

# L-Band All Sky Survey

## L-BASS

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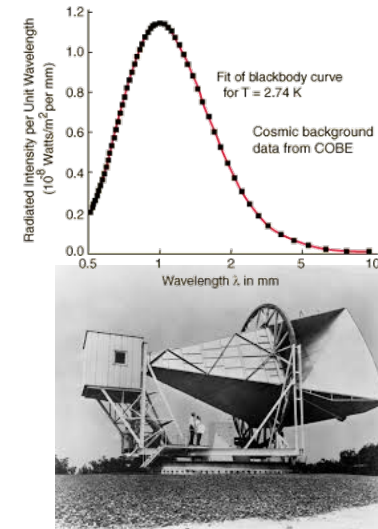
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# Overview - 1

Radio sky mapped at many frequencies and resolutions:

- In space: absolute calibration to  $\ll 0.1\text{K}$  has been achieved @  $>30\text{ GHz}$  (COBE 1990)
- Ground-based at low frequencies (large size of antenna)
  - Antenna temperature from reflecting dishes not well-calibrated against an absolute temperature scale (sidelobes)
  - Penzias & Wilson: *horn* @  $4\text{ GHz}$ :  $\Delta T \sim 1\text{K}$  (but no maps)



## New Astrophysical Motivations for absolute calibration to 0.1K

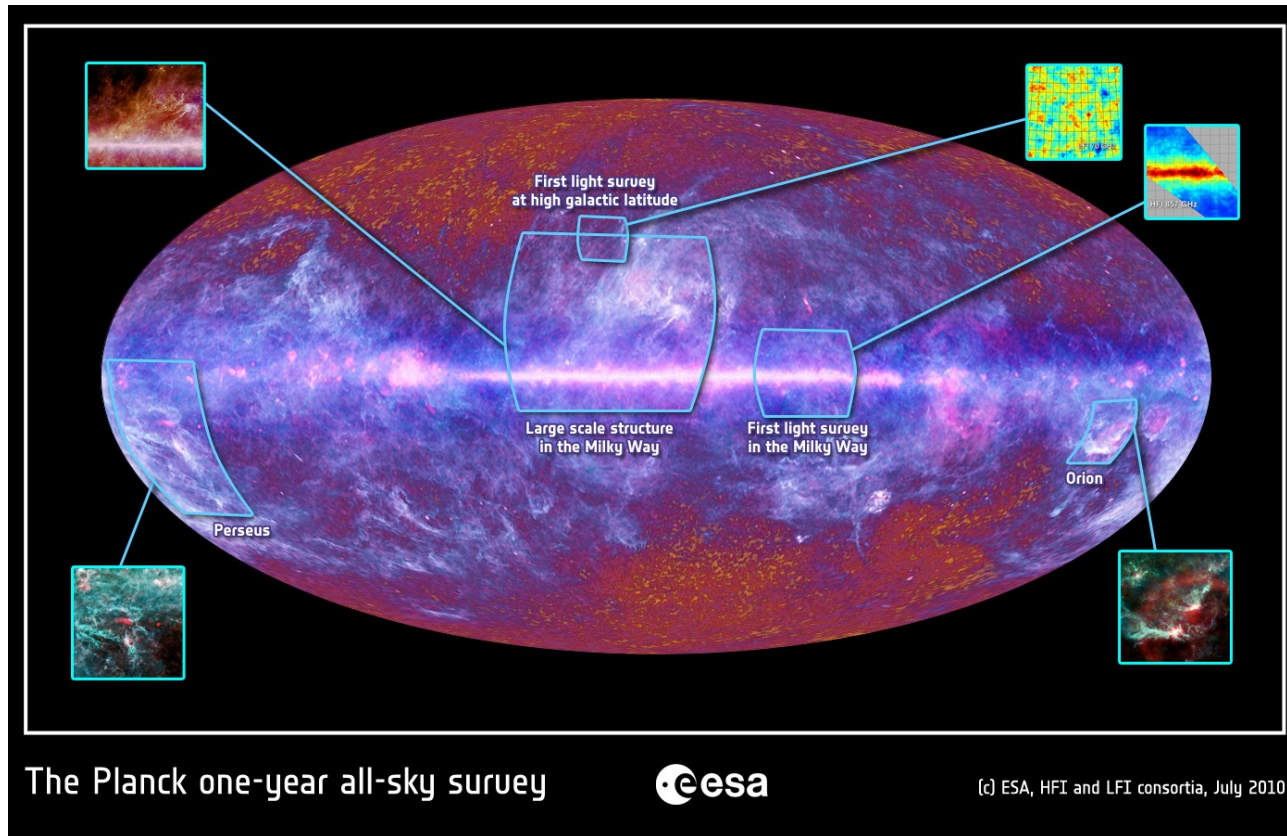
- Fundamental calibration of Galactic “foreground” radiation obscuring the Cosmic Microwave Background (CMB) radiation.
- Settling the ARCADE-2 “unexpected emission at  $\sim 1\text{GHz}$ ” claim
- Probing the early universe via deviations from CMB Black Body

# Overview - 2

## A combination of innovations in our approach:

- Ultra-stable CMB spacecraft-type receiver: measures the power difference between two input channels.
- Two identical large horn antennas with ultra-low sidelobes:
  - one looks at NCP to provide a fixed reference;
  - one scans the meridian to map the *relative* sky to  $\sim 1\text{mK}$
  - cost-effective corrugated horn construction
- Large black-bodies are difficult to make  $\rightarrow$  establish the *absolute* temperature of the NCP to 0.1 K by swapping one horn for matched coaxial load in an active cryostat.
- Measure variations in atmospheric emission

# Science: Planck mission 1st year map

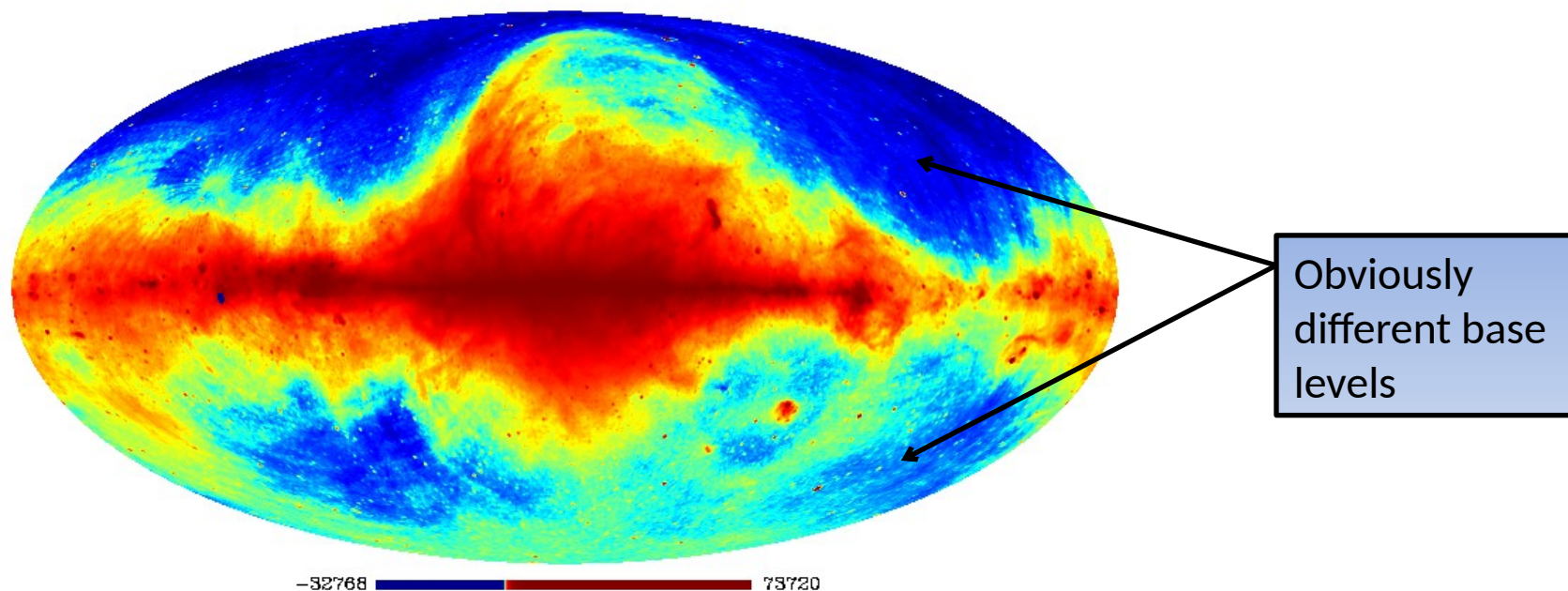


Multi-frequency maps are required to dissect and subtract out the emission from the Milky Way arising from several different radiation mechanisms.

Comparable resolution low frequency maps can only be made from the ground with large reflecting antennas.. BUT

# Problem: 1.4 GHz map made with big dishes

reich\_lb21\_ns512.fits: UNKNOWN1



Maps made with reflecting antennas *always* suffer from unmodelled position-dependent sidelobe pickup → base levels are poorly calibrated.

