Technology to support future CMB experiments

Testing and Calibration

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Testing and Calibration are both fundamental but different tasks

- Calibration involves the instrument as a whole (but some specific subsystems)
- Testing is an activity involving devices, subsystems and entire systems
  - It time consuming (sometimes frustrating)
  - It requires dedicated set-ups and well defined testing procedure which often are the result of a boots-trap phase when all the experimental criticalities show up
- Testing involves:
  - ✓ Electronics
  - ✓ Active components (LNAs)
  - ✓ Passive components (antenna systems)
  - ✓ Cryogenics
  - ✓ Infrastructures (telescope mountings, dome), Star Sensors

System Level Tests (fundamentals)

FUNDAMENTAL OBJECTIVES OF THE TESTS @ SYSTEM LEVEL

- To characterize the interaction between the sub-units/units composing the system.
  - The integration strategy/model is determinat in disentangling between effects.
  - It is mandatory that the units/ sub-units have been aready fully characterized at lower level of the integration.
- To fully characterize the system in its relevant environment or in ambient conditions representative of the operational conditions.
  - It is mandatory to define in advance the use cases of the instrument
- To optimize the system to get the best performance ‘as a system’

System Level Tests (fundamentals)

RULES OF THUMBS

- The time and the money that you think to save giving some tests at Unit/subunit level up, will be lost, increased by a considerable quote, in the next System level Phase.
- Any lacks of information during the initial test phases increases the complexity of the analysis (time=costs) in the following phases to fill the gap; analysis can not always compensate a lacking characterization.

System Level Tests (interdependency)

<u>THE DESIGN AND TEST PHASES ARE MUTUALLY DEPENDENT</u>

- Design the instrument thinking in advance to how you want/can test it. Design is also designing the test phase: requirements are nothing if you do not have adequate tools to verify them.
- A ‘state of the art’ Instrument will be useless if you can not characterize it.
- Involve from the beginning of the project all the relevant figures playing a role in the Instrument definition and characterization:
  - Assembly, Integration and Verification phases start with the Design phase.
  - The Design phase must be shaped on the Assembly Integration Verification phase.

System Level Tests (interdependency)

THE SYSTEM LEVEL AND THE UNIT LEVEL TEST PHASES ARE MUTUALLY DEPENDENT

- The two phases must be thought at the same time
- Properties which can be tested at Unit Level often can not directly be verified at System level: state at the beginning of the project what to test and when: whenever a verification 'leaks' from a phase to another, some information is missed.

Testing set-up is quite different for coherent radiometers and bolometers

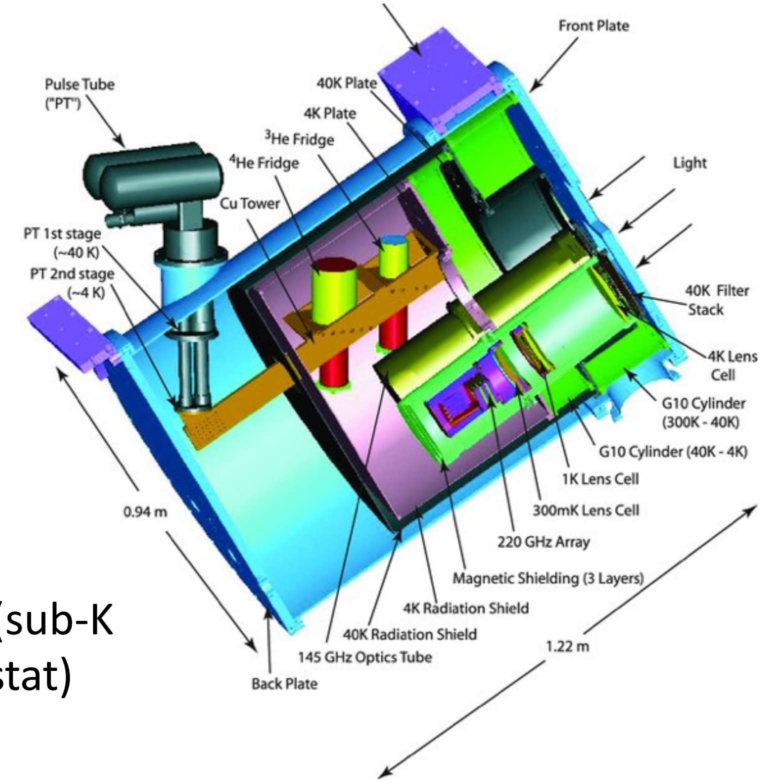
The reason is mainly cryogenics:

- Coherent Radiometers (LNAs) work around 20K by cryocoolers: easy to operate, high cooling power, relatively cheap.
  Cryogenic set-up in labs are close to the one of the instruments

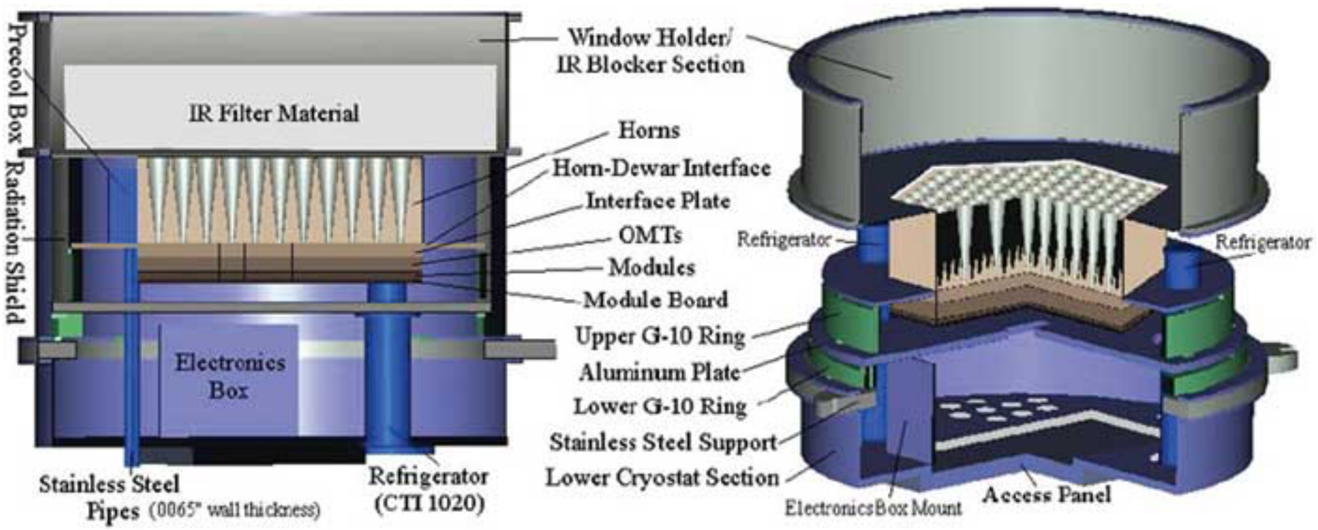
- Bolometers (NTD-Ge, TES, mKID) work well below 1K with complex and expensive cryostats (He3, ADR, Dilution) with low cooling power
  Lab set-up is often far from the instrument cryostat

I'll focus on *Coherent Radiometers*

Testing set-up is quite different for coherent radiometers and bolometers



ACT (sub-K cryostat)

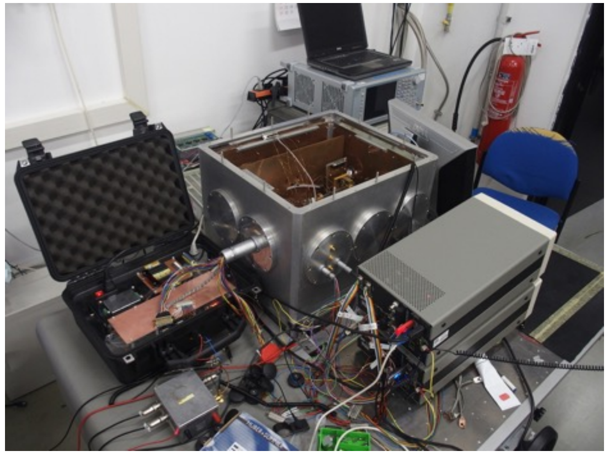


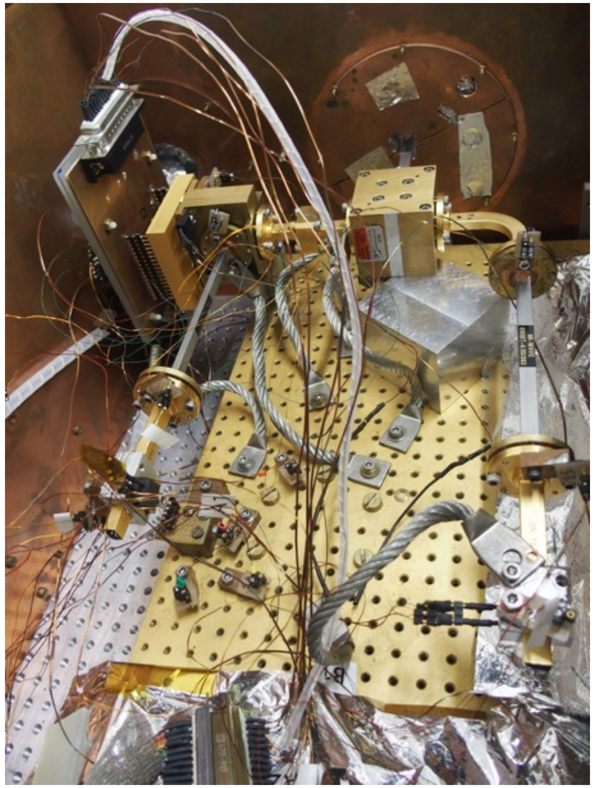
QUIET (20K cryostat)

