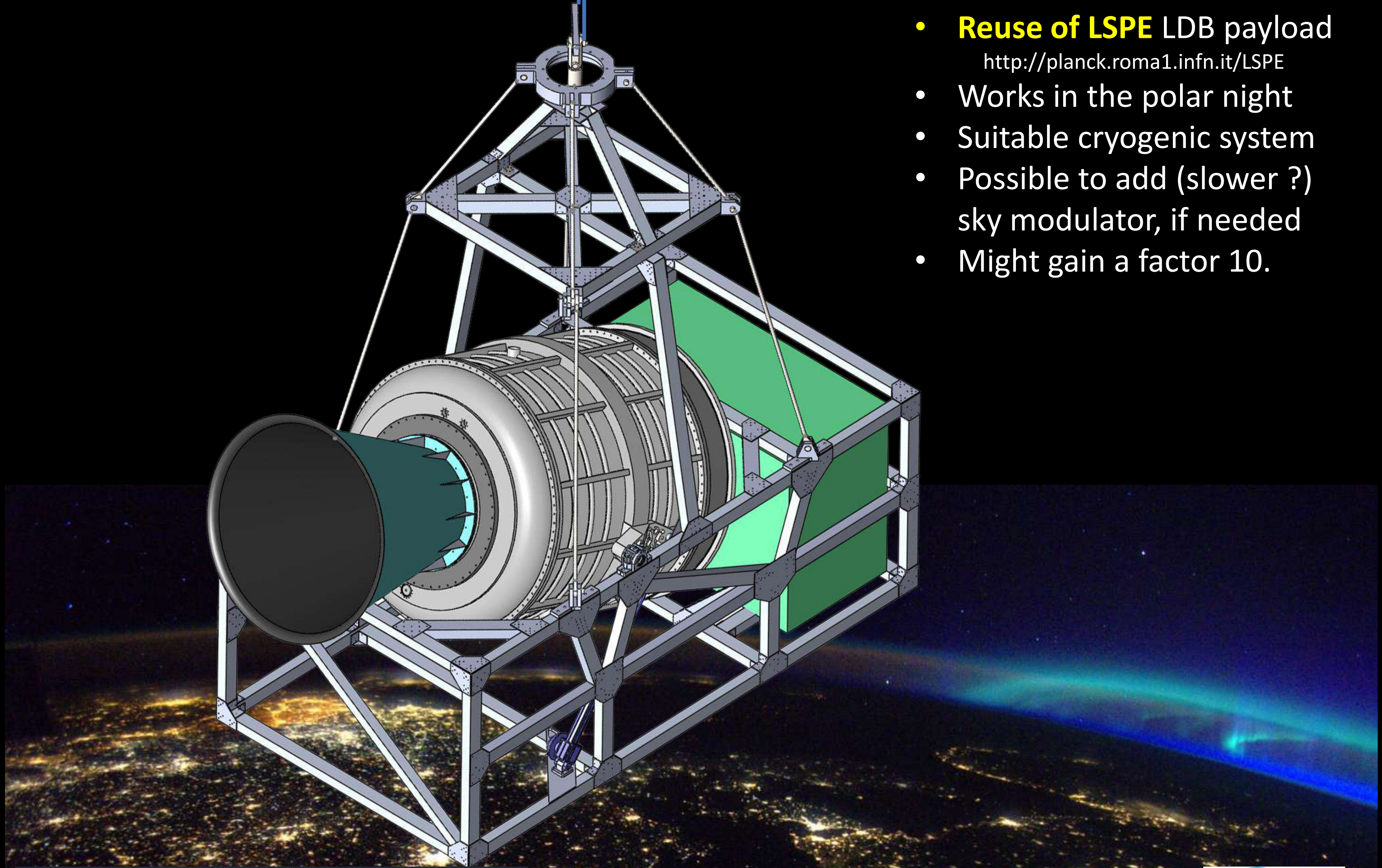


$r_{RT} < -60dB$
$@\, 100GHz$

$r_{HFSS} < -50dB$
$[100{,}300]GHz$

The future of COSMO: a balloon-borne instrument

- **Reuse of LSPE** LDB payload
  http://planck.roma1.infn.it/LSPE
- Works in the polar night
- Suitable cryogenic system
- Possible to add (slower ?) sky modulator, if needed
- Might gain a factor 10.