May play role in discordant fits at low resolution from Planck maps with otherwise successful cosmological theory ( $\Lambda$ -CDM)

# The ARCADE2 mission (prime: JPL)



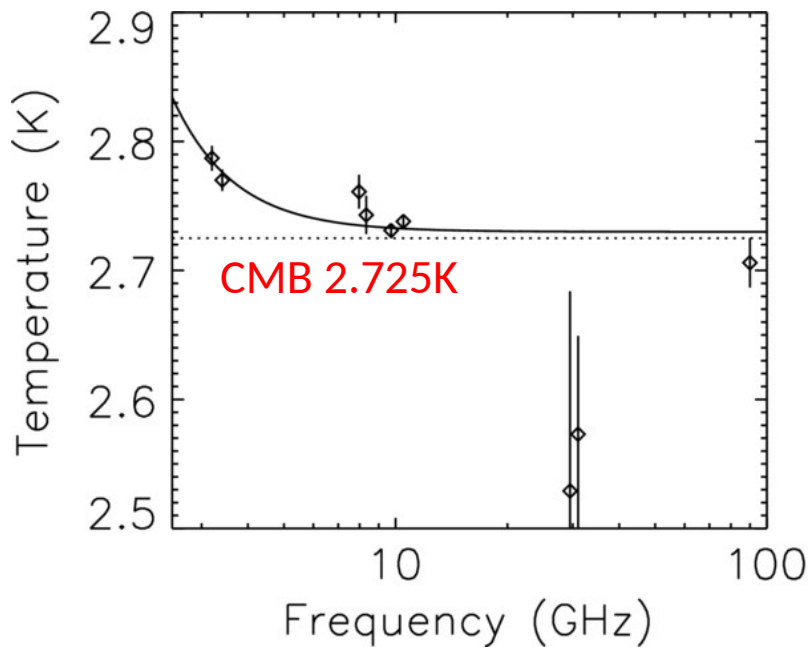
2006 flight of a balloon-borne radiometer suite from 3-30 GHz

Calibrated with respect to cryogenically-cooled black-body (absorber) loads

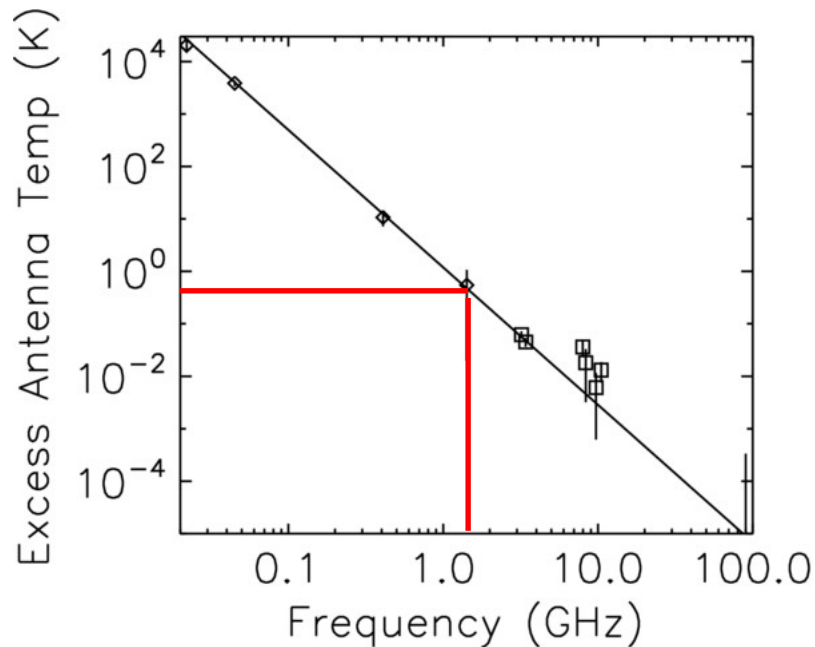
Claim unexpected component of all-sky emission contributing  $\sim 1\text{K}$  at 1 GHz

Many recent theory papers interpreting this result e.g. as annihilation from Dark Matter.