The STRIP community has a accumulated a deep experience on testing

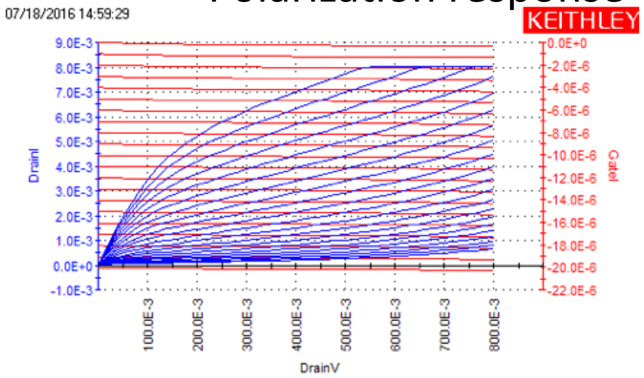
STRIP Unit Level Testing:

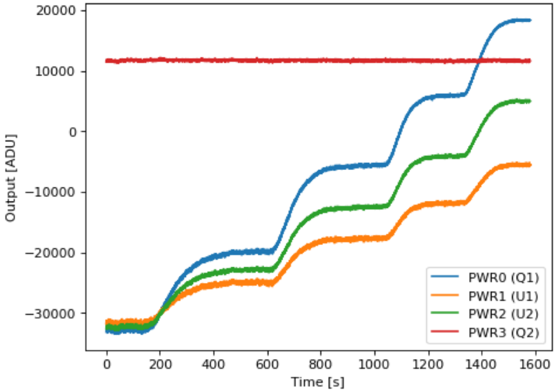
- It is almost a complete radiometer testing
  - Active components verification
  - LNAs bias points
  - Cryogenic set-up
  - Bandwidth
  - Noise Temperature
  - Gain
  - 1/f instabilities
  - Polarization response

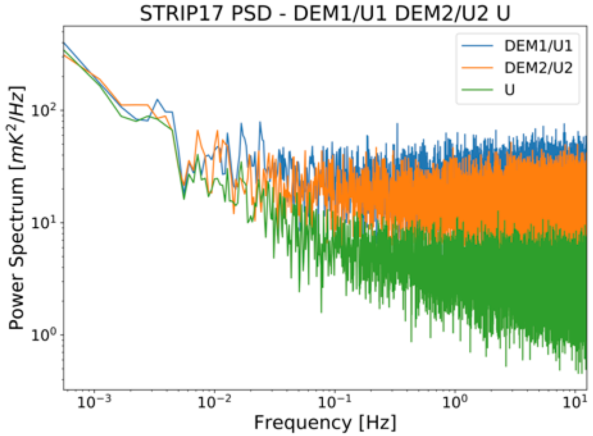




UniMiB Cryo and mm Lab







The STRIP community has a accumulated a deep experience on testing

STRIP Unit Level Testing:

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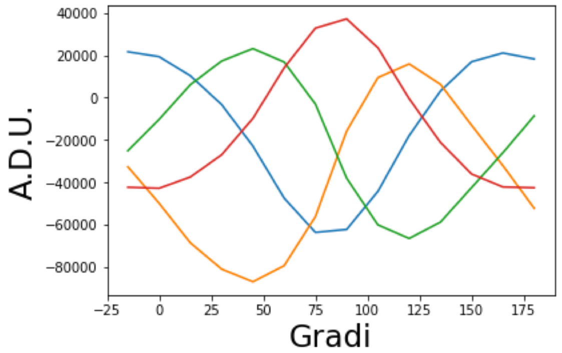
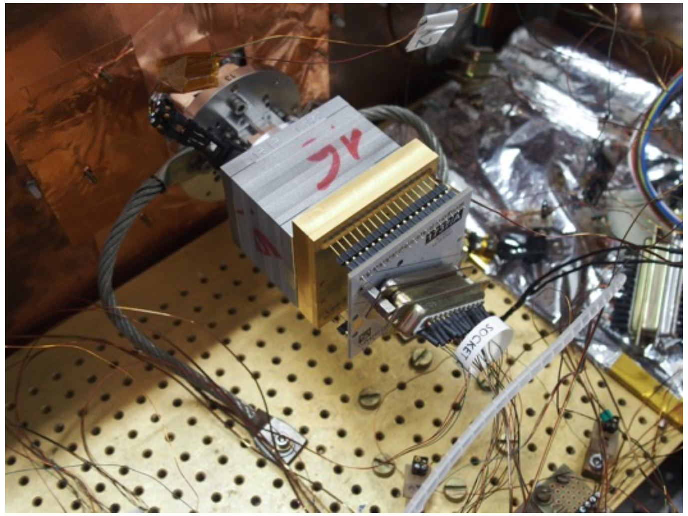
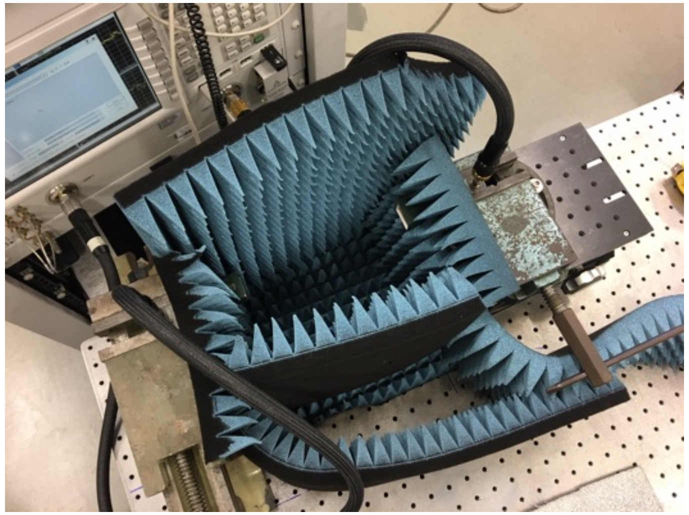
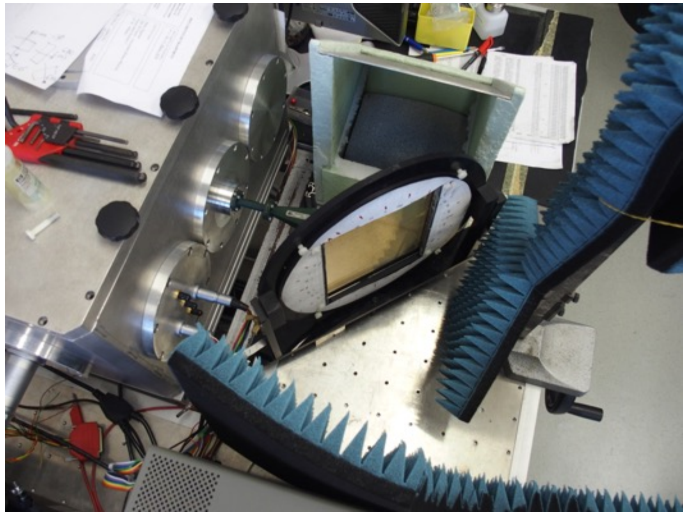


