The REACH global 21cm instrument

Daniel Molnar

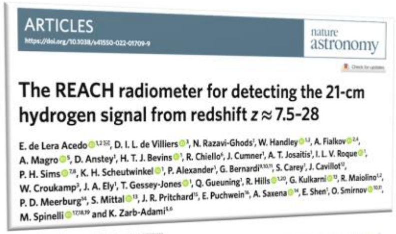
Cavendish Astrophysics

Kavli Science focus meeting, 06/02/2024

Structure of the talk

- REACH collaboration
- REACH Radiometer system
  - Receiver design
- Calibration
- Future directions

REACH global experiment


ARTICLES
https://doi.org/10.1038/s41550-022-01709-9
nature astronomy

The REACH radiometer for detecting the 21-cm hydrogen signal from redshift $z \approx 7.5$–28

E. de Lera Acedo[1,2], D. I. L. de Villiers[3], N. Razavi-Ghods[1], W. Handley[1,2], A. Fialkov[2,4], A. Magro[5], D. Anstey[1], H. T. J. Bevins[1], R. Chiello[6], J. Cumner[1], A. T. Josaitis[1], I. L. V. Roque[1], P. H. Sims[7,8], K. H. Scheutwinkel[1], P. Alexander[1], G. Bernardi[9,10,11], S. Carey[1], J. Cavillot[12], W. Croukamp[3], J. A. Ely[1], T. Gessey-Jones[1], Q. Gueuning[1], R. Hills[1,20], G. Kulkarni[13], R. Maiolino[1,2], P. D. Meerburg[14], S. Mittal[13], J. R. Pritchard[15], E. Puchwein[16], A. Saxena[14], E. Shen[1], O. Smirnov[10,11], M. Spinelli[17,18,19] and K. Zarb-Adami[5,6]

PIs

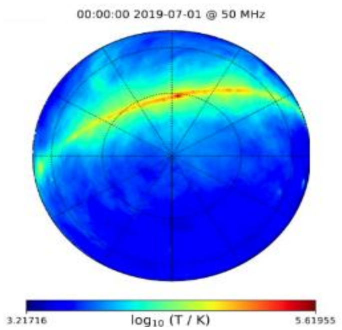
WP leads

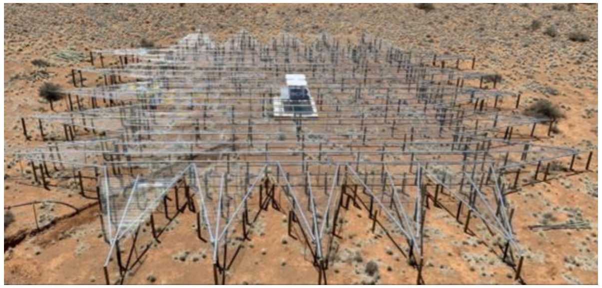
Cavendish Astrophysics

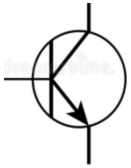
KICC

https://www.astro.phy.cam.ac.uk/research/research-projects/reach/collaboration

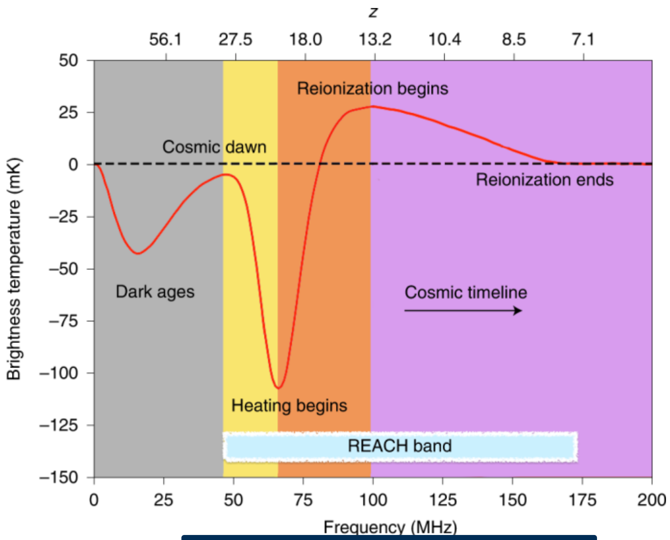
Introduction







$$P(\mathrm{Data}|\theta)P(\theta) = P(\theta|\mathrm{Data})P(\mathrm{Data})$$



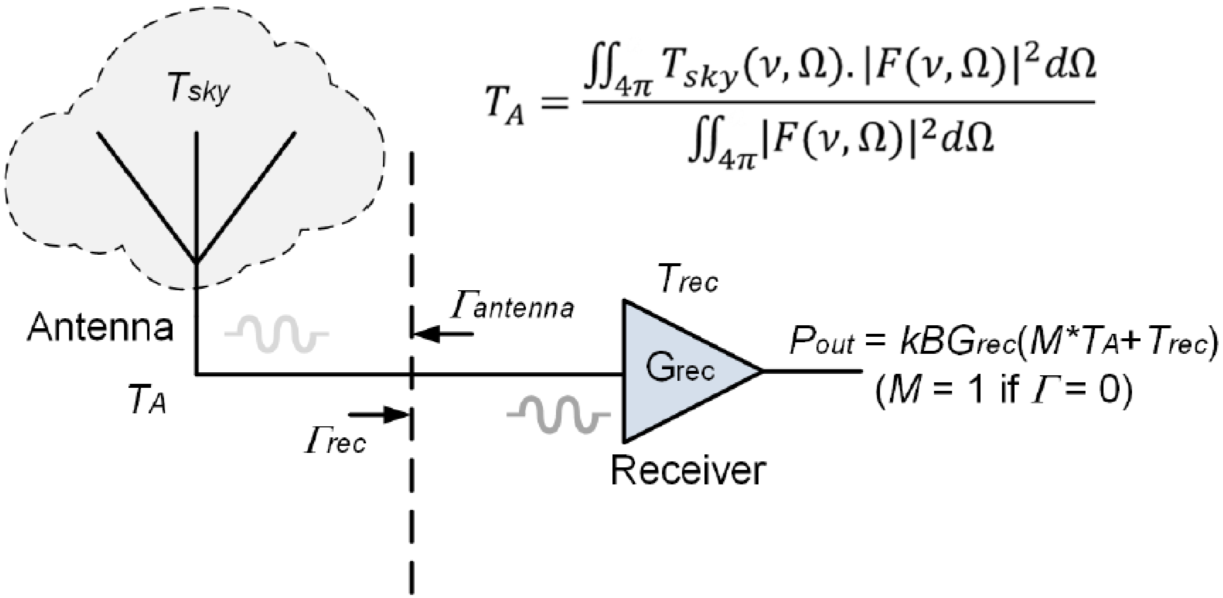
Antenna → Receiver → Detected Signal

J.Cumner et al:Journal of Astr.Instr Vol. 11, No. 01, 2250001 (2022)