# ARCADE2 excess emission



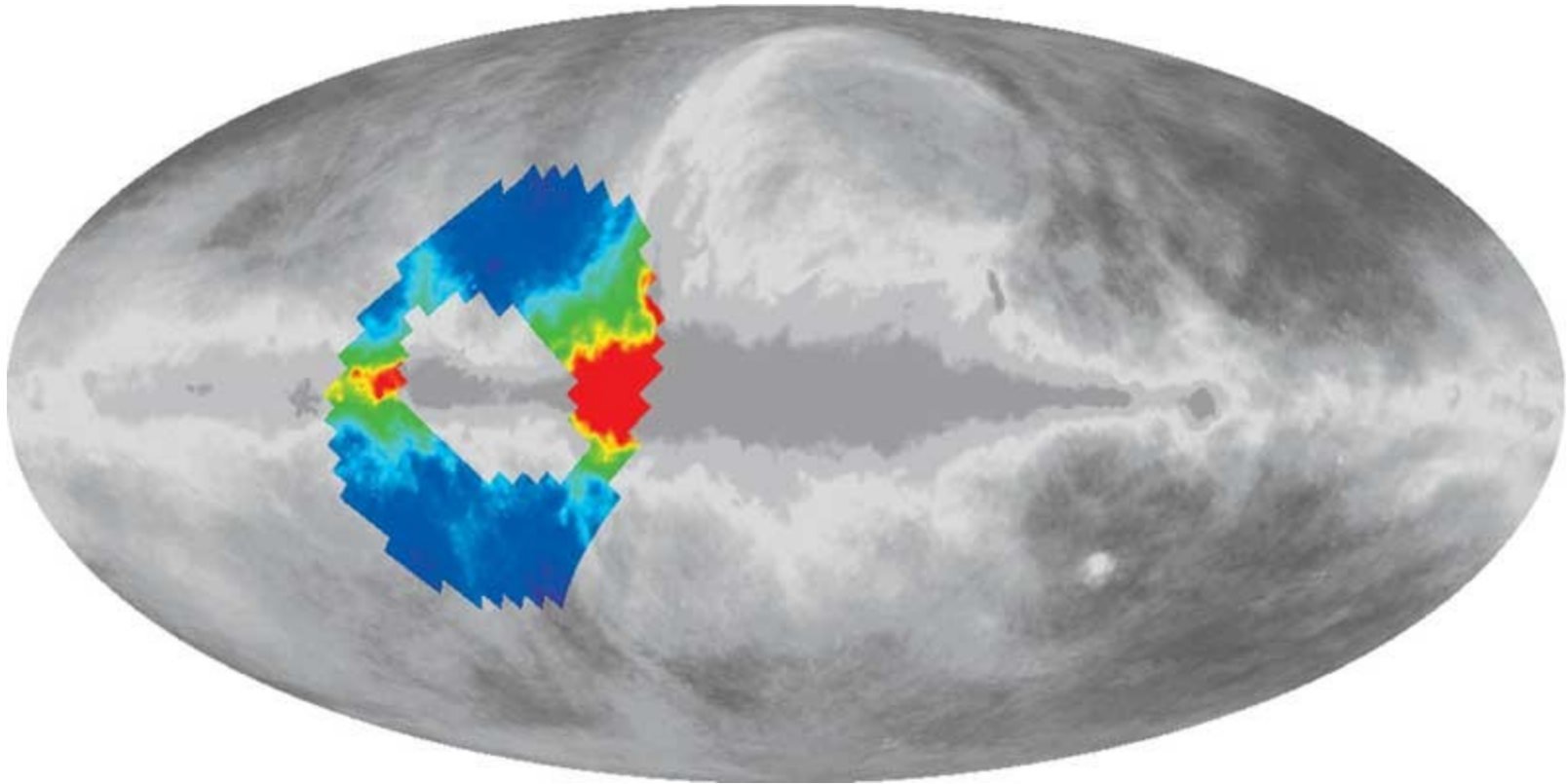
Measurements down to 3 GHz



Extrapolation down to 10's MHz

Predicted excess at 1.4 GHz: 0.5 – 0.6 K

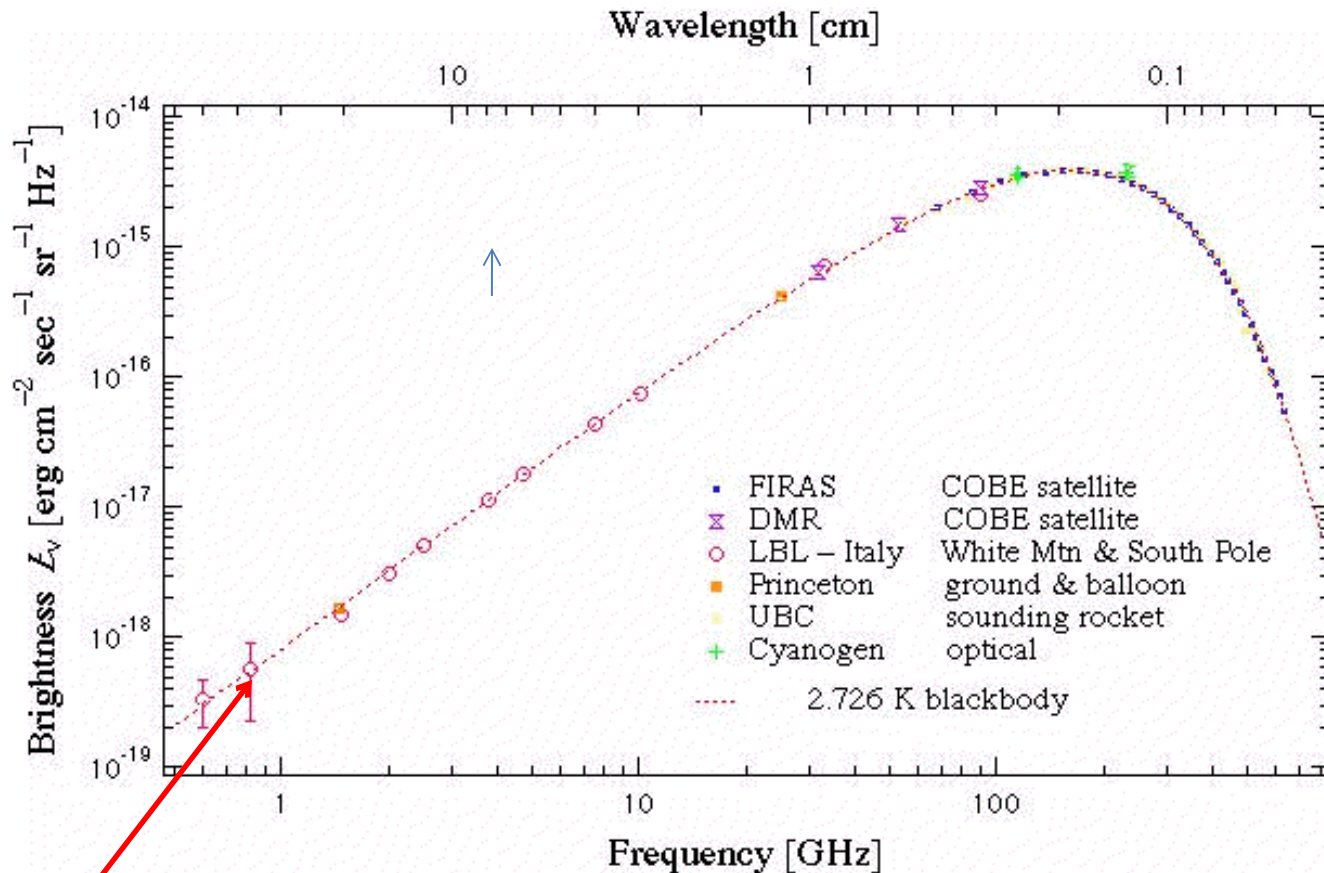
## ARCADE-2's weakness ?



ARCADE viewed only  $\sim 7\%$  of the sky (coloured)

Inadequate subtraction of the Galactic emission is the potential Achilles heel so we aim to map the entire sky.

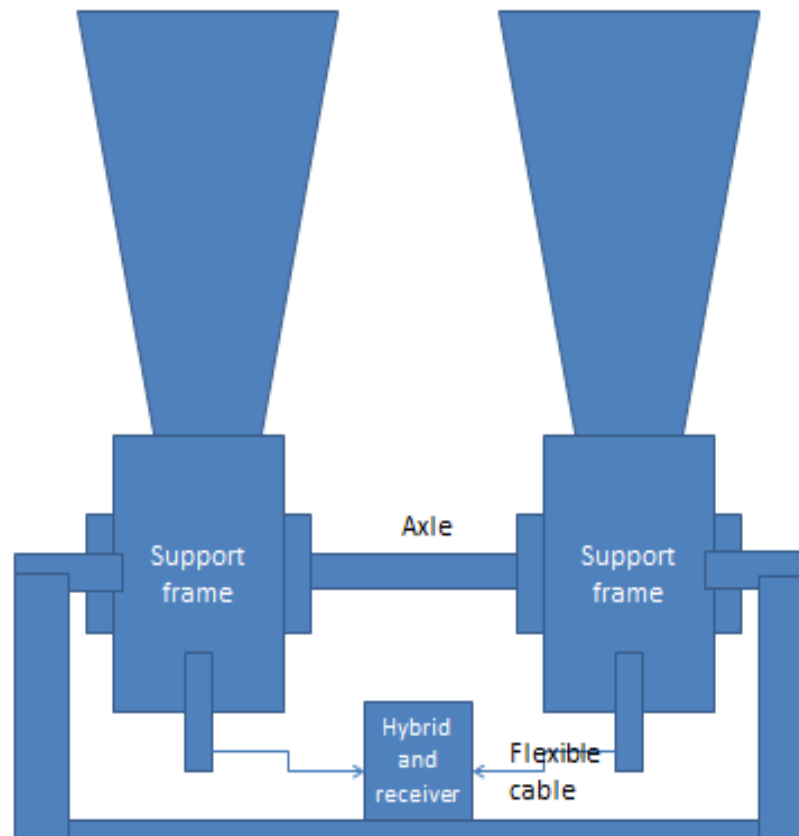
# CMB deviations from Black-Body



Measurements of (or limits on) deviations from perfect Planck curve around 1 GHz can provide information on Universe at age 10,000-20,000 years

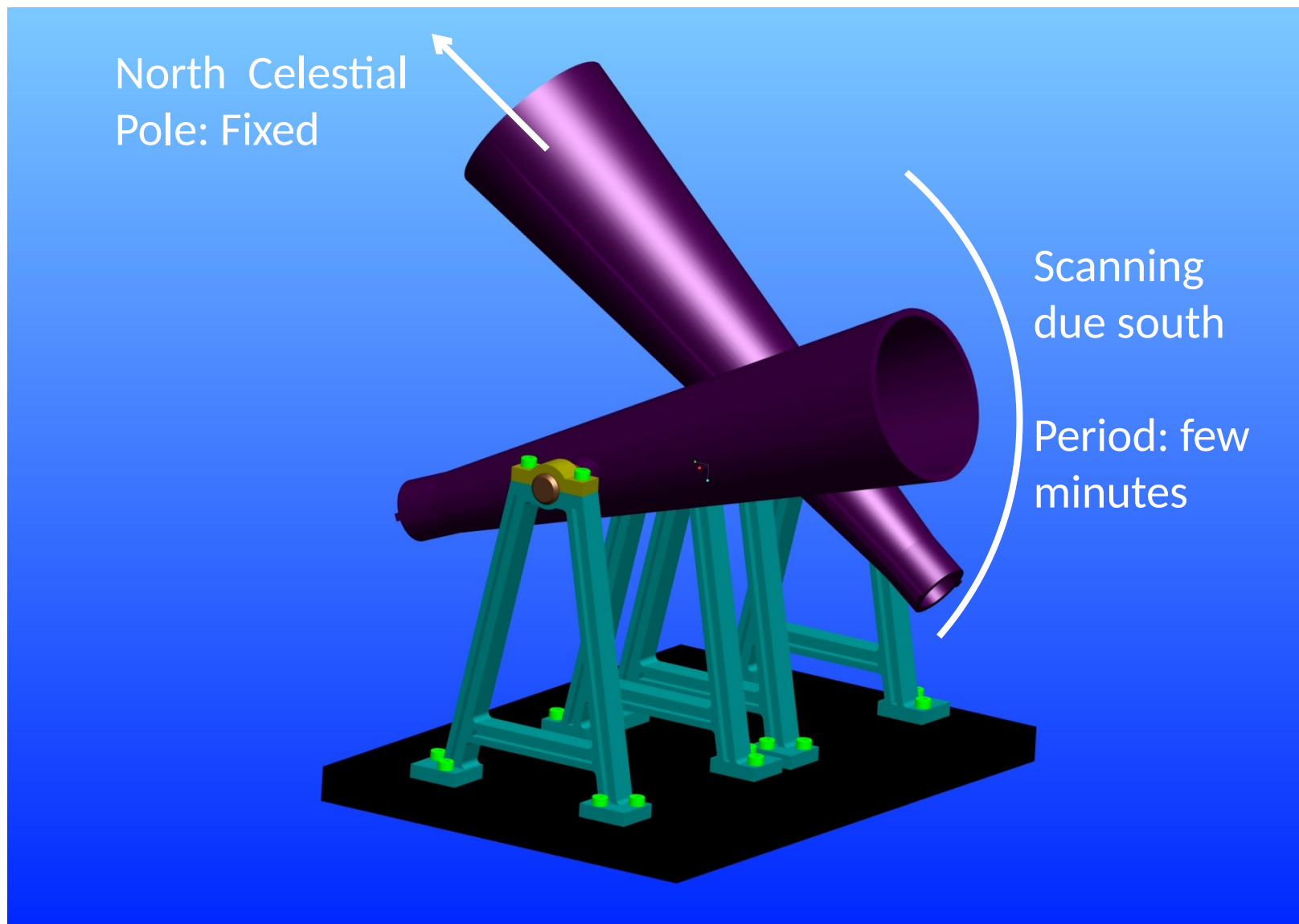
- Need accuracy of  $<0.1\text{K}$
- Current best limits  $\sim 0.2\text{K}$
- Will produce a paper!