70 polarimeters in Q band
10 polarimeters in W band

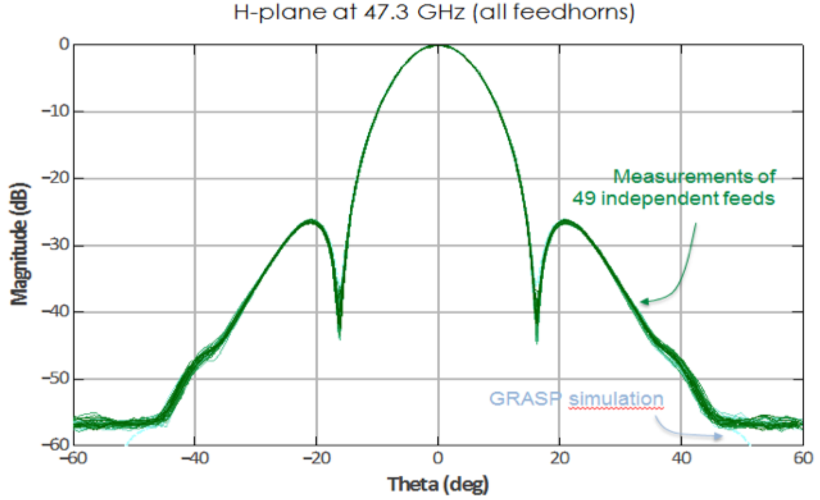


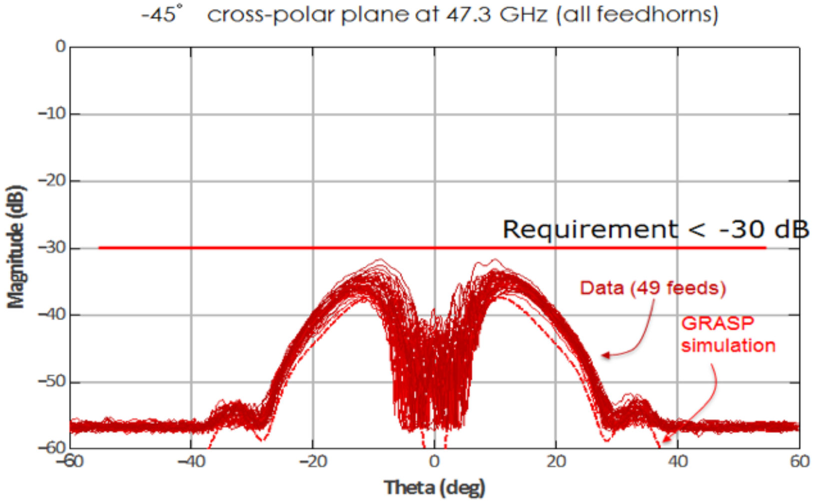




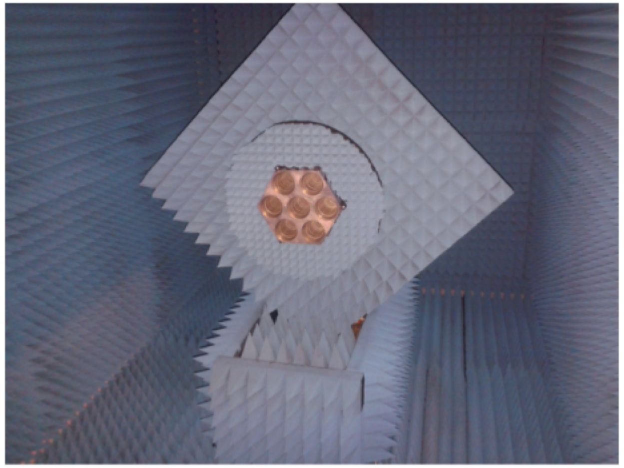
UniMiB Cryo and mm Lab

The STRIP community has a accumulated a deep experience on testing



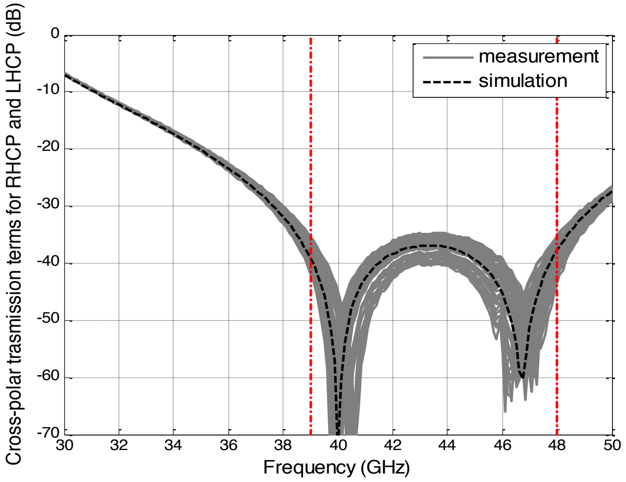


The 49 Q band feeds characterized in the anechoic chamber of the University of Milano

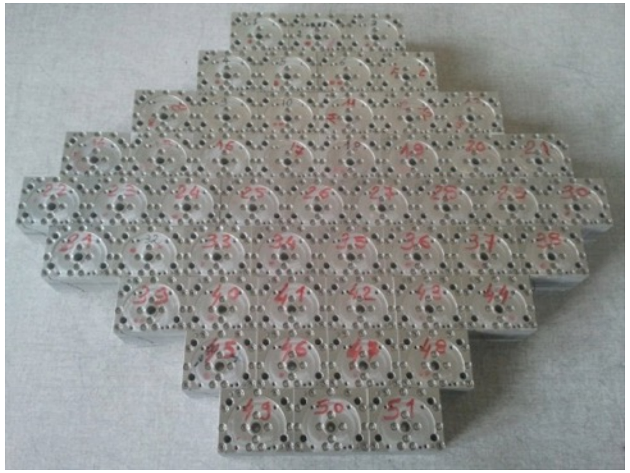


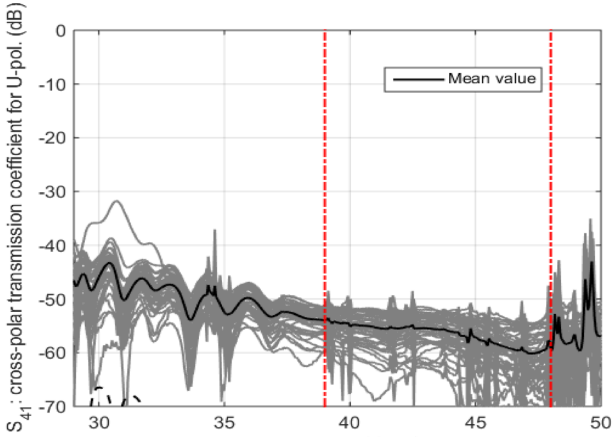
The STRIP community has a accumulated a deep experience on testing