E. de Lera Acedo et al: Nat Astron 6, 984–998 (2022)

Receiver Calibration

- Schematic representation of a global 21cm receiver
- Noise is added to the signal by the receiver
- Can be characterized by a noise temperature (degrading the SNR from in- to output)



Noise parameters

- In general, 4 real parameters are needed to characterize a noisy receiver
- This could be extended to noisy NPorts (Bucher and Molnar in prep)
- The noise temperature in general (noise parameter):

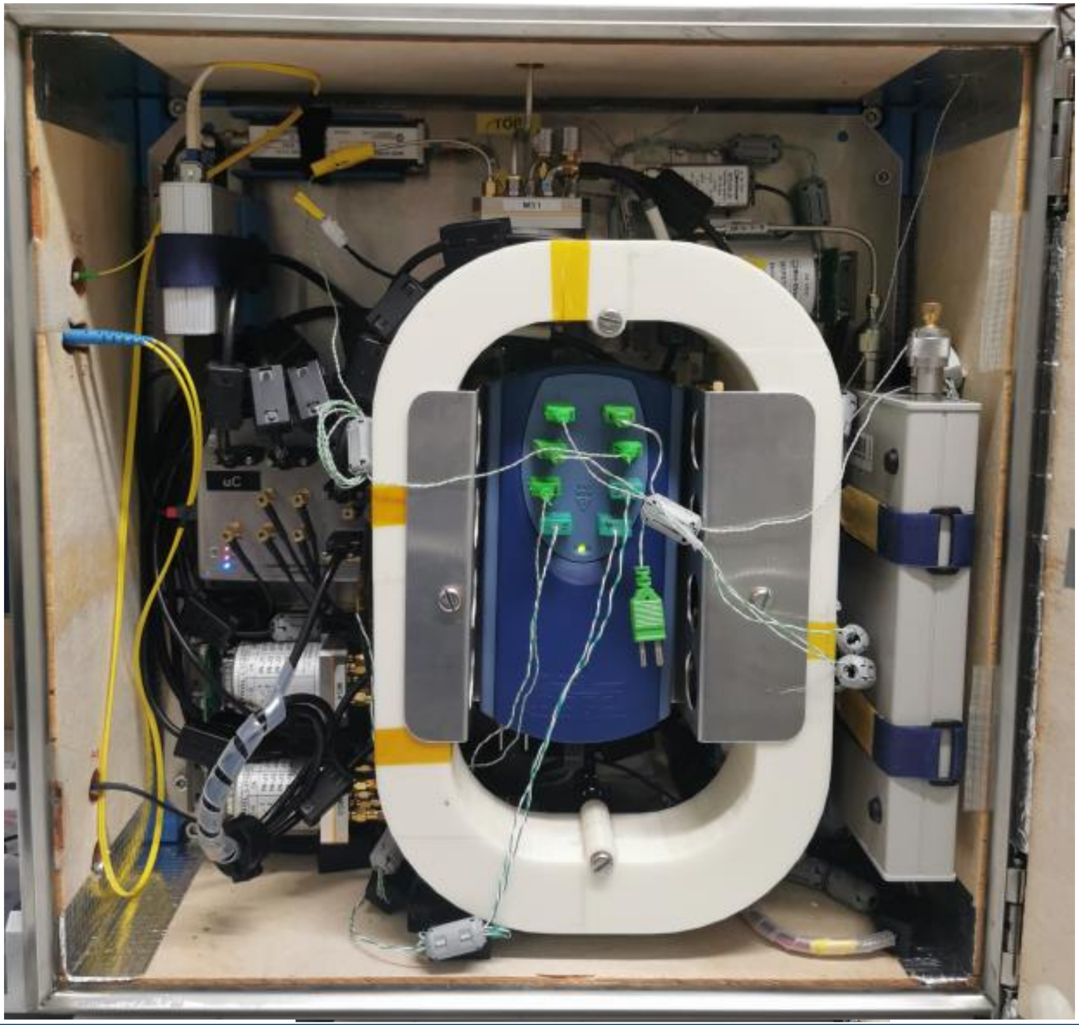
$$T(\Gamma_s) = T_{\min} + T_0 \frac{4R_N}{Z_0} \frac{|\Gamma_s - \Gamma_{\mathrm{opt}}|^2}{(1-|\Gamma_s|^2)\,|1+\Gamma_{\mathrm{opt}}|^2}$$