# Initial schematic of set-up



Use low loss cables for well-calibrated and reliable connection between horns and static receiver (cf. waveguide joints)

## A new schematic of set-up



# COBE Satellite Horn (JPL 1980)

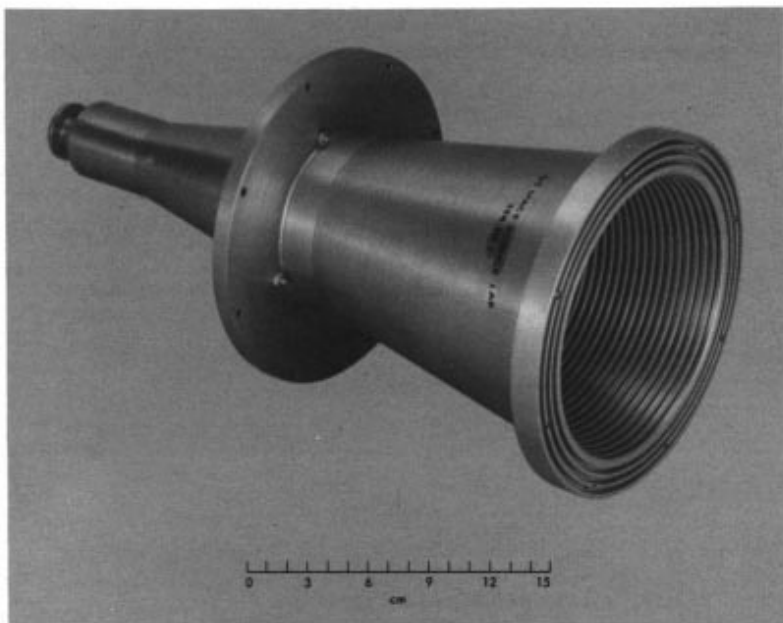


Fig. 1. Test horn—corrugated, conical scalar feed horn antenna. Flare angle is 10 deg, and groove spacing is approximately 0.5 wavelengths. Choke grooves on rim face are to suppress potential backlobe radiation.

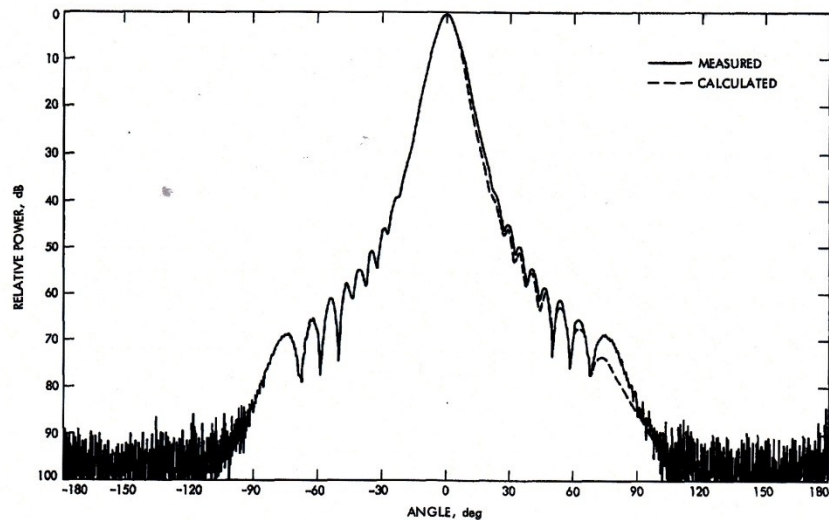


Fig. 4. *H*-plane radiation pattern of test horn. Receiver noise dominates below 90 dB.

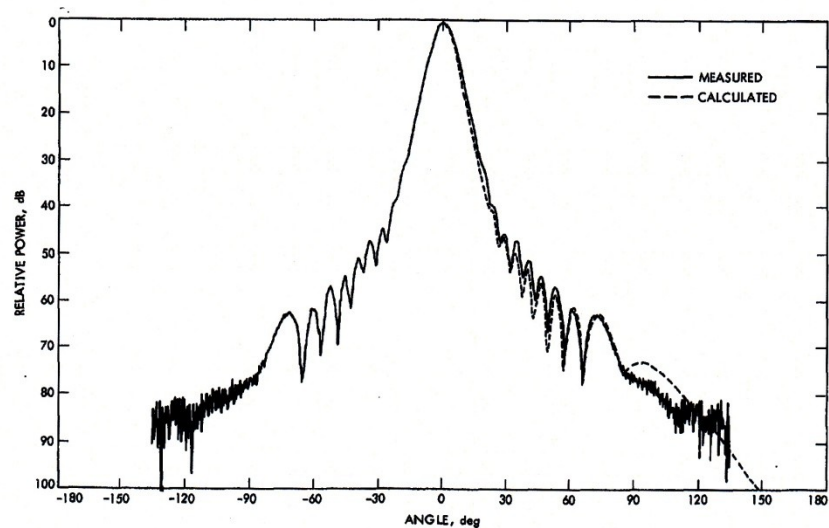
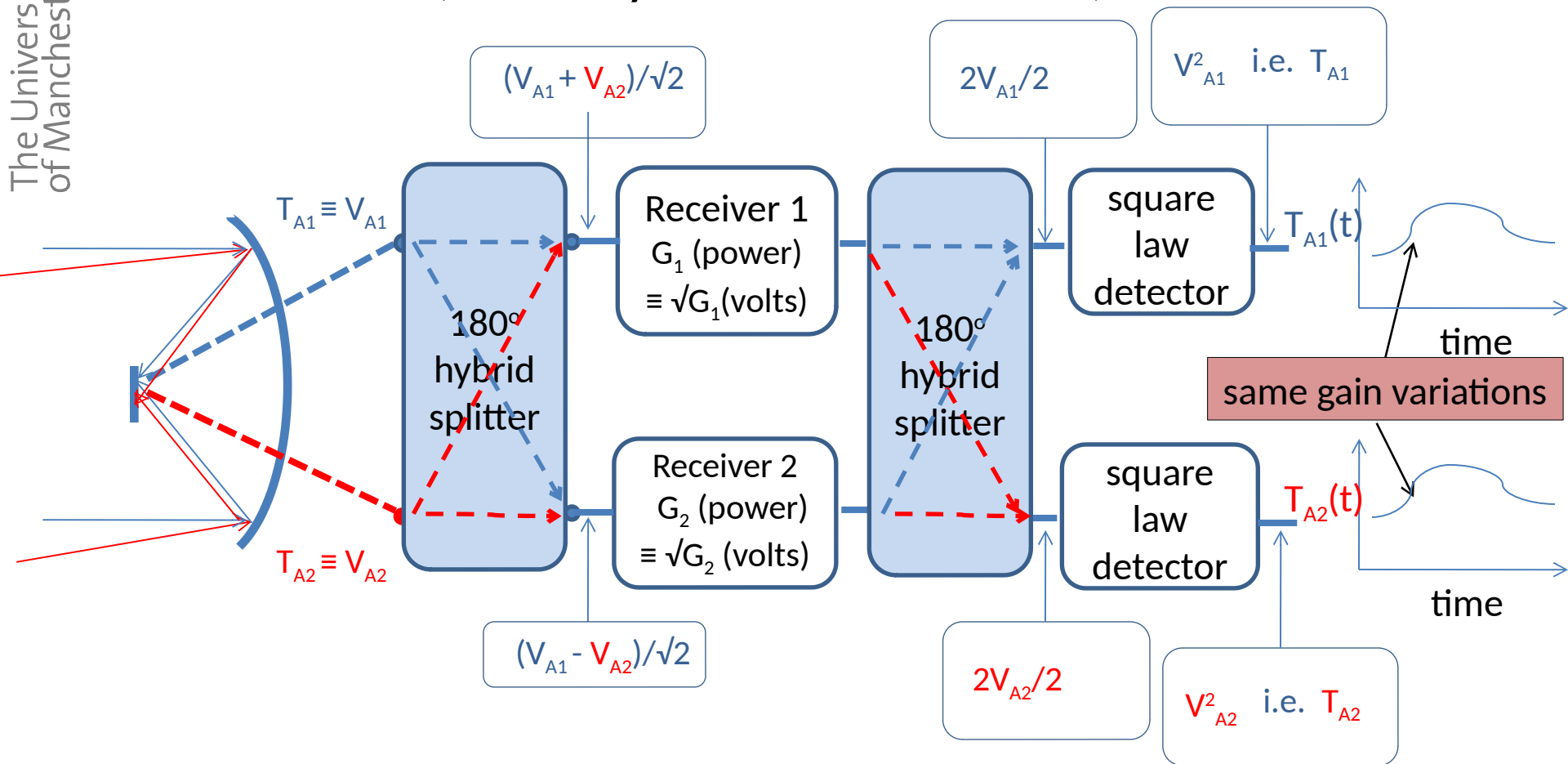