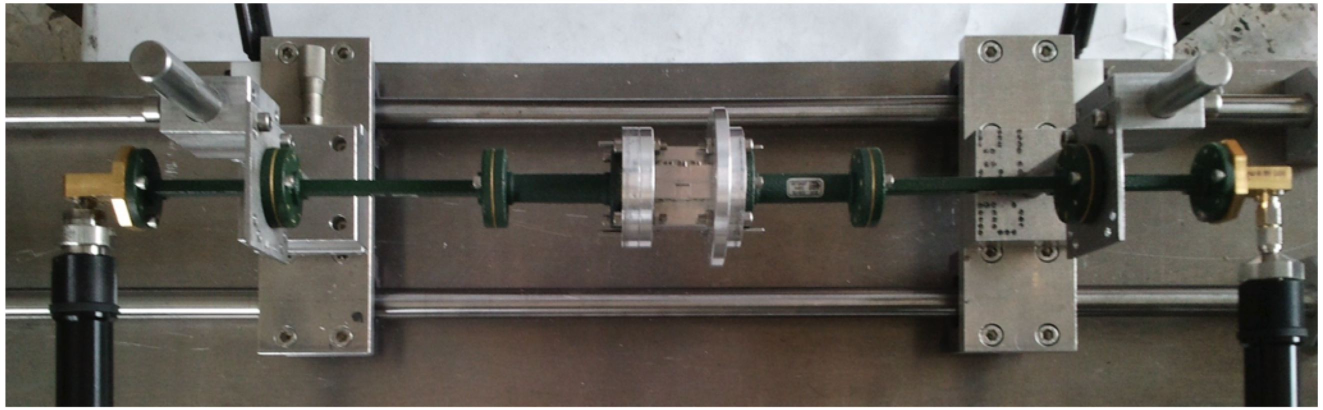
Polarizers



OMTs



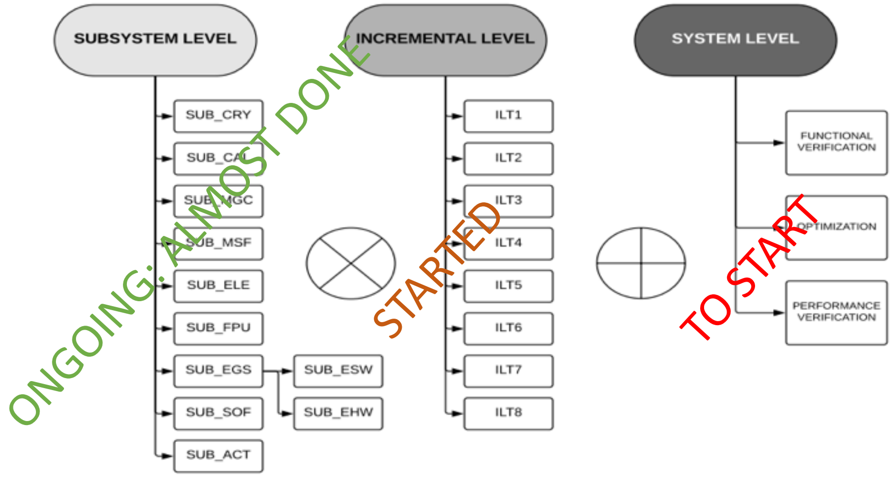


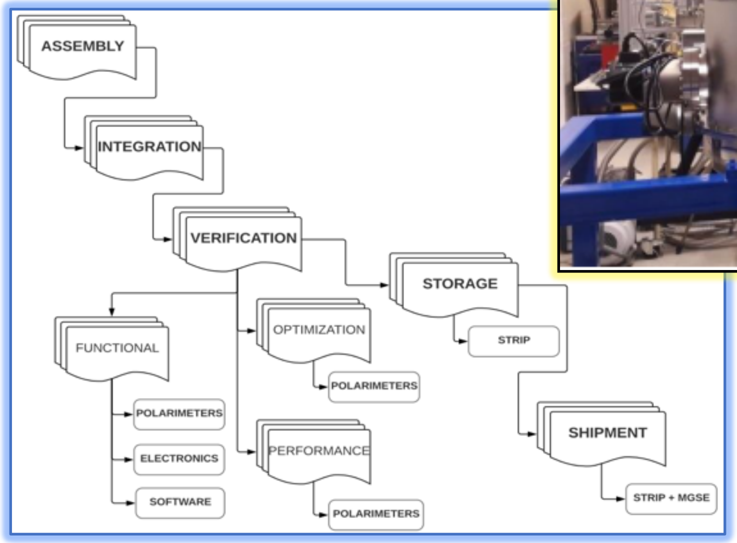


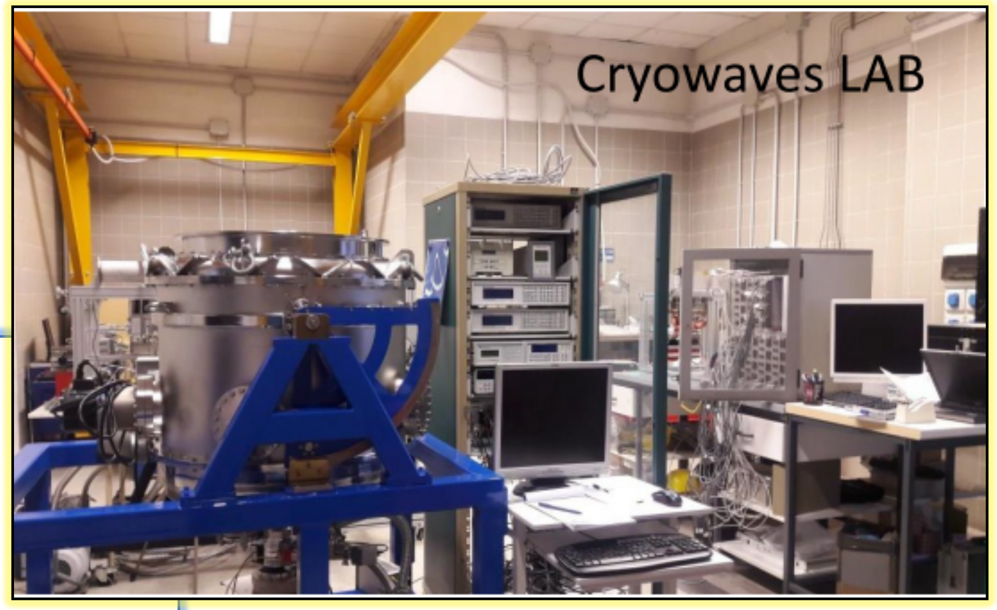
IEIIT_CNR passive components Designed assembled and characterized in house

STRIP System level Tests: Planning (1)

AIV PHASE started on December 2018 and is ongoing in Bologna at the INAF-OAS *Cryowaves* Lab (see also the F. Villa Talk).
End foreseen by late Summer 2019 (TBC).
STRIP is a complex instrument: planning the test campaign is fundamental for its success.

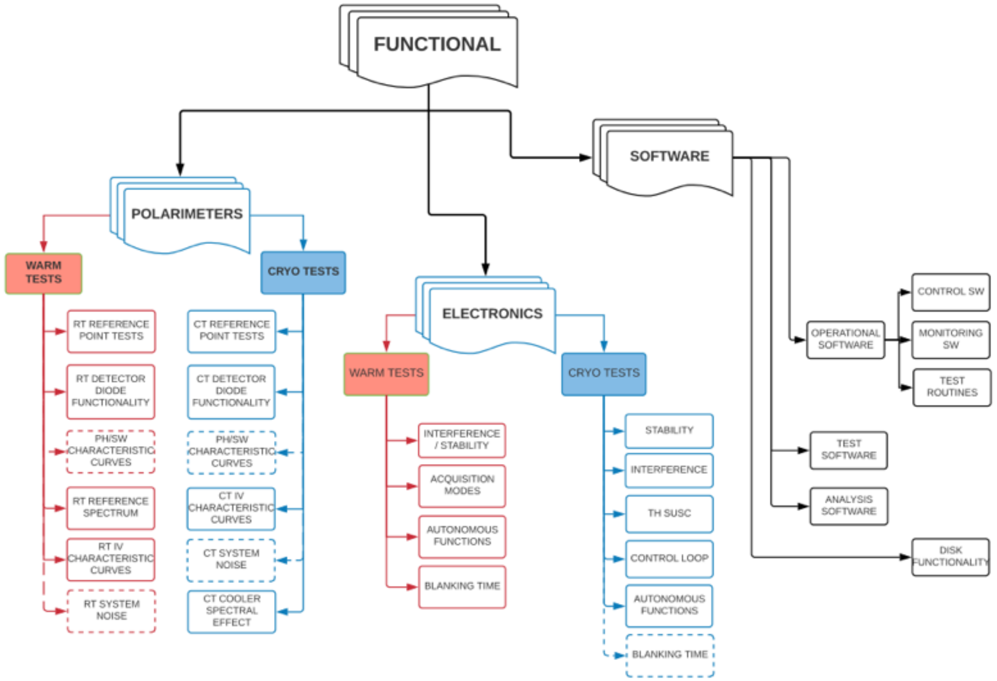


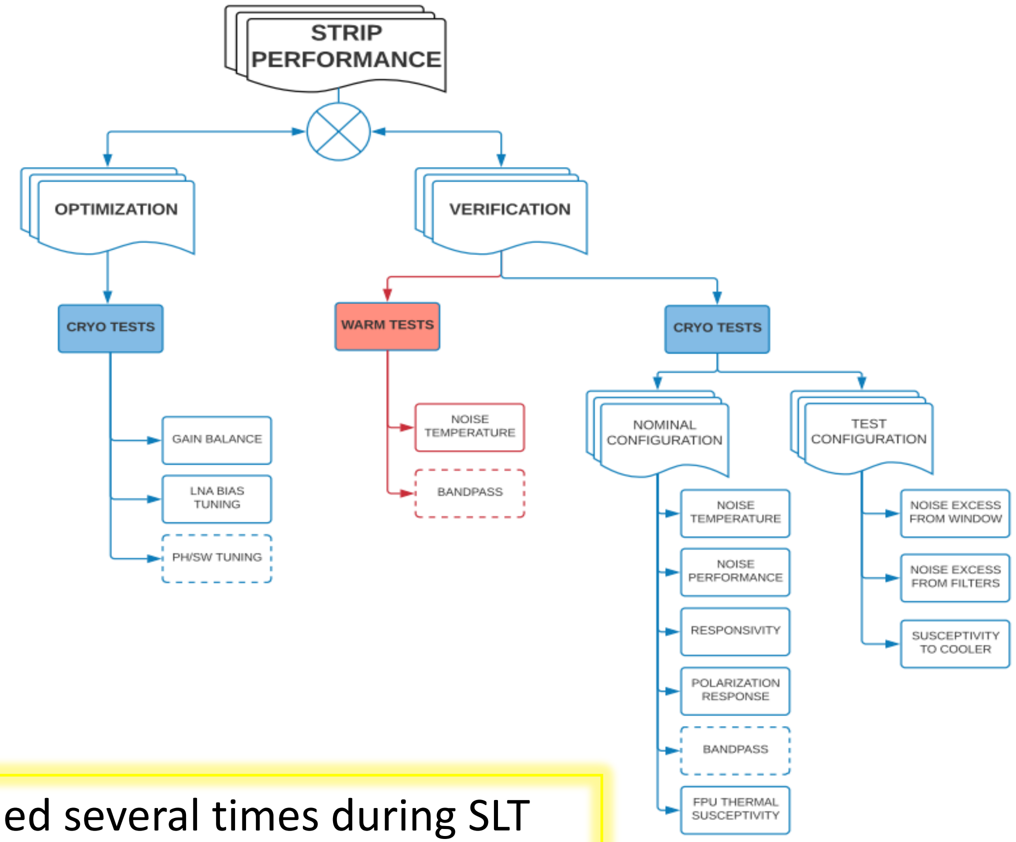




STRIP System level Tests: Planning (2)

FUNCTIONALITY TESTING IS AS IMPORTAN AS PERFORMANCE





- Functionality is being routinely verified several times during SLT
- Results set reference points for future (operations) health checks