- NB: we use the different but equivalent formulation of noise waves

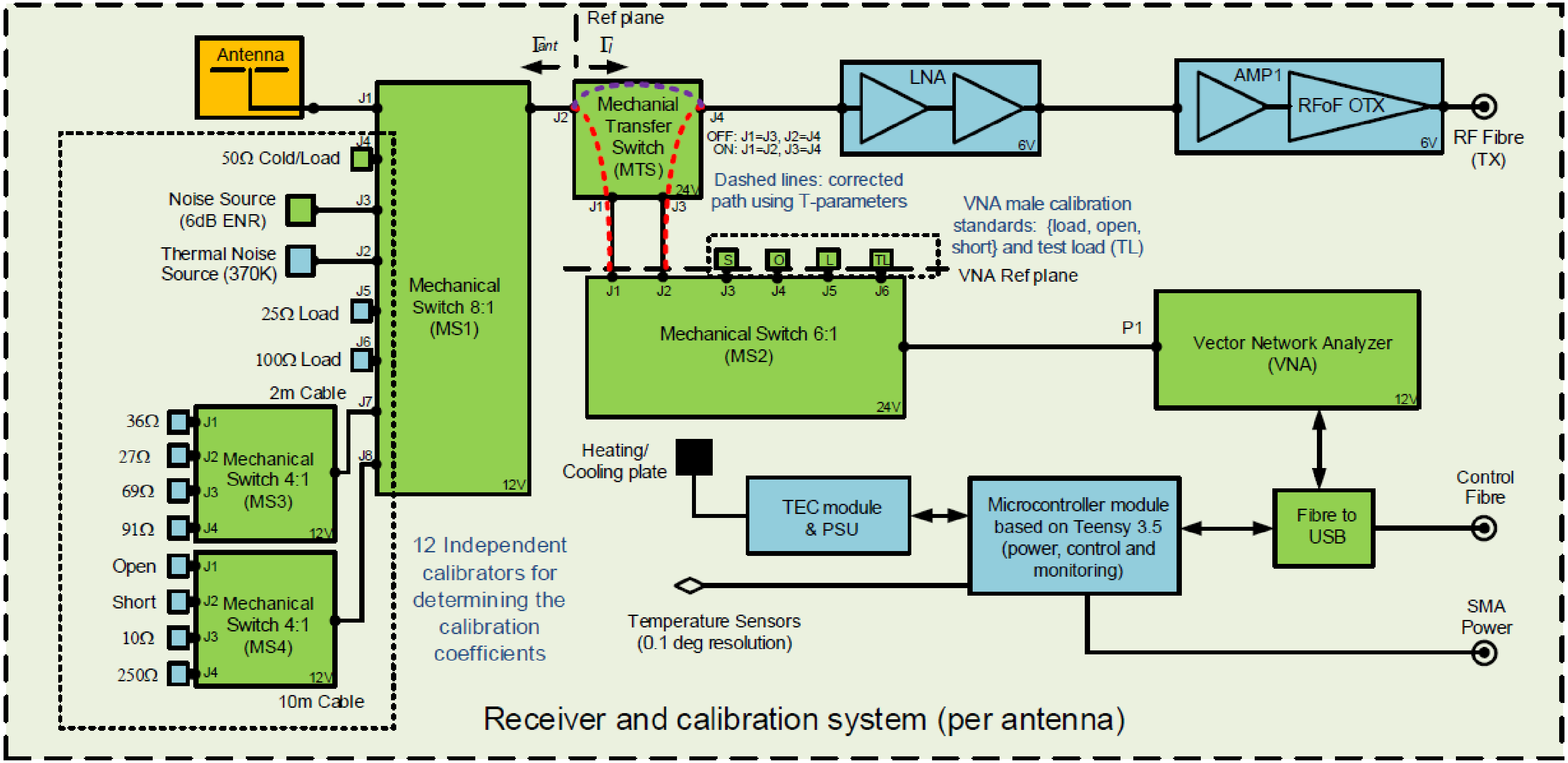
Receiver design

- Components and sensitivity was designed for 20mK sensitivity
- Cover the antenna S11 smith chart
- The calibration is done in situ for each run
- Currently commissioning phase but data has already been produced!

N. Razavi-Ghods, I.Roque et al: arxiv:2307.00099v2



The REACH Receiver chain

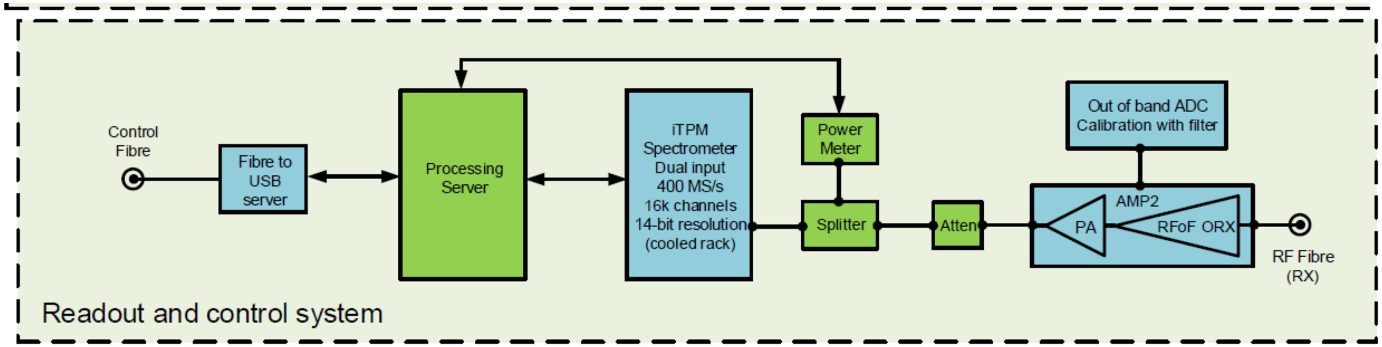


The schematic of the Front end of the REACH receiver

Digital Backend

- RFI proof boxes house the spectrometer and services nodes
- Connected to Front end receiver through fibre

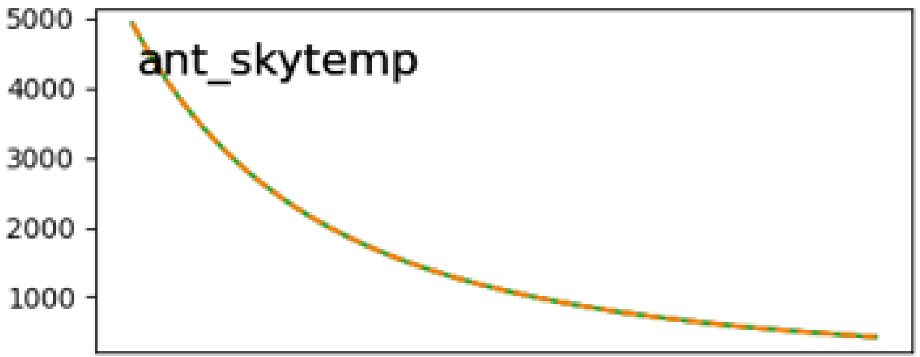
Picture courtesy of S.Pegwal



Calibration strategies

- The final goal is to correct for impact of receiver on the power measured from antenna

- Bayesian (conjugate prior based), Polynomial, least squares fit and machine learning for solving for the unknown receiver parameters