Fig. 5. *E*-plane radiation pattern of test horn



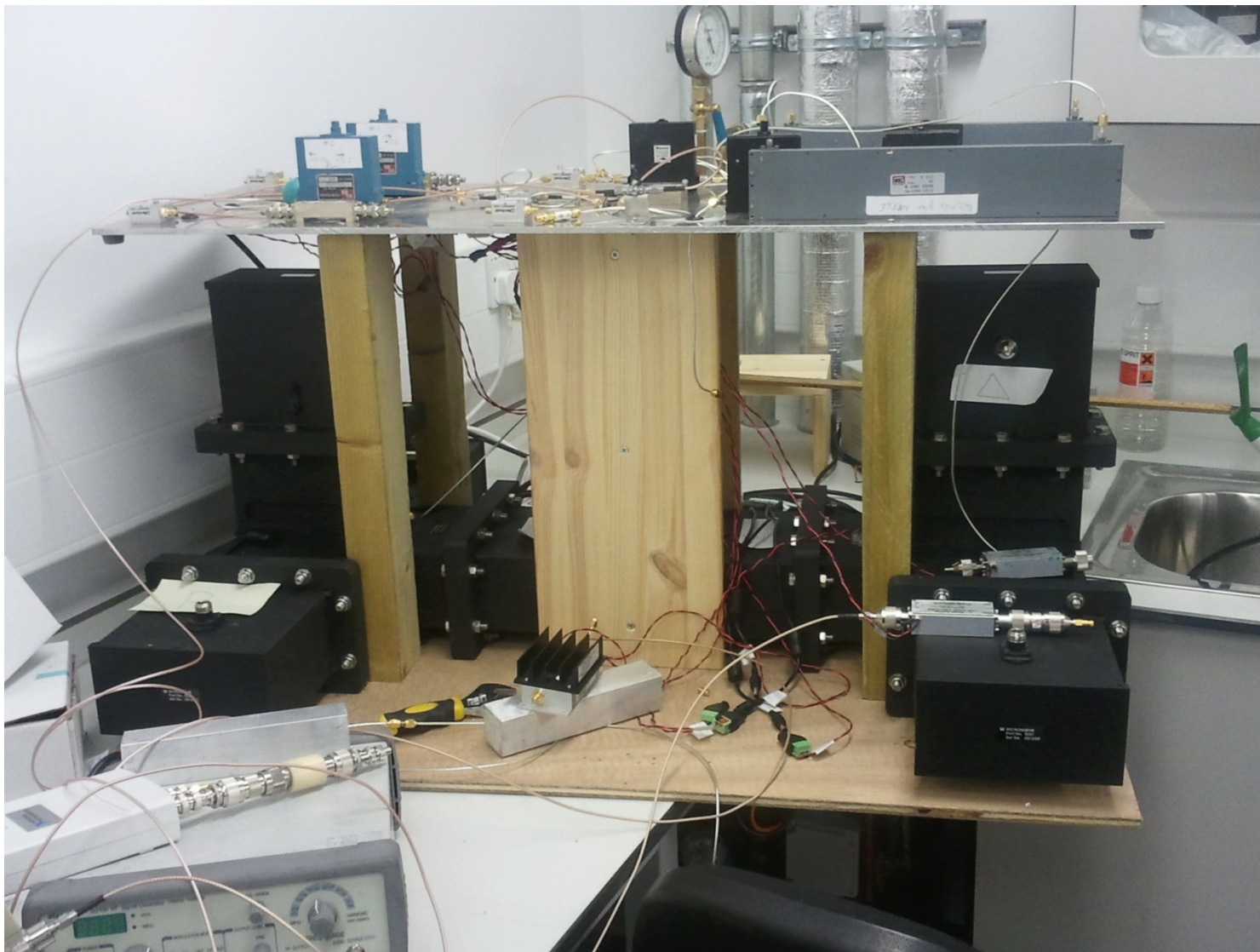
Outer parts of the L-BASS horns with the builders

# Twin-hybrid correlation receiver (with sky as reference load)



The voltage outputs  $V_{A1}$  and  $V_{A2}$  (alternatively  $V_{LOAD}$ ), have passed through both receivers and hence are subject to *the same* gain fluctuations. Hence, after square law detection the powers ( $T_{A1}$  and  $T_{A2}$  or  $T_{LOAD}$ ) vary together and the difference  $T_{A1} - T_{A2} \rightarrow$  zero if the receiver inputs are exactly balanced.

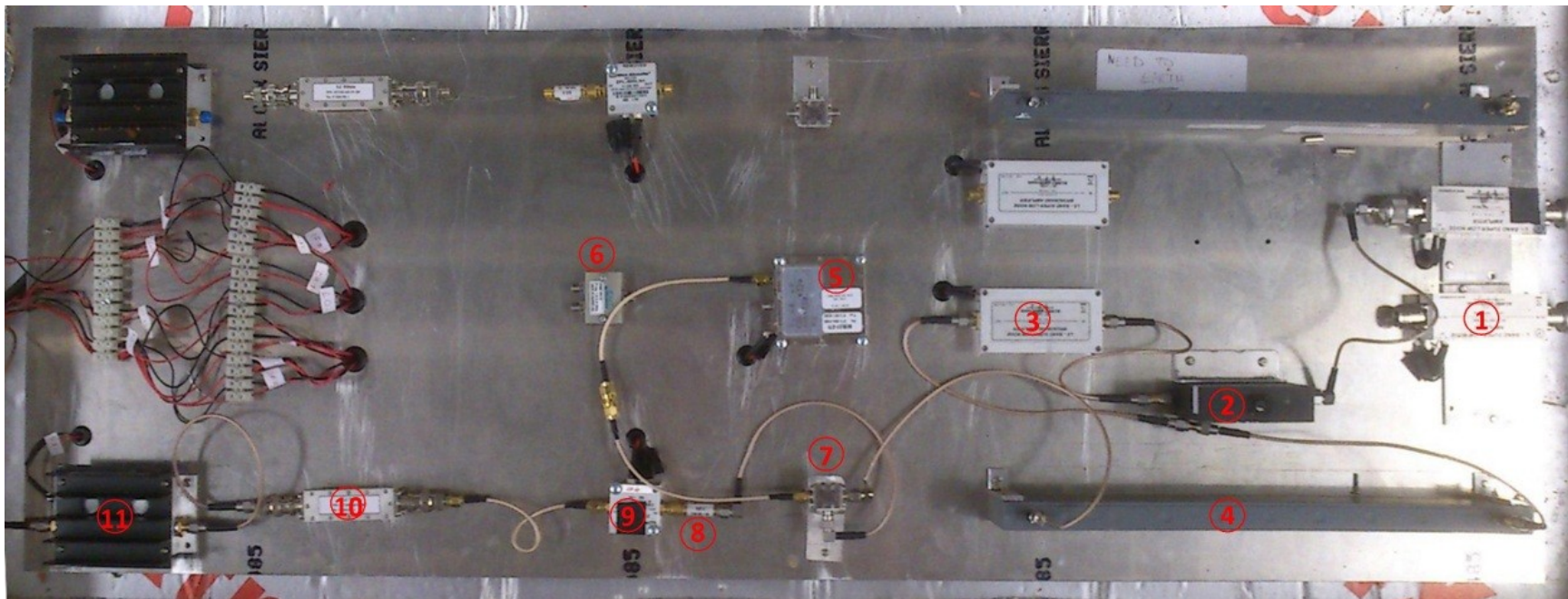
# 180° Hybrids: "Magic-Tees"



# Reduction in 1/f gain fluctuations

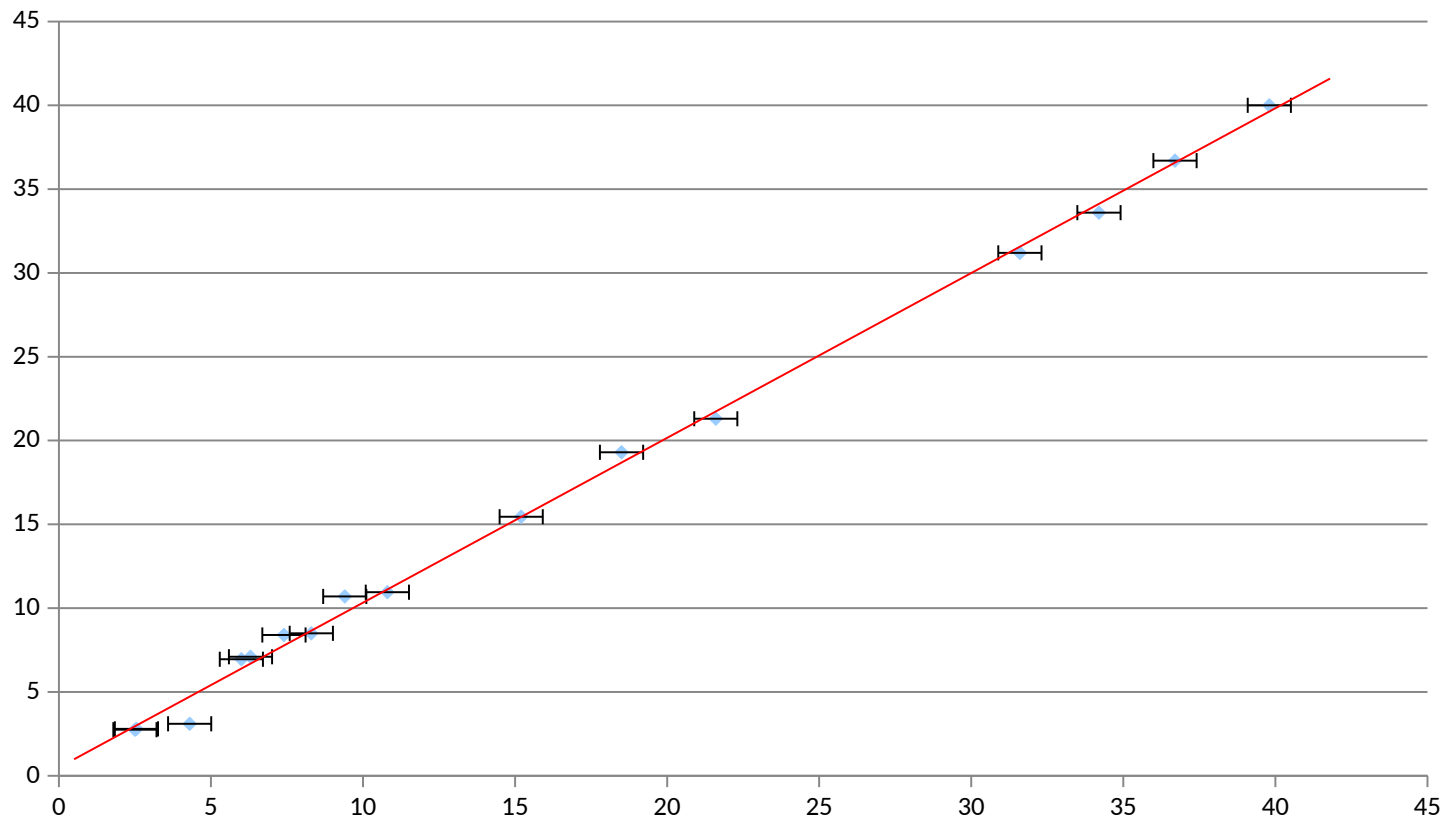
- Hybrids split power 50:50 and invert phase by  $180^\circ$   
→ perfect cancellation of fluctuations between hybrids
- Hybrids imperfect → large fluctuations not suppressed
  - Manchester Planck-LFI radiometer achieved reduction in  $f_{\text{knee}}$  by a factor  $\sim 10^{3.5}$  from 100 Hz → 10's mHz
- L-BASS intrinsic  $f_{\text{knee}} \sim 2$  Hz (higher thermal noise)
- Hybrids: split to  $0.25 \pm 0.3\%$  ; phase invert to  $0^\circ.2$ 
  - expect post-hybrid  $f_{\text{knee}} > 1000$  s
  - still need to check performance of IF stages
  - may need RF phase switch to modulate o/p power