STRIP System level Tests: characterizations

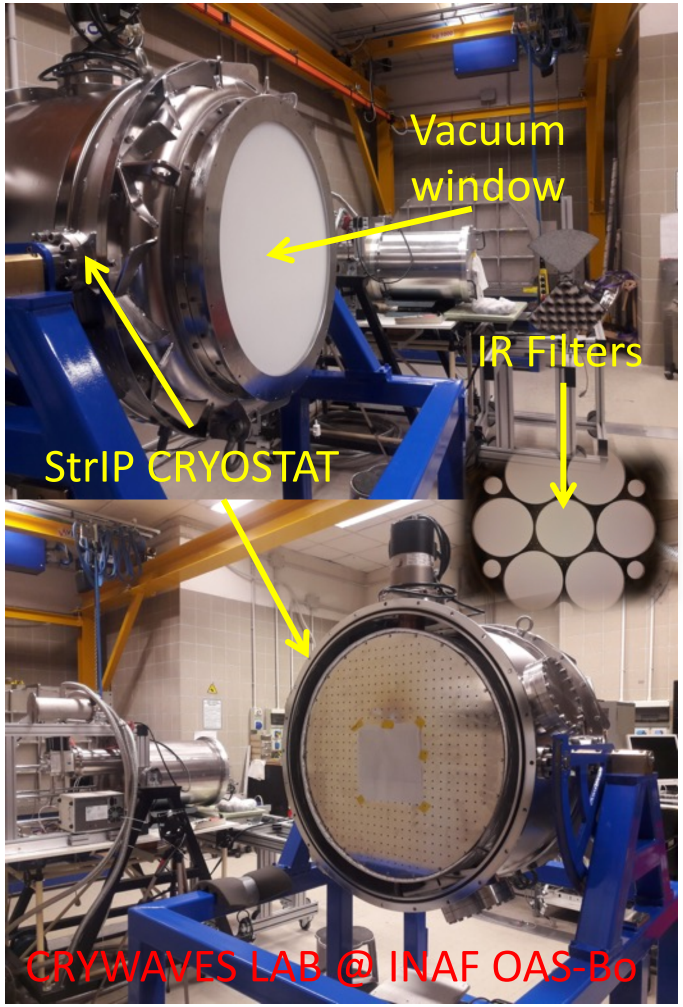
WHAT TO CHARACTERIZE IN STRIP
(or in instruments with similar radiometric architecture)

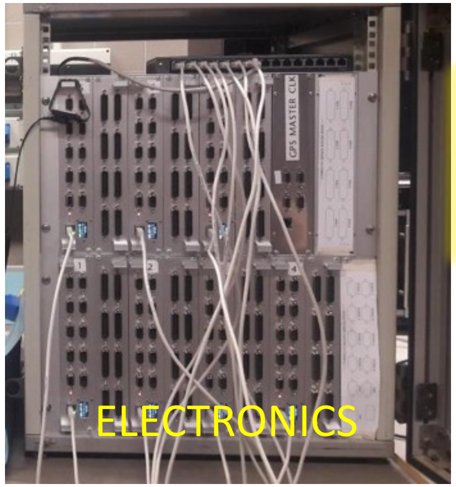
- Noise: System Temperature/WN , 1/f
- Response : Gain/Bandpass, I responsivity, spectral components, spikes, glitches, LNAs Linearity
- Polarization: Q/U responsivity; I->Q/U leakage
- Sensitivity/susceptivity: to environmental thermal conditions (LNAs temperature, Bias supply temperature), to EMC/EMI disturbance, interference to spectral components of the cooler, to instability in the electronics
- Loss: (Noise excess) from the IR filters and from the vacuum window
- Loss :(Noise excess) Electronics: ADU to Physical units transfer functions, bias supply stability, linearity, missing codes, susceptibility. Harness: Intereference between bias lines/ Ph-Sw lines and Sci-signals
- Cryogenic environment: balance of the cryostat thermal model

WHAT TO OPTIMIZE

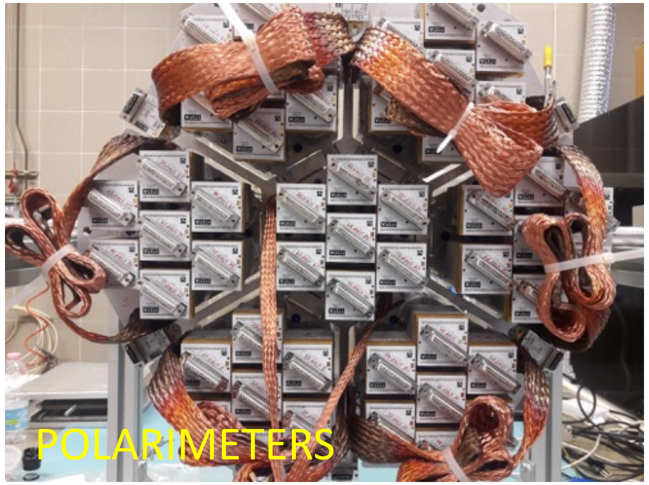
- Noise and Gain (LNAs Bias Tuning)
- Compression point (if needed)
- Balance (paired legs >> LNAs, Ph/SW)
- Default switching state (optimize 1/f, noise, spectral components)
- Blanking time (PH/SW risetime and shape)
- Electronics: dynamic range (Gain/offset >> S/N)
- FPU position in the cryostat
- Cooler/compressor specs

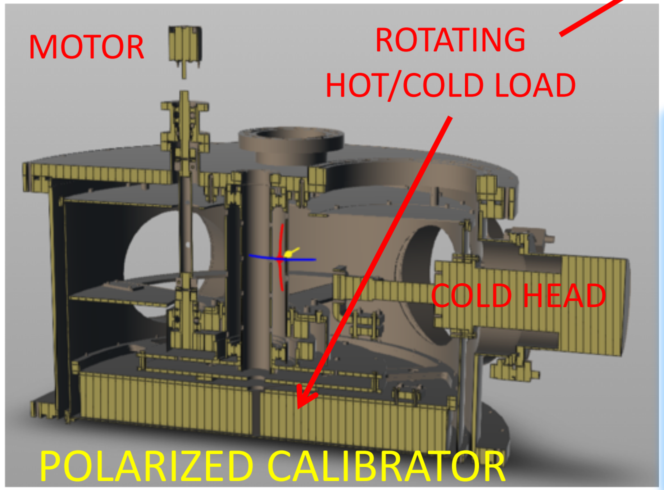
STRIP System Level Tests: Hardware & Equipement @INAF-OAS Bo

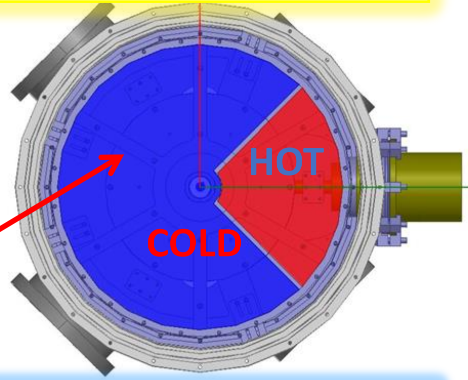




ELECTRONICS:
8 ADC Boards (55 Channels)
8 HK Bias/ Boards (55 Channels)
GPS/SYNC BOARD







CALIBRATOR:
D: 540 mm
2 stages cooler (20K ; 80K)
Emissivity: ε > 0.999
Polarization sensitive: ~ 5 %
T (K): 20K – 50K
IR Filter present
Rotation: -/+ 180°
Cycletime: 10 sec

Calibration

Calibration is performed at various levels

- Lab level with artificial calibrators
- Site level with
  - internal calibrators (calibration marks) to monitor long term performances
  - Far field sources on towers or drones to trace beams and (why not) polarization angles
  - Celestial calibrators

Calibration of the receivers gain stability is one of the main systematic uncertainties of a CMB polarization experiment, especially at the low multipoles

- ❖ Dipole is not a polarized signal (It should be observed in total intensity a thing that high sensitive polarimeters aren't thought for)
- ❖ Few well-known polarized "natural sources" are available
- ❖ A limited portion of the sky can be observed by ground-based observations and strong "natural calibrators" (e.g. Crab Nebulae, Moon, etc.) could be not always observable
- ❖ **Need for artificial calibrators to calibrate STRIP receivers**
  - ➢ **Internal calibrator** (for relative power monitoring during STRIP operations)
  - ➢ **System calibrator (in the lab: cryogenic polarized calibrator)**

Routine calibrations are essentially monitors of performances: STRIP internal calibrator example

Objectives

- Monitoring and calibration of the gain stability of the LSPE-STRIP Q/W receivers

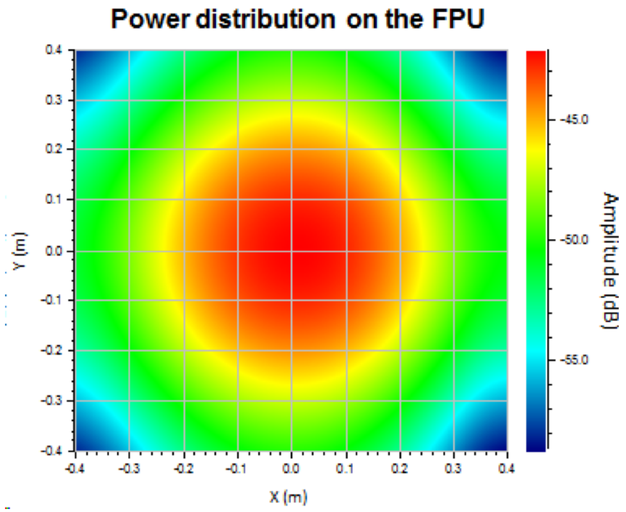
Technical requirements

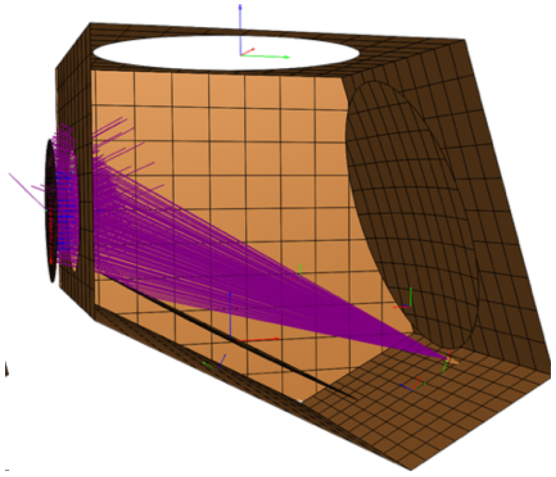
- Input power at receivers should not be much greater than sky signal
  - P_cal < -85 dBm at the polarimeters input
  - S/N ratio guarantees fast calibration time
- Power stability (of order of 0.05 dBm)
  - vs environment temperature changes
  - vs time