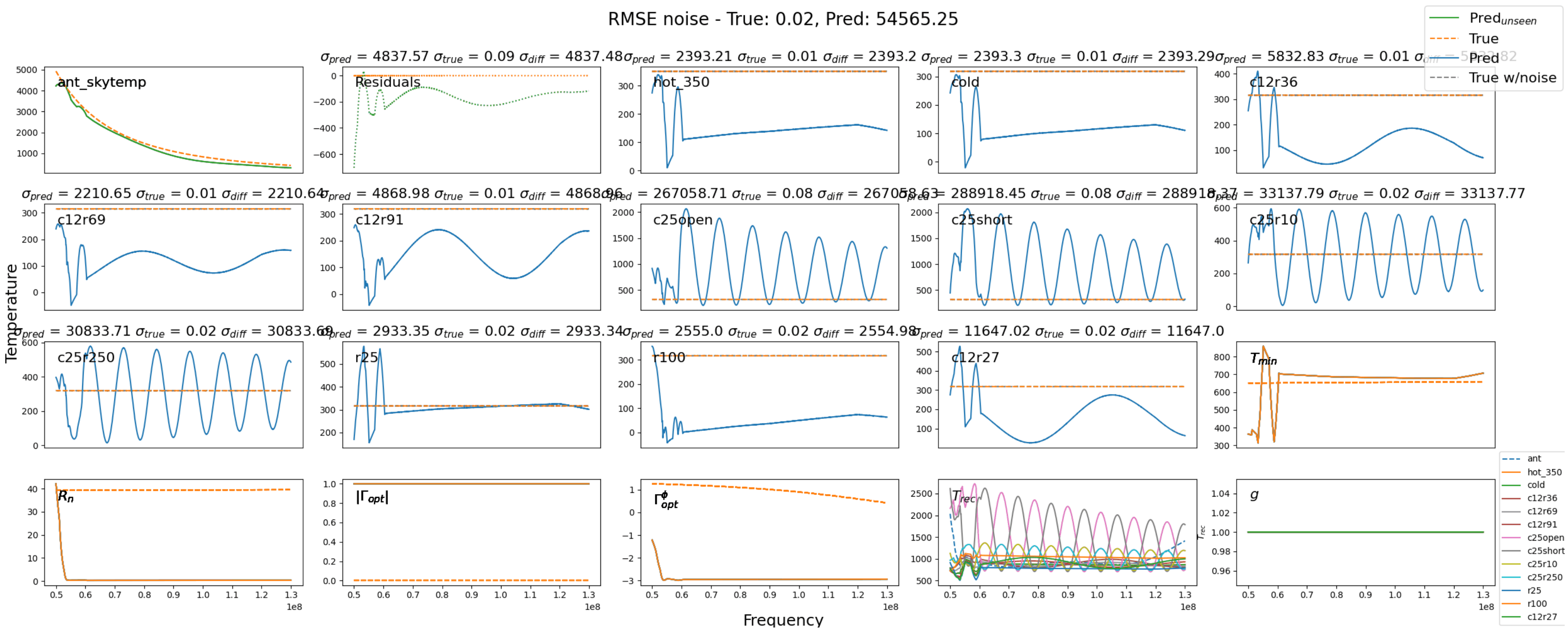


$\sigma_{pred} = 0.01$ $\sigma_{true} = 0.01$ $\sigma_{diff} = 0.0$

Sam Leeny, with Harry Bevins

I L V Roque+, *MNRAS*, https://doi.org/10.1093/mnras/stab1453

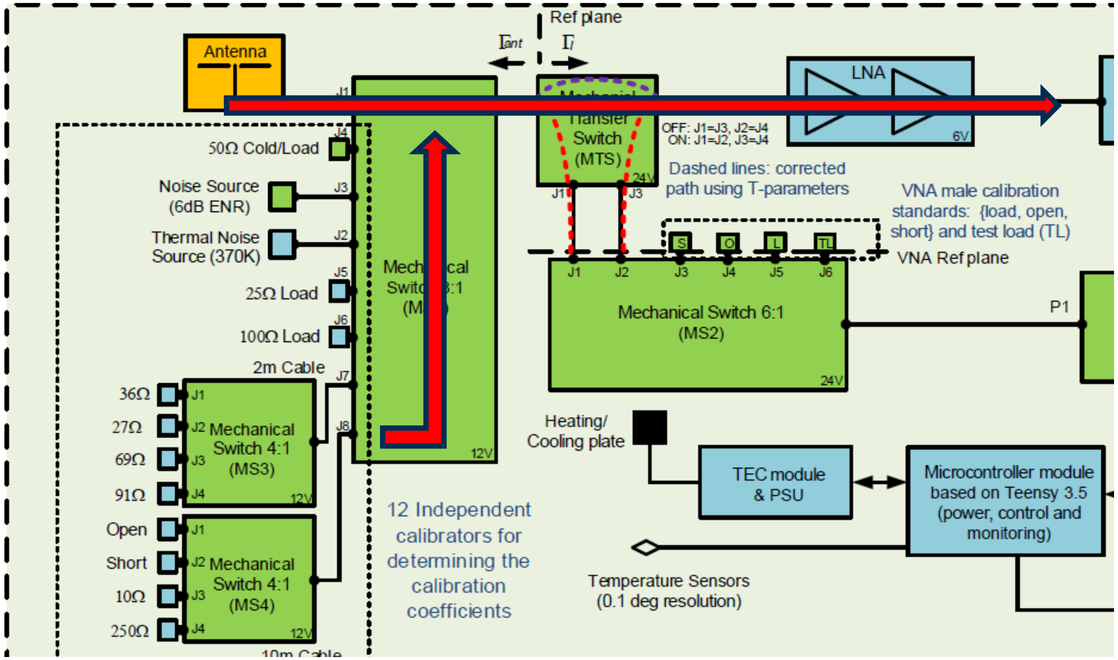
Calibration- ML in action



Courtesy of Sam Leeny

Forward modelling

- Forward modelling is crucial to understand the system and mock data generation

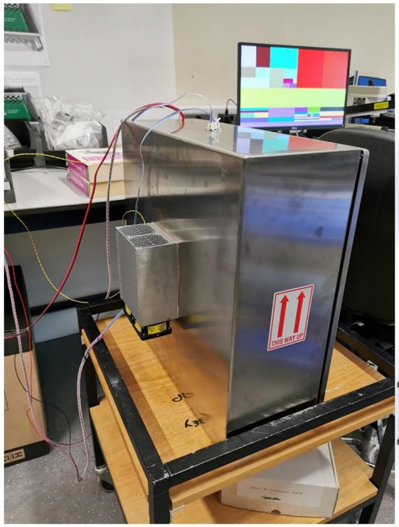


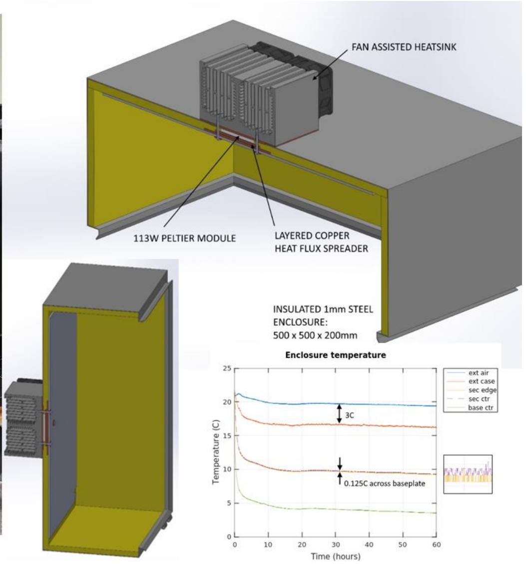
- Currently we are developing a system for systematic ranking of calibration methods based on mock data

Thermal considerations

- Thermal stability crucial for calibration and operation
- Temperature resolution of sources affects overall sensitivity too
- The current design relies on a complex system of control mechanism

$$T^*_{source} = T_{NS}\frac{P_s - P_L}{P_{NS} - P_L} + T_L$$





N. Razavi-Ghods, I.Roque et al: arxiv:2307.00099v2

Future directions

- Thermal management improvements
- Calibration strategy selection
  - Implications beyond REACH
- REACH phase 1 with one dipole antenna, further antennae on site at Karoo
- 2nd system being built for test purposes and beyond at Cambridge

MRAO at Cambridge

Thanks

UNIVERSITY OF CAMBRIDGE

Main references :

- [1]: N. Razavi-Ghods, I.Roque et al: Radiometer Design for the REACH global 21-cm experiment (arxiv:2307.00099v2.pdf (arxiv.org))
- [2]: I.L.V.Roque et al: Bayesian Noise wave calibration for 21-cm global experiments