# Heterodyne Receiver: 1<sup>st</sup> version



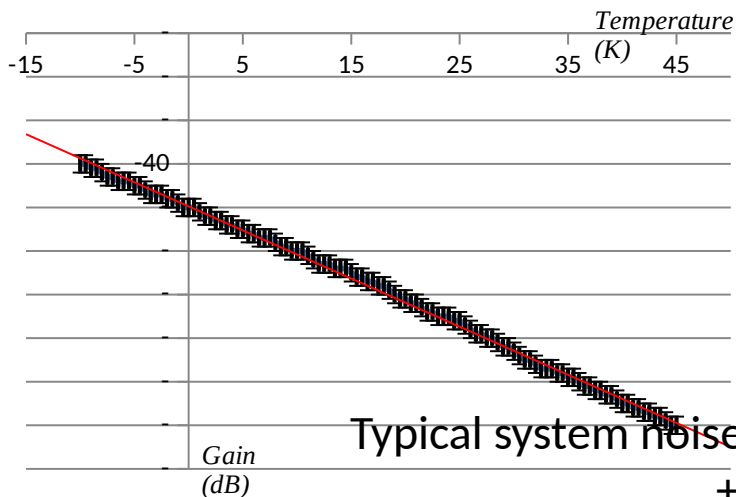
The constructed receiver. The channel 1 (CH1) components are, from the far-right: 1: Narrowband LNA; 2: RF Isolator; 3: Broadband LNA; 4: RF Filter; 5: LO; 6: Power Splitter; 7: Mixer; 8: Low-Pass Filter; 9: IF amplifier; 10: IF Filter; 11: IF power amplifier. With exception to the LO and Power Splitter, all components are mirrored in CH2.

# Heterodyne Receiver initial linearity tests



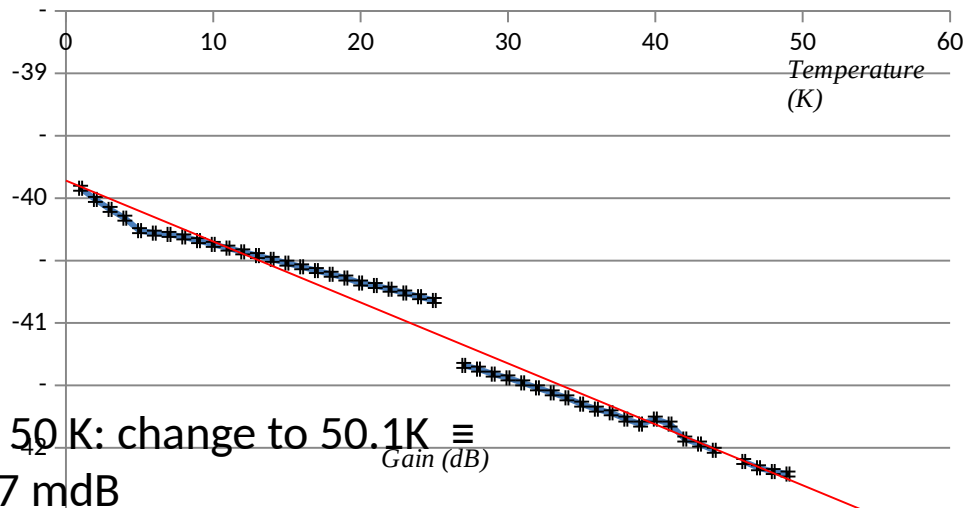
**Input signal attenuation versus output receiver power using commercial power meter. More tests needed with actual detector system**

# Measurement of temperature sensitivity of receiver



Gain vs. temperature  
CH2 broadband LNA.

$-11.0 \pm 0.02$  mdB/K



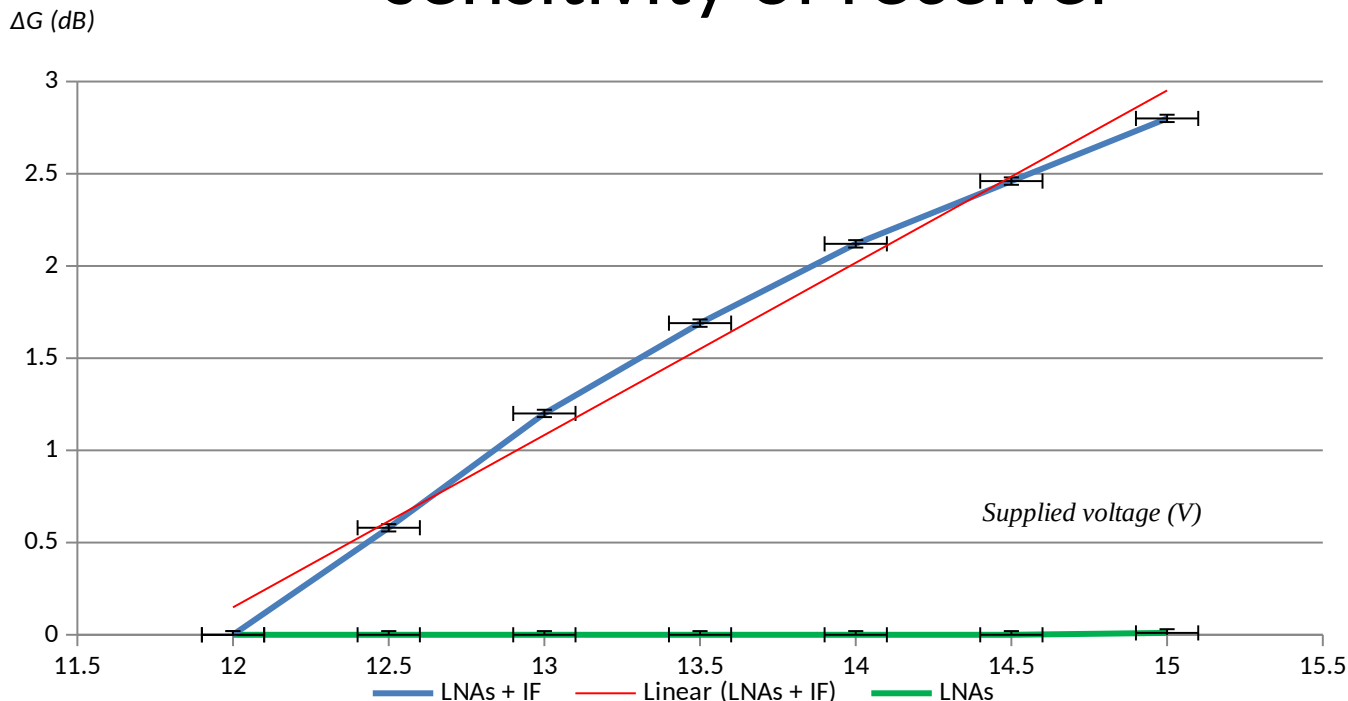
Gain vs. temperature  
partial receiver (3 stage) chain

$-30.6 \pm 0.15$  mdB/K

cf. Bahl (2009):  
typical sensitivity 10 mdB/K/stage

Stabilise physical temperature to  $\sim 0.1$ K  $\rightarrow$  gain variation  $\equiv$  3.1 mdB  
Equivalent to change from  $T_{\text{sys}} = 50$ K to  $T_{\text{sys}} = 50.035$ K