Proposed solution

- **High stability power source directly illuminating Q/W feed-horns of the FPU**

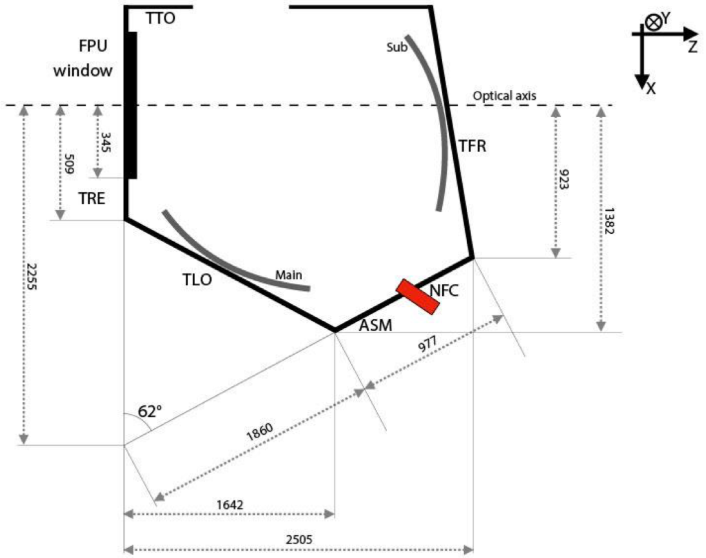
STRIP Internal Calibrator



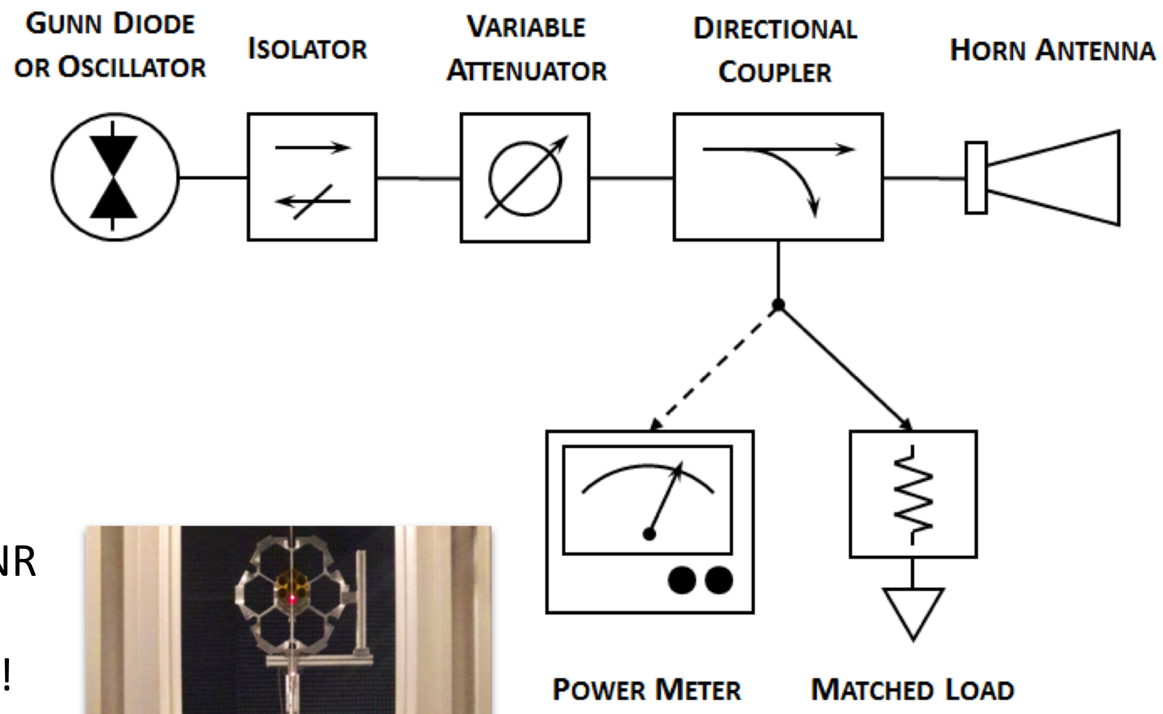


Study of the optimal illumination with GRASP

- ❖ Internal calibrator is placed between the two reflectors
- ❖ Direct illumination of the STRIP FPU
- ❖ Optimization of the polarization angle of the source radiation
  - ➢ Q-band: ~22.5° from the vertical polarization
  - ➢ W-band: 7.5° (or multiples) from the vertical polarization



STRIP Internal Calibrator



Conceptual design of Q/W internal calibrator

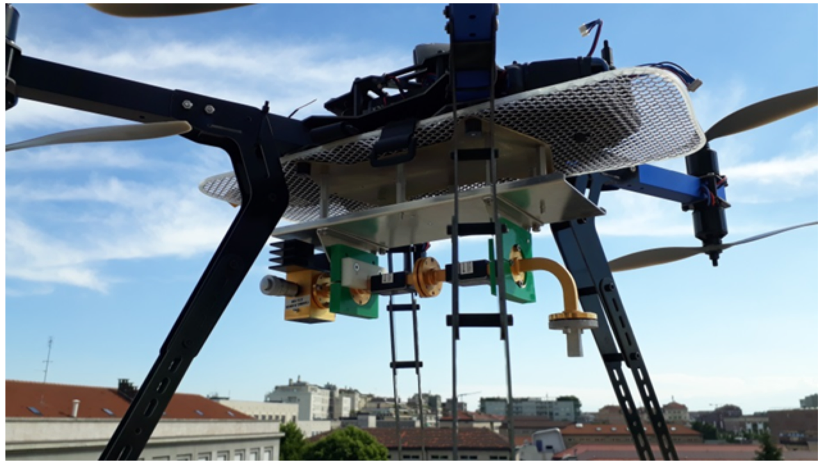
- Q-band calibrator is **based on VCO**
- W-band calibrator is **based on Gunn diode**
- No broadband noise source has been used due to low ENR
- Both Q and W band sources allow for in band calibration!
- Tone frequency sweep
  - Q-band: 39-48 GHz
  - W-band: 91-97 GHz

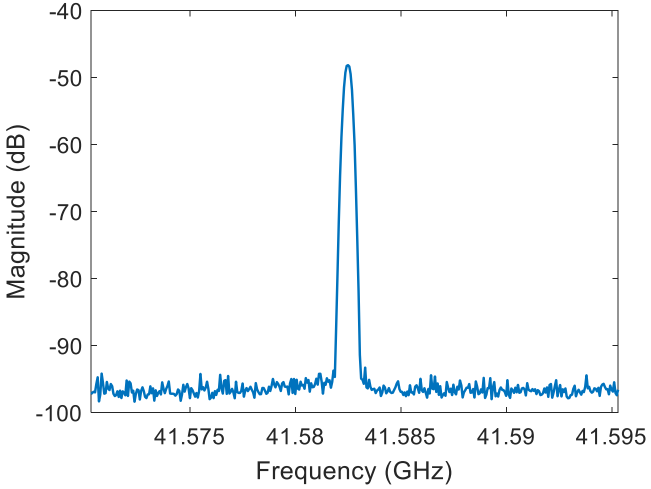
Far Field Calibration Sources

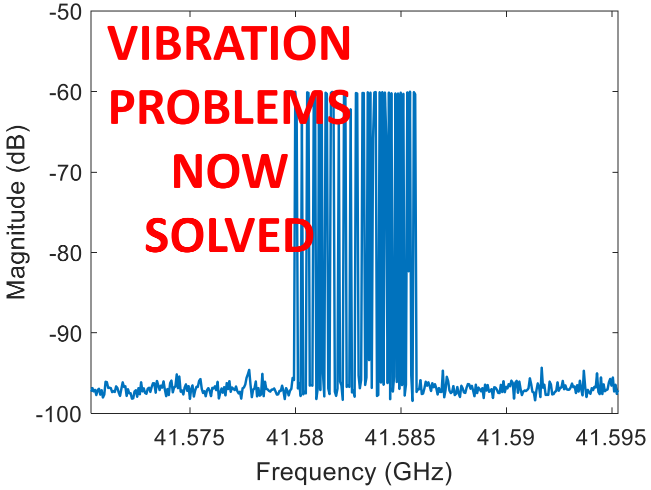
By DRONE (developed by CNR-IEIIT in Turin)