Calibration metric

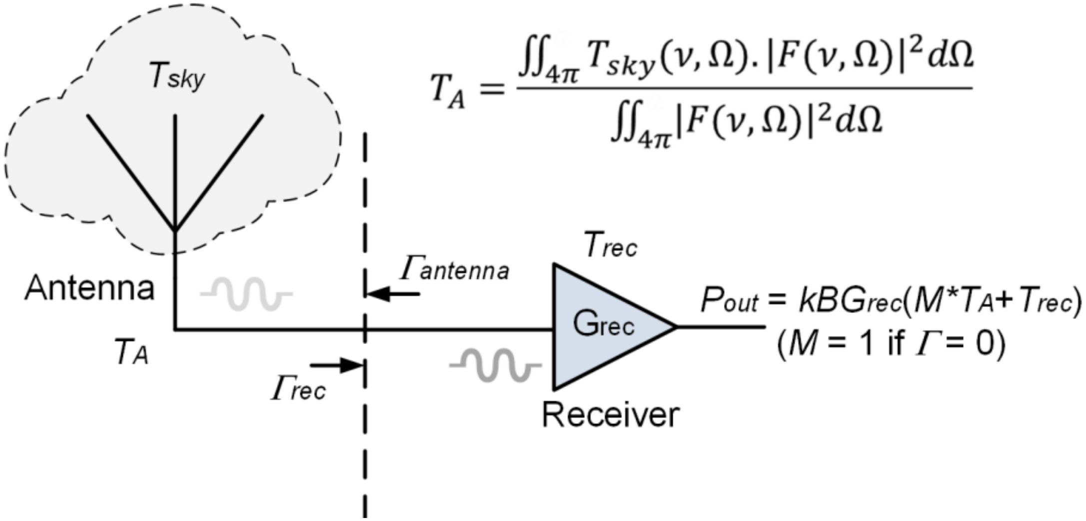
- Courtesy of H.Bevins

How do we do that? Mock data?

- Mock data standard
  - Mock 1 - With Cables + flat antenna
  - Mock 2 - With Cables at different temperatures to loads + flat antenna
  - Mock 3 - With power law antenna + cables
  - Mock 4 - With power law antenna + cables at different temp to loads
  - Mock 5 - With power law antenna + 21cm Signal + cables
  - Mock 6 - With power law antenna + 21cm Signal + cables at different temp to loads

Calibration

- The radiometer is based on the 3-way Dicke switching
- Calibration is based on EDGES (noise waves) formalism



$$T_A = \frac{\iint_{4\pi} T_{sky}(\nu,\Omega).|F(\nu,\Omega)|^2 d\Omega}{\iint_{4\pi} |F(\nu,\Omega)|^2 d\Omega}$$

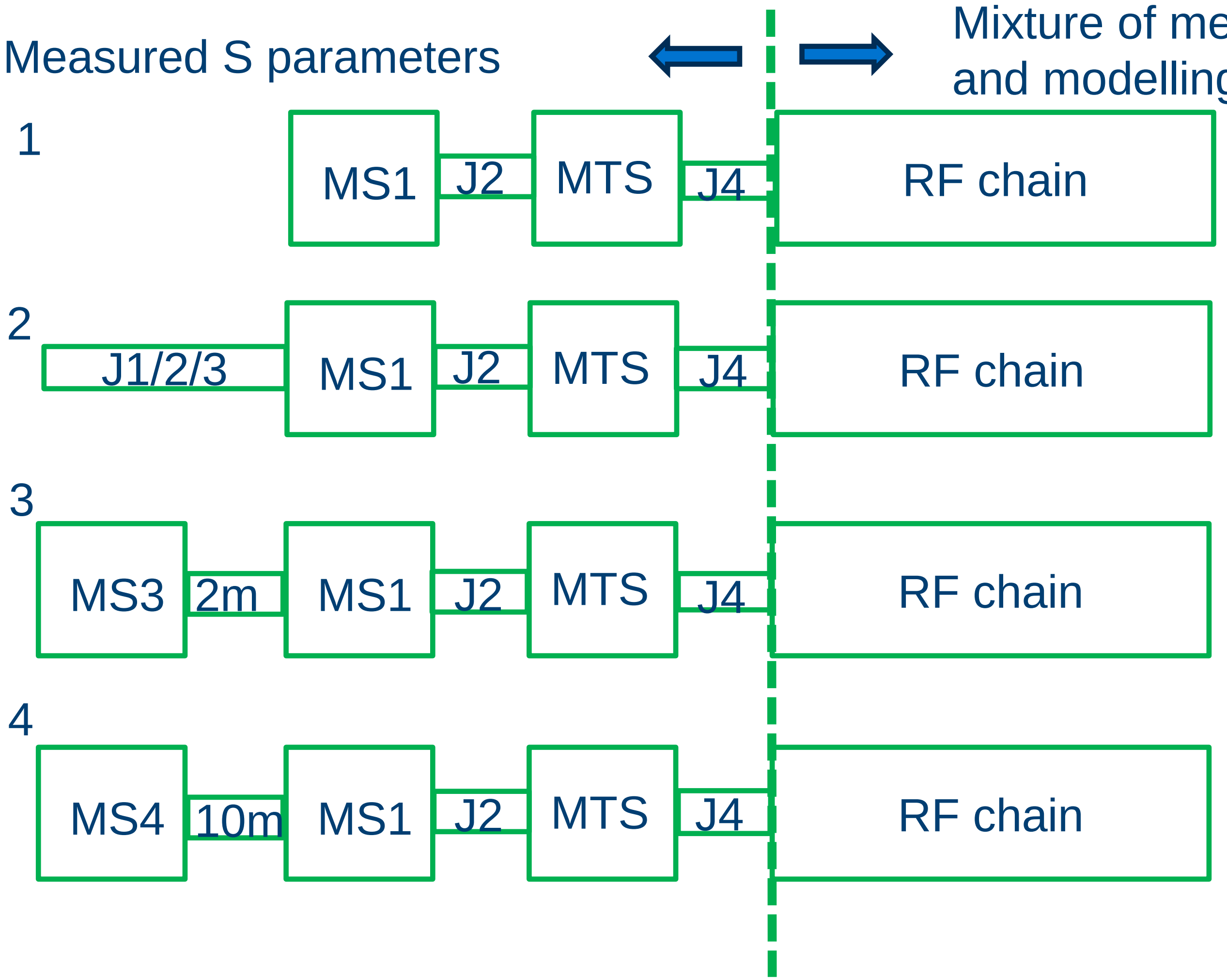
$$T_{\mathrm{NS}}\left(\frac{P_{\mathrm{source}}-P_{\mathrm{L}}}{P_{\mathrm{NS}}-P_{\mathrm{L}}}\right)+T_{\mathrm{L}} = T_{\mathrm{source}}\left[\frac{1-|\Gamma_{\mathrm{source}}|^2}{|1-\Gamma_{\mathrm{source}}\Gamma_{\mathrm{rec}}|^2}\right]+T_{\mathrm{unc}}\left[\frac{|\Gamma_{\mathrm{source}}|^2}{|1-\Gamma_{\mathrm{source}}\Gamma_{\mathrm{rec}}|^2}\right]+T_{\mathrm{cos}}\left[\frac{\mathrm{Re}\left(\frac{\Gamma_{\mathrm{source}}}{1-\Gamma_{\mathrm{source}}\Gamma_{\mathrm{rec}}}\right)}{\sqrt{1-|\Gamma_{\mathrm{rec}}|^2}}\right]+T_{\mathrm{sin}}\left[\frac{\mathrm{Im}\left(\frac{\Gamma_{\mathrm{source}}}{1-\Gamma_{\mathrm{source}}\Gamma_{\mathrm{rec}}}\right)}{\sqrt{1-|\Gamma_{\mathrm{rec}}|^2}}\right]$$