# Measurement of voltage sensitivity of receiver



**$0.93 \pm 0.01$  dB/V**

LNAs are voltage stabilised

IF amplifiers not stabilised : quoted at  $\Delta G = 0.33$  dB/V

**Stabilise supply voltage to 5 millivolt  $\equiv$  4.7 mdB**

**Equivalent to change from  $T_{\text{sys}} = 50$  K to  $T_{\text{sys}} = 50.055$  K**

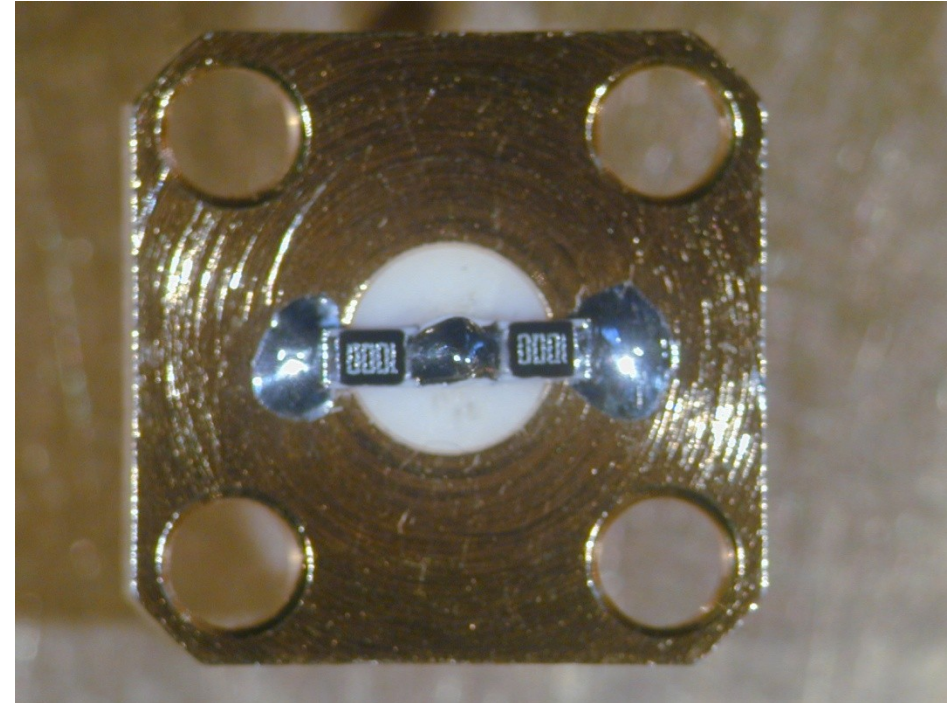
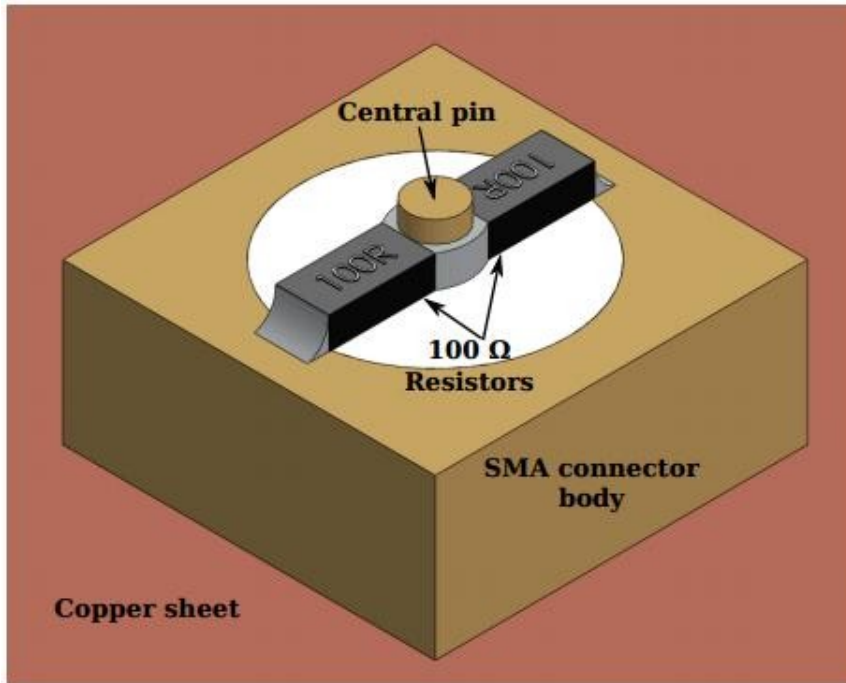
# Cryogenic Calibration - 1



Coaxial resistive load within existing Very Small Array (VSA) cryostats (much simplified from above)

Measure physical temperature with commercial (Lakeshore) equipment.

# Coaxial load - 1



In-house JBO design (E.Blackhurst) of resistive coaxial load - as used in Manchester/Oxford/Caltech "C-BASS" project.

Commercial load did not work well at cryogenic temperatures.

# Coaxial load - 2

## Basic scheme (JBO cryo experience)

- Load on metal block → “cold head ” via metal braid
- Mount sensor diode on block (manufacturer’s guidelines)
- Connect load to radiometer via semi-rigid stainless steel cable
  - Thermal conduction via copper inner – to be modelled
  - Measure temperature gradient along cable for calculation of additional noise contribution from cable loss.

**Active heating** : to counteract possible  $T_{\text{offset}}$  diode  $\leftrightarrow$  load resistors

- Vary load temperature by few K
- Use *difference* between two states – OK if  $T_{\text{offset}}$  is same.

**Note: GSFC have tested a cold load scheme with active heating and we will also consult NPL again**

# Monitoring within cryostat

## Lakeshore Model 218E Temperature Monitor + Si diodes

- 218E accommodates 8 diode inputs.
- DT670 diode specs: range: 1.4K to 500K  
accuracy: 10-20 mK
- Need 3 more for measurements along cable

# Ambient Temp Control & Monitoring

## JPL and GSFC tests for space-borne L-Band radiometer

- Physical temperature control to <1K ideally to 0.1K
- Control with Thermo-electric heating pads
- Distributed (thermistor) measurement to <0.1K

## NPL advice:

- Small Pt resistance devices measured with a good digital voltmeter can measure T to 0.1K
- Best local company is Isotech (Southport)

# External Monitoring - 2

Three measurement systems assessed in M.Phys. project aimed at calibration of PMMW imaging targets

## 1. Resistive Temperature Device (RTD)



Pt tipped probe - calibration  $\pm 0.09\text{K}$   
(checked against ice water)  
→ absolute measurements given  
good thermal contact

## 2. IR Spot Thermometer: offset $\sim 0.03\text{K}$ scatter $\pm 0.2\text{K}$

→ good for quick checks of relative changes over large areas (care over emissivity)

## 3. (Old) IR Camera: offset $\sim 0.25\text{K}$ scatter $\pm 0.25\text{K}$

→ good for quick checks of relative changes over large areas (care over emissivity)

CERTIFICATE OF CALIBRATION		Page 1 of 1 pages	
Date of Issue 18th March 2010	Certificate Number 180310N6	Approved Signatory	Signature
Certificate Issued By:  Electronic Temperature Instruments Ltd Dominion Way, Worthing West Sussex BN14 8WU England Telephone +44 01903 202151 Facsimile +44 01903 202445 email: sales@eti.co.uk Website: www.eti.co.uk		J. Carswell	
Customer Name: UNIVERSITY OF MANCHESTER Address: SCHOOL OF PHYSICS & ASTRONOMY ALAN TURING BUILDING MANCHESTER M13 9PL		J. Mokrarn	
Order Number: M13 9PL	Date Received: 17th March 2010	D. Carter	
Date Calibrated: 18th March 2010	Ambient Temperature: 22 °C $\pm$ 2 °C	Ref Number: 242/24003	
Ambient Humidity: < 60 %rh	Temperature Scale: International Temperature Scale of 1990		
Inst Description: ETI PRECISION INDICATOR	Sensor Type: 130mm PT100 PENETRATION PROBE		
Inst Serial Number: D1008026	Sensor Serial Number: P0826		
Calibrated Range/Scale: -18.0 $\pm$ 100 °C / 0.1 °C RESOLUTION	Procedure: The instrument was stabilised at ambient temperature, then calibrated by comparison with two traceable references in stirred liquid baths. Immersion depth: 110mm		
Results	Test Temperature °C	Instrument Reading °C	
	0.00	0.0	
	-18.00	-18.0	
	0.00	0.0	
	40.00	40.1	
	70.00	70.2	
	100.00	100.3	
	0.00	0.0	
Uncertainty of Measurement $\pm 0.04$ °C $\pm$ Instrument Resolution.			
End of Report			

# Real-time gain measurement

Real-time gain normalisation using noise diode signal injected via waveguide directional coupler (*not in the PIF budget*)

AGILENT diode temperature sensitivity  $<0.01\text{dB/K}$

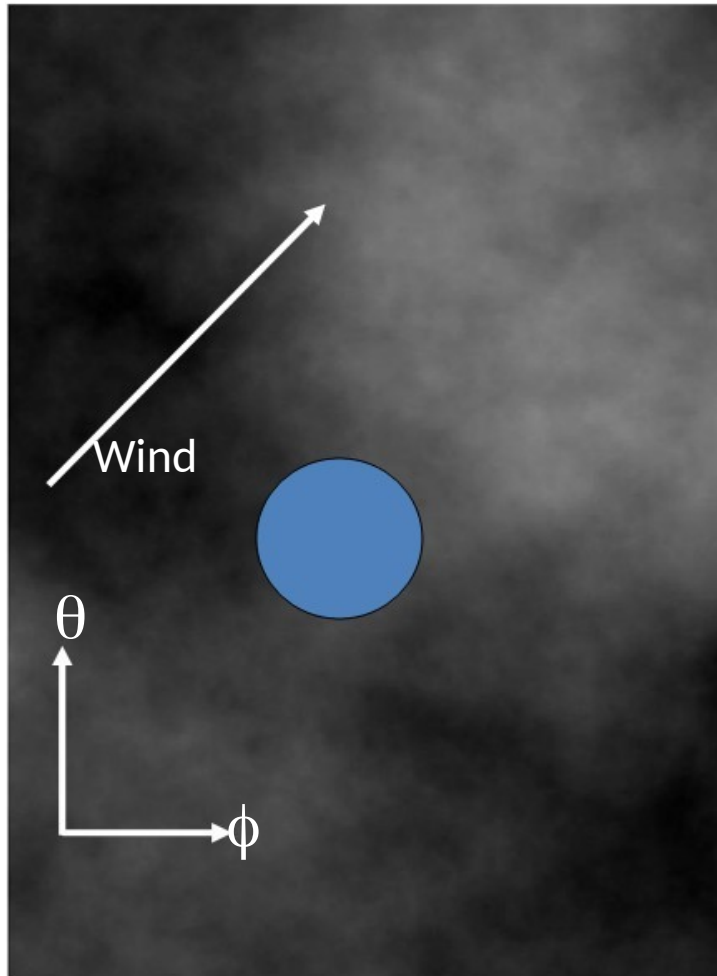
→ control physical temperature to  $0.1\text{K}$

→ variation  $<0.02\%$  i.e.  $<0.01\text{K}$  at  $T_{\text{sys}} = 50\text{K}$

→ JPL experience suggests driving with constant current

**To be further explored (in conjunction with NPL).**

# Atmospheric emission



1.4 GHz atmospheric emission  $1.6 \pm 0.3$  K  
(optical depth  $\tau \sim 6 \times 10^{-3}$ )

Majority from  $O_2$  - well-mixed but pressure dependent (slow and only few % effect)

Variation from liquid water drops - not all in obvious clouds and not well mixed  $\rightarrow$  emission fluctuates.