Heritage of SKA activity

Beam Pattern testing







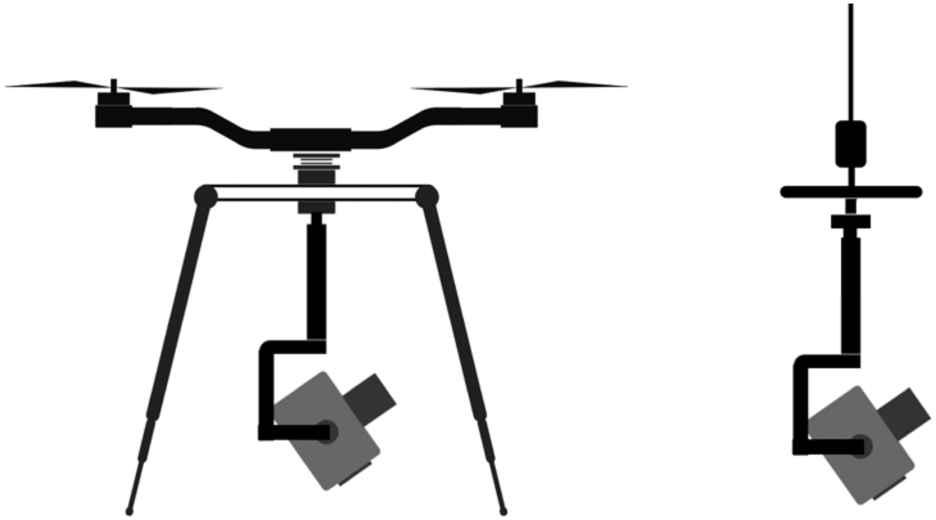
Requirements for artificial calibrators

1) Far field distance

2) High elevation to stay away from ground signals, so the source should be mounted on something that flies (drones, balloons, satellites…)

3) Fully operative experiments (deployment during telescope operations)

4) High accuracy, well characterized sources (need a lot of work in the lab)



Artificial calibrators

Well characterized, bright, modulated point source in the **far field**, visible for enough time at high elevation angles

$$d_{\mathrm{f}} = \frac{2D^2}{\lambda}$$

For small apertures (<1m) and/or low frequencies(<60GHz)

$d_f \sim 10^2$ m

It goes up to $d_f \sim 10^3$ for larger diameters and higher freqs

Calibrator accuracy

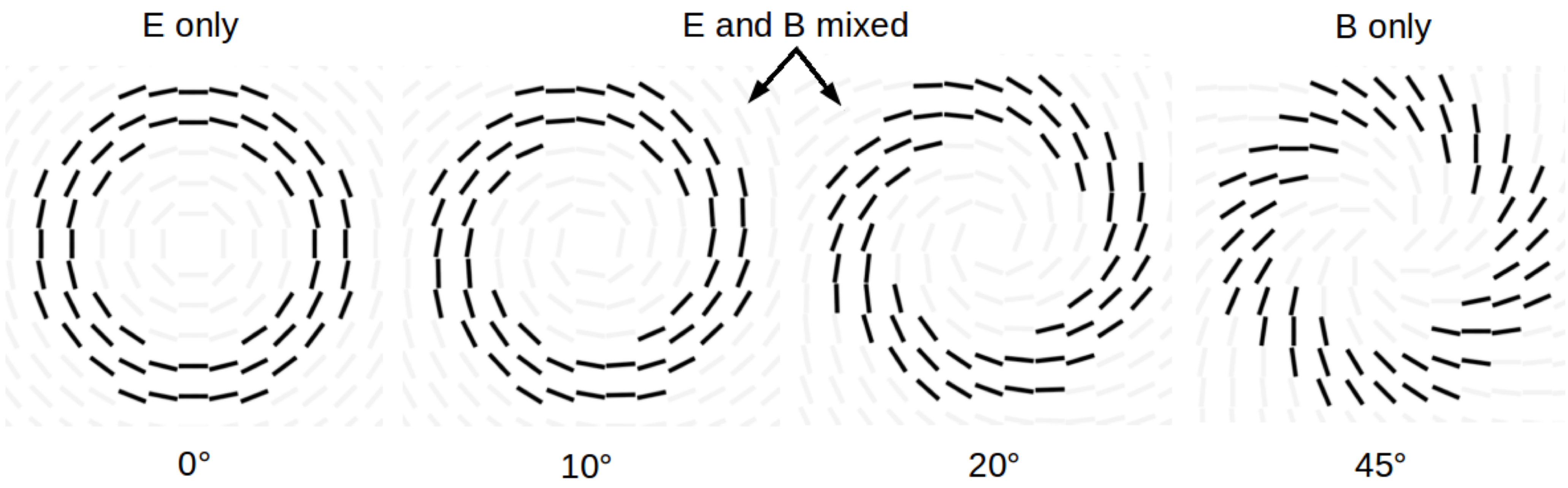
Position Accuracy: From GPS ~2 m, which translates in ~1° for a drone, 20 arcsec for a balloon, subarcsec for a satellite

Angle Accuracy: ~1 arcmin. Subarcmin (i.e. ~20 arcsec) harder but feasible in principle

Source emission accuracy: depends on the source.

For example, a narrow band source based on a Gunn has a typical frequency Stability of ~5MHz/°C, Power Stability: ~10^{-2} dB/°C, Bandwidth: ~2% of central frequency. Programmable sources are more stable when used on drones and can do frequency sweeps.

Absolute Polarization Angle



Absolute Polarization Orientation refers to the polarimeter detectors' direction measured in celestial coordinates. A miscalibration (i.e. a rotation bias for the detector orientation) mixes E and B modes. Such a ***systematic*** rotation is degenerate with Cosmic Birefringence (CB or CPR). It also affects other cosmological parameters.

Absolute Polarization Angle

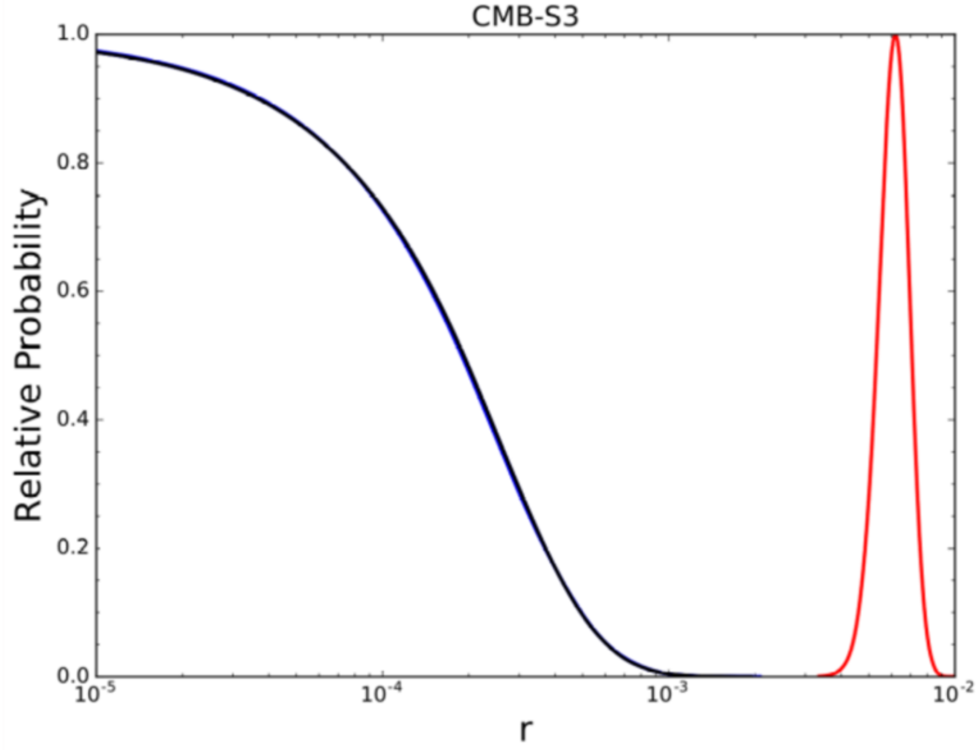
It is hard!

Uncertainty range: Existing experimental methods provide accuracy of ~1deg.
A miscalibration of 0.5 deg in the polarization orientation translates into a spurious B-mode signal corresponding to a tensor-to-scalar ratio of $r \sim 0.01$.
Smaller values of r will require sub-arcmin accuracy.

“Self calibration” methods suffer from foreground emission and limit science goals

Absolute Polarization Angle is a small, but critical systematic.
Several science goals involved

Absolute Polarization Angle



Plot by L. Pagano
From Nati et al. 2017

RED: rotation of 1°, corresponding to current accuracy
BLUE: rotation between 0.01° and 0.001°

Celestial calibrators fit for STRIP and other northern sky telescopes

The main sources detected in intensity and polarization by WMAP (see Weiland et al., 2011) and PLANCK (see Ade et al., 2016).