S-parameters for simulations

Current efforts: building models for mock data generation

Each configuration(1-4) meant to represent a possible RF path

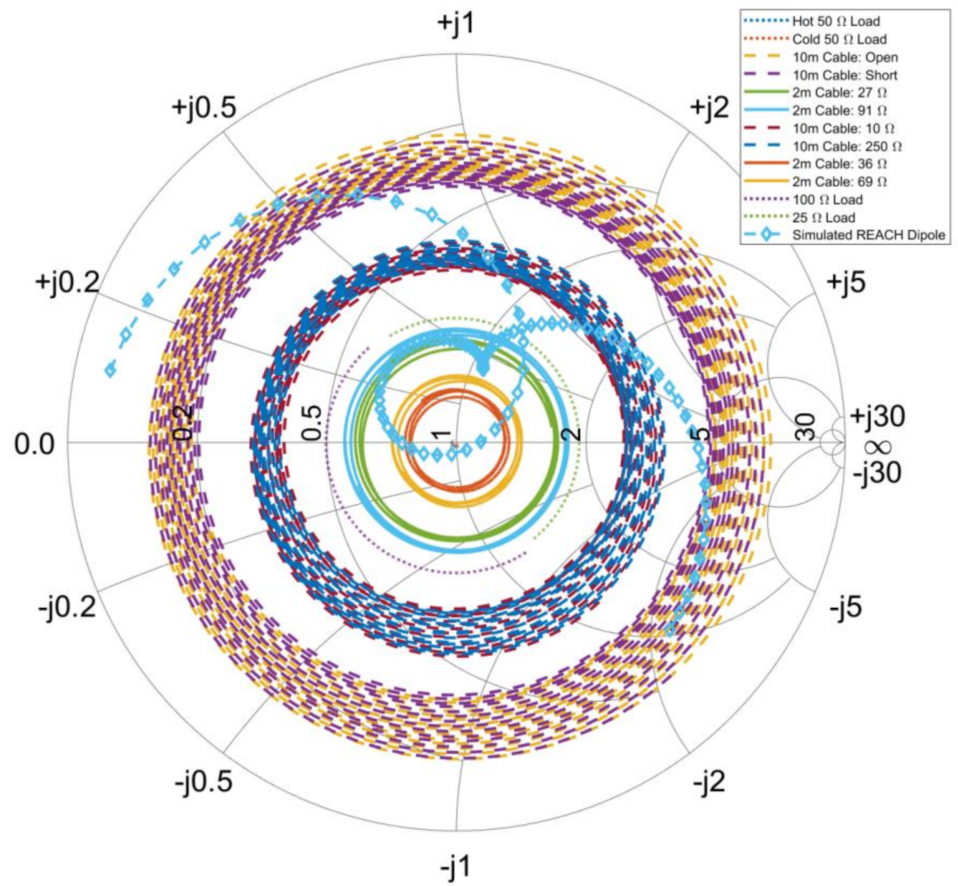
For each block we have S parameters



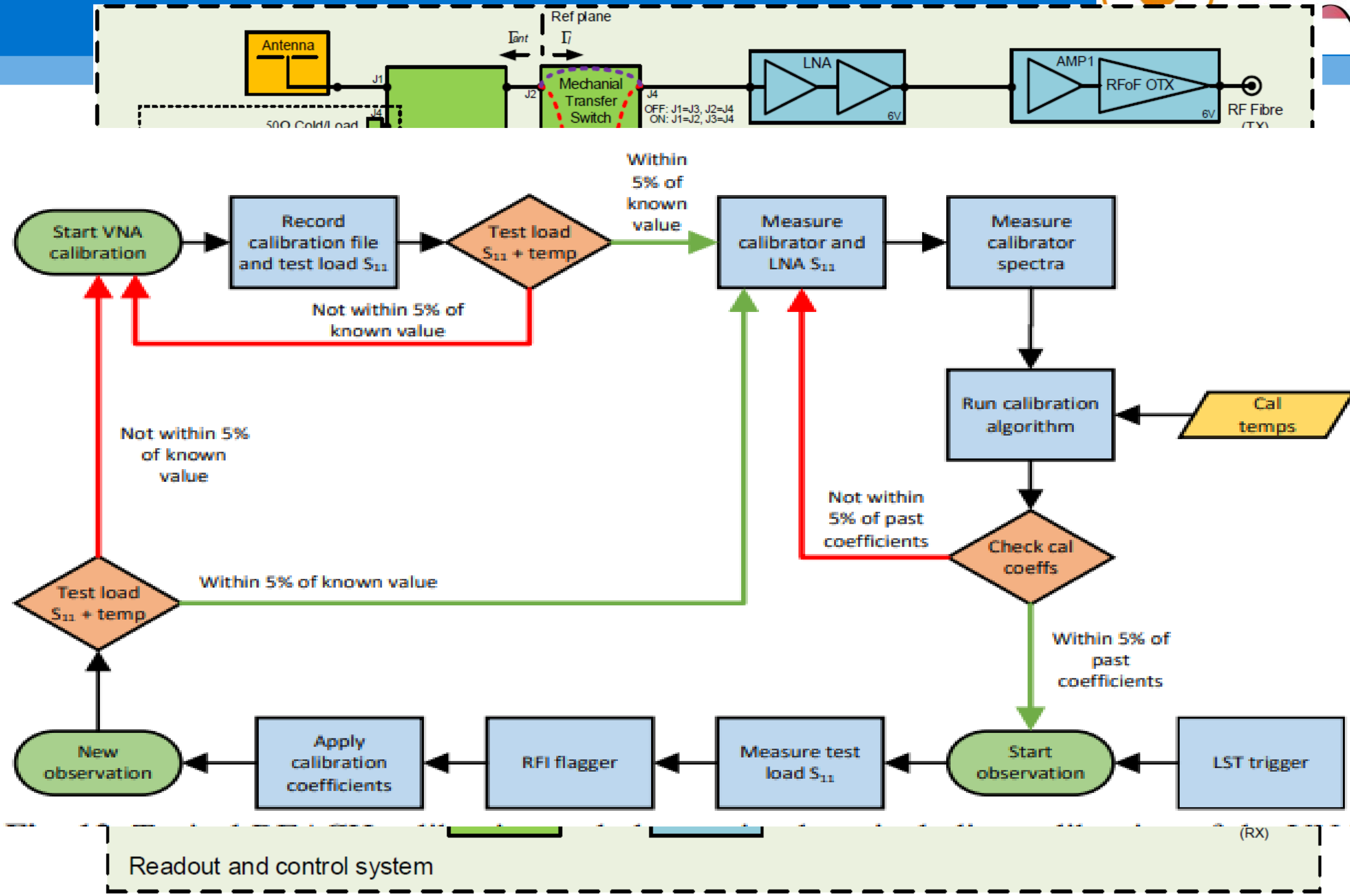
Ji: small semi rigid coax 2m/10m: the long coax cables (for these two we also have simulation)