$\rightarrow$  calibrate quantitatively by measuring i-r brightness during observations

$\rightarrow$  *observe primarily in clear sky conditions !*

**Visualisation of variations in optical depth of the *clear* atmosphere**

# Aurora Cloud Sensor III



4 sensors

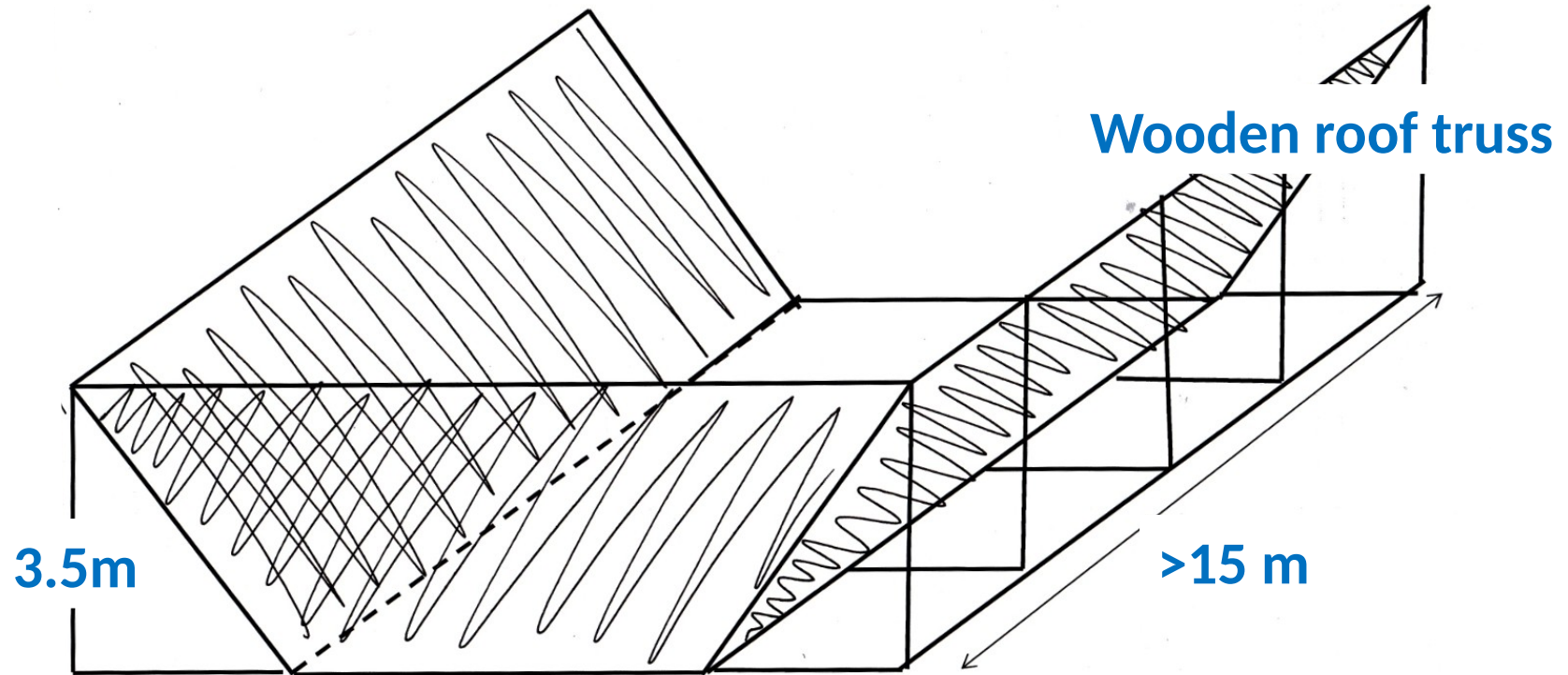
- Light
- Precipitation
- Ambient temperature
- IR sky

IR sensor: time series data written to computer (QinetiQ software)

Calibrated against data from UoM's Whitworth meteorological observatory.

→ new information on night-time sky conditions during data taking

# Mesh ground screen (schematic)



Transmission loss for ground radiation ~ 20 dB for 12.5mm mesh ( $0.06\lambda$ )  
 ~ 30 dB for 6mm mesh ( $0.03\lambda$ )

# Summary

An absolutely calibrated map of the radio sky at 0.1K level is needed:

- to help interpretation of CMB data from recent Planck mission;
- to settle the ARCADE2 controversy;
- to look for evidence of non-thermalisation in the early universe.

The team understands the astronomical issues well.

The uncertainty budget is dominated by a series of systematics.

The team has the knowledge and experience to tackle each in turn.

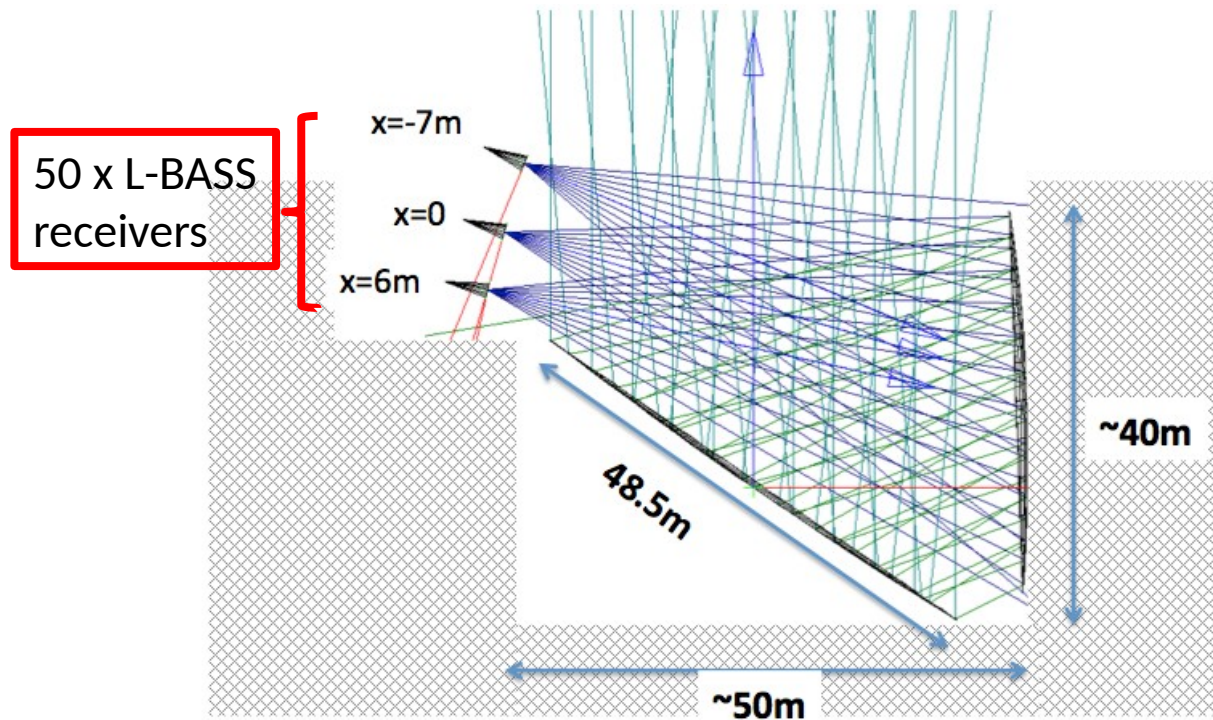
The equipment is relatively low-cost but requires innovations in:

- Architecture: twin tippable horns + v. stable comparison receiver
- Low-cost horn construction: large and with very low-sidelobes
- Coaxial cryogenic load: in place of microwave absorber at  
cryogenic temperature
- Measurement of atmospheric water variations

# The End

## ...and finally “BINGO”

- L-BASS is a (scientific standalone) precursor to BINGO – a cosmology telescope to map the sky in the 21cm line of atomic hydrogen.
- Technical lessons learned from L-BASS system directly applicable



# The Mounts



MUST  $\Delta$ -frames  
(2 per horn)

Commercial gearbox + motor drives available  
Elevation measurement using existing magnetic encoders (12-bit)