WMAP observed **10** objects in five frequency bands (23–94 GHz):

- the outer planets (Mars, Jupiter, Saturn, Uranus, and Neptune)
- five fixed celestial sources (Cas A, Tau A, Cyg A, 3C274, and 3C58)

PLANCK observed more than 100 polarized sources in 9 spectral bands, from 30 to 857 GHz.

Main polarized sources, suitable for calibration purpose from STRIP site, are:

- Cas A
- Tau A
- Cyg A
- 3C274
- 3C58.

Supernova Remnants

Quasars

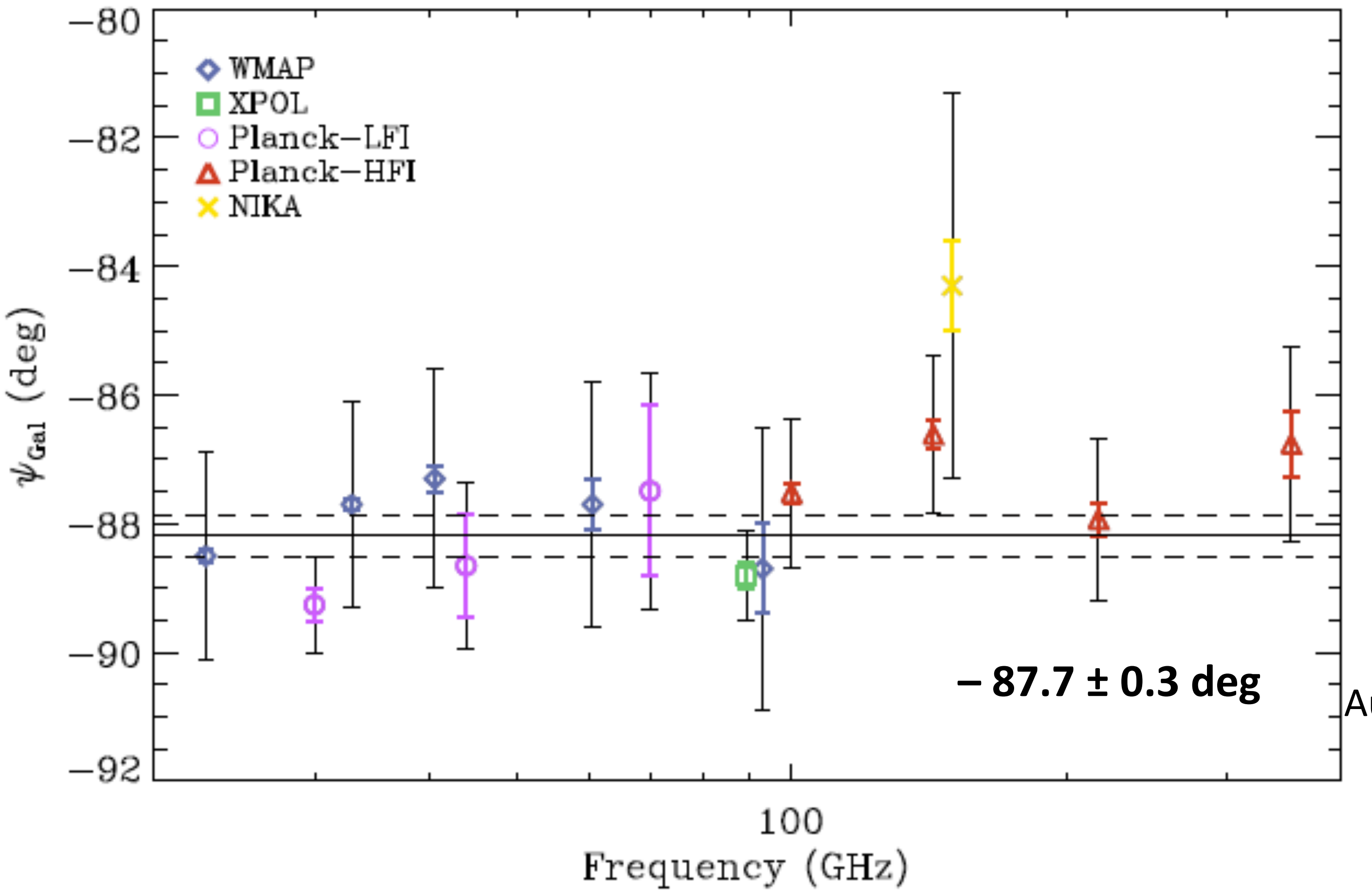
Let’s focus on Tau A

Tau A is an extensively studied **supernova remnant**, hosting the CRAB pulsar, originated around year 1054 at 2kpc from the Earth at the position: RA (hms) = 05 34 32; dec (dms) = 05 34 32.
Angular extension is **7x5 arcmin**, expansion rate is 1500 km/s. Microwave emission is mainly synchrotron. Observed **flux** in W-band is S ~ 215-260 Jy; in Q-band S ~ 315-290 Jy. **Polarization** degree ~ 7%.

In the last years **Crab Nebula** has been observed in intensity and polarization by:

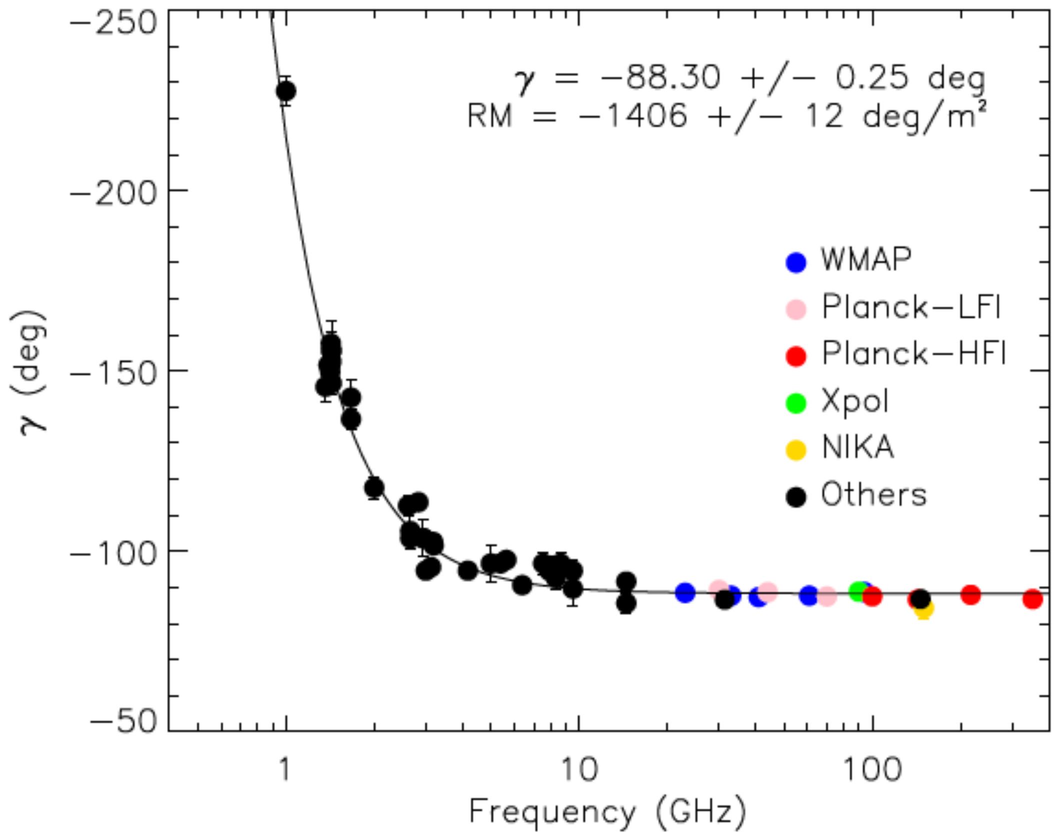
- **IRAM telescope at 90 GHz** (Aumont, J., et al., 2010),
- **WMAP** in five bands, from 23 to 94 GHz (Weiland et al., 2011),
- **PLANCK** in 9 bands, from 30 to 857 GHz (Ade et al., 2016, 2018),
- **IRAM telescope at 150 GHz** (Rittaco et al., 2018).

Combining all recent measurements at different frequencies, and assuming no variation of the **polarization angle** with frequency, Rittaco et al. (2018) derived a value of **– 87.7 ± 0.3 deg**.



Aumont, et al., (2018)

Measurements at lower frequencies are affected by **Faraday rotation**. A fit to all data leads to a polarization angle compatible with the previous value.



Genova-Santos, et al. (2018)

Genova-Santos et al. will conduct **SRT-SARDARA** observations to map the polarized emission of the entire **Crab nebula**
The expected **statistical error** on the polarization angle will be **0.1 deg** per channel or sub-band (32 independent measurements in K-band)

(Potential) Pretty good news from C-Bass! 0.1 deg accuracy

Conclusions

- The route to $r=10^{-3}$ passes through testing and calibration
- To observe CMB most of the time is spent in the lab also to work on calibrators
- The design of a new instrument must incorporate AIV plan
- The investment in expertise and facilities (order is not by chance) is time consuming and money can’t accelerate it