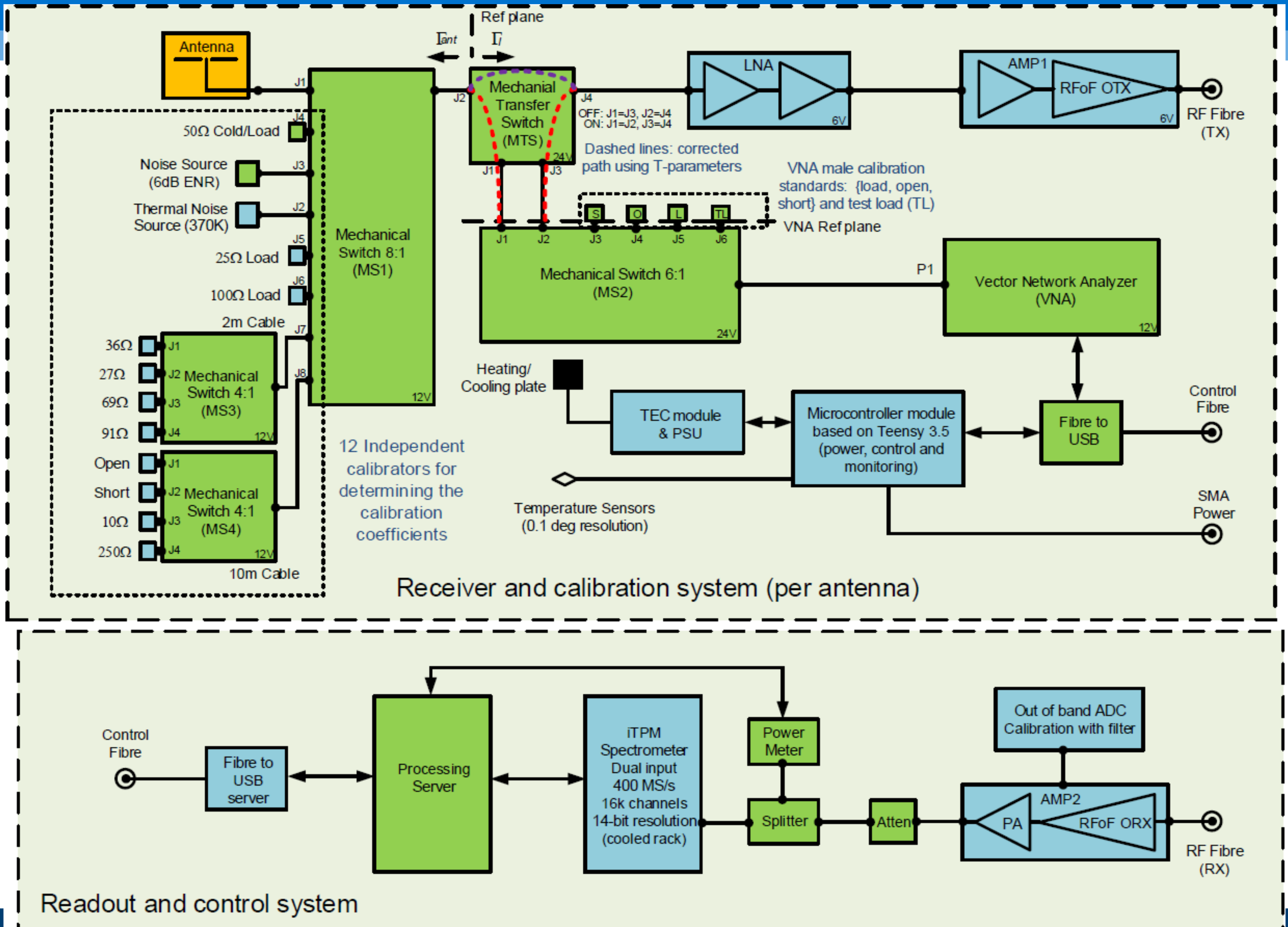
Antenna and calibrator impedances

- Smith Chart showing the simulated dipole antenna impedance and the sources
- Antenna impedance shown is between 50-150MHz