Cosmic Orbital and Suborbital Microwave ObservationS

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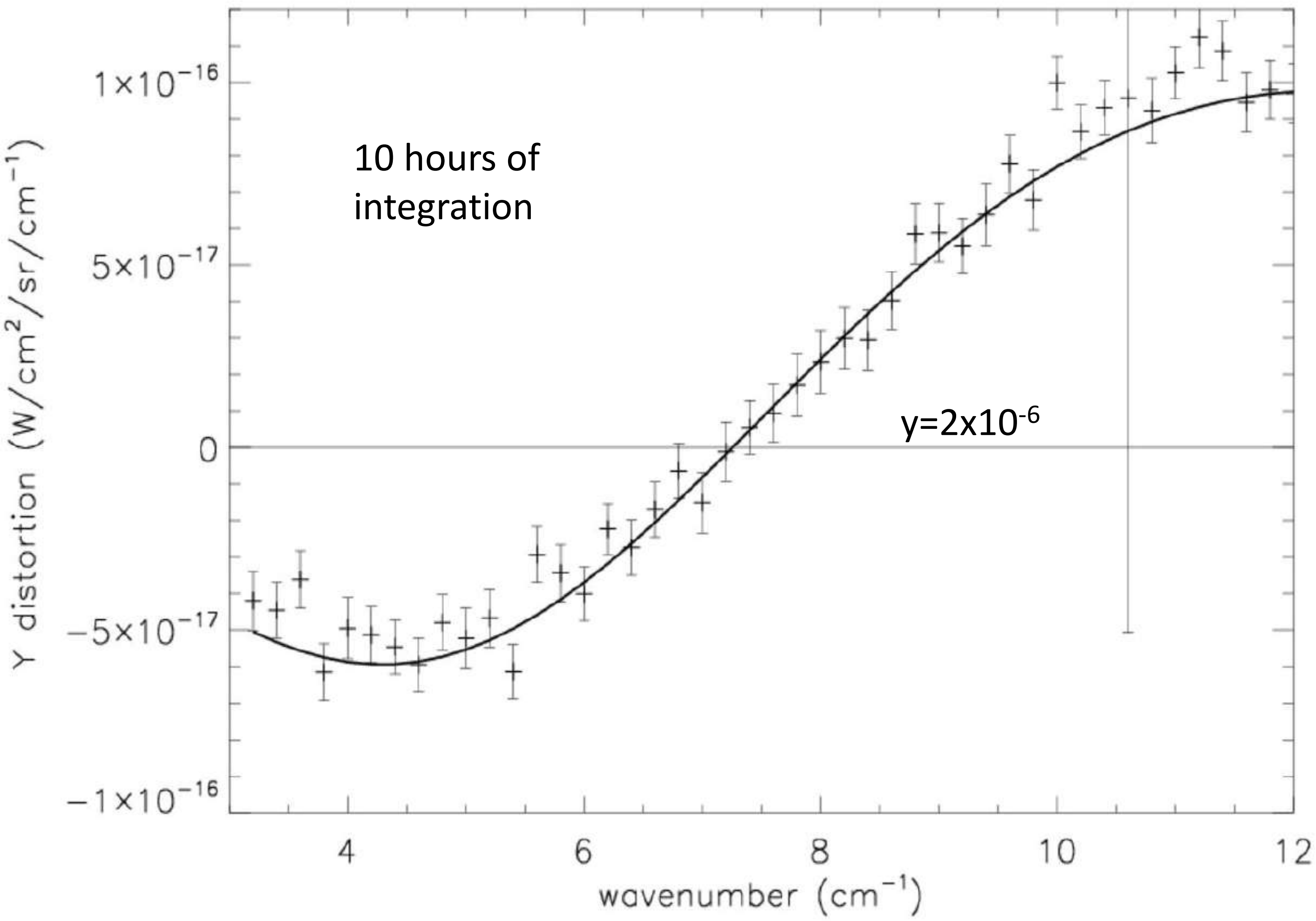
The future of COSMO: a balloon-borne instrument


10 hours of integration

$y=2x10^{-6}$

Feasibility study carried out with ASI – COSMOS project.
Synergic effort in France (BISOU, hear B. Maffei later)

Cosmic Orbital and Suborbital Microwave ObservationS

Agenzia
Spaziale
Italiana

Conclusions

- COSMO is a first attempt to measure the spectral distortions of the CMB monopole from the ground.
- It beats atmospheric noise and measures atmospheric emission using fast modulation and detectors.
- If this strategy is effective, the sensitivity is enough to measure the largest spectral distortion, arising from comptonization at recombination / reionization / ionized baryons in the universe.
- It paves the way to more accurate measurements with the same approach, to be carried out with COSMO on a stratospheric balloon (see also the synergic proposal BISOU)
- Can (and should) be complemented with low-frequency *monopole* spectral distortion measurements (e.g. The Tenerife Microwave Spectrometer (TMS) or the Array of Precision Spectrometers for the Epoch of RecombinAtion (APSERa/DISTORTION).