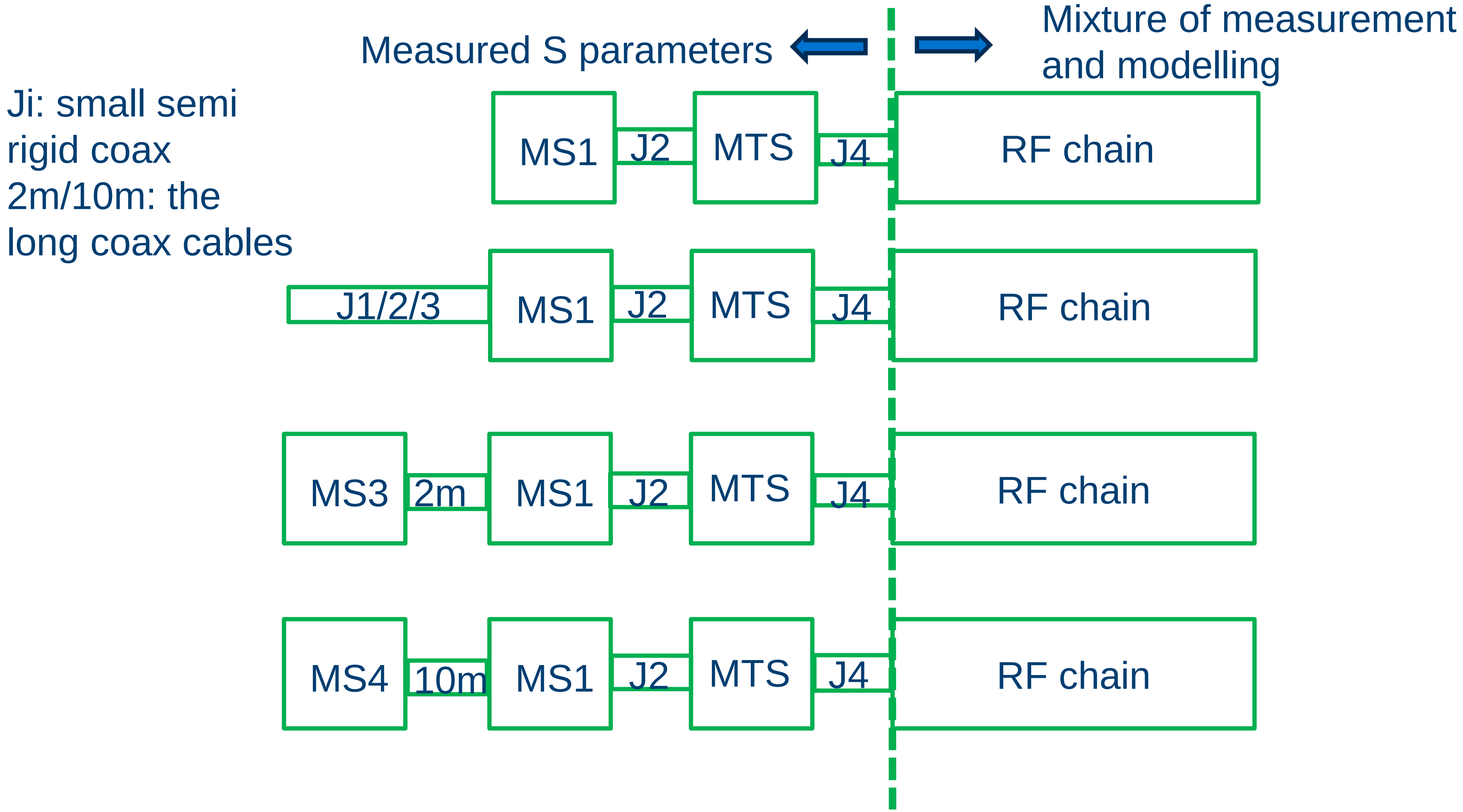


Schematic of the Receiver

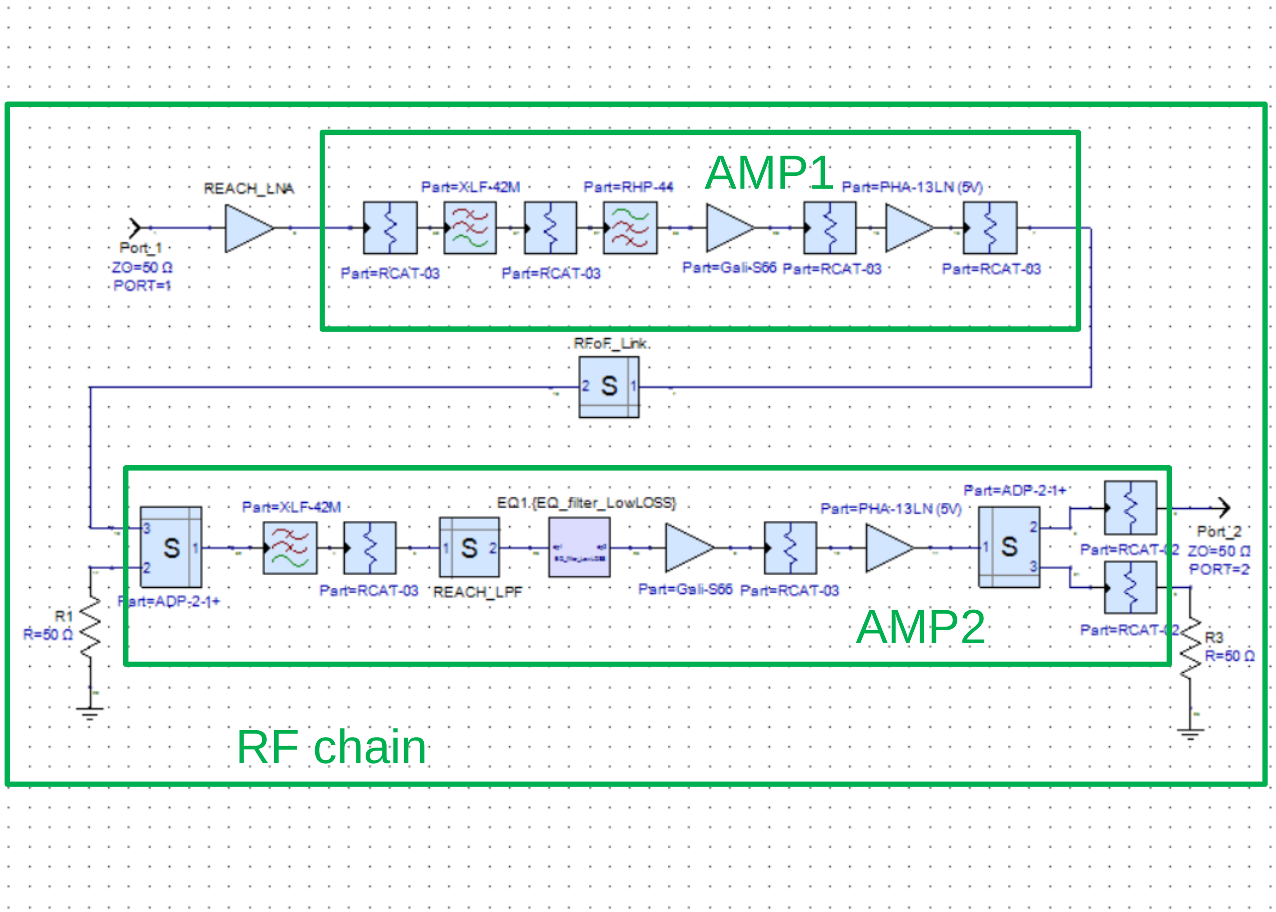




Ref plane
Γ_{ant}
Γ_l
Antenna
J1
J2
J4
Mechanial Transfer Switch (MTS)
24V
OFF: J1=J3, J2=J4
ON: J1=J2, J3=J4
LNA
6V
AMP1
RFoF OTX
RF Fibre (TX)
Dashed lines: corrected path using T-parameters
VNA male calibration standards: {load, open, short} and test load (TL)
VNA Ref plane
S
O
L
TL
50Ω Cold/Load
Noise Source (6dB ENR)
Thermal Noise Source (370K)
25Ω Load
100Ω Load
2m Cable
Mechanical Switch 8:1 (MS1)
12V
Mechanical Switch 6:1 (MS2)
P1
Vector Network Analyzer (VNA)
36Ω
27Ω
69Ω
91Ω
Mechanical Switch 4:1 (MS3)
Open
Short
10Ω
250Ω
Mechanical Switch 4:1 (MS4)
10m Cable
Heating/ Cooling plate
TEC module & PSU
Microcontroller module based on Teensy 3.5 (power, control and monitoring)
Fibre to USB
Control Fibre
12 Independent calibrators for determining the calibration coefficients
Temperature Sensors (0.1 deg resolution)
SMA Power
Receiver and calibration system (per antenna)
Control Fibre
Fibre to USB server
Processing Server
iTPM Spectrometer Dual input 400 MS/s 16k channels 14-bit resolution (cooled rack)
Power Meter
Splitter
Atten
Out of band ADC Calibration with filter
AMP2
PA
RFoF ORX
RF Fibre (RX)
Readout and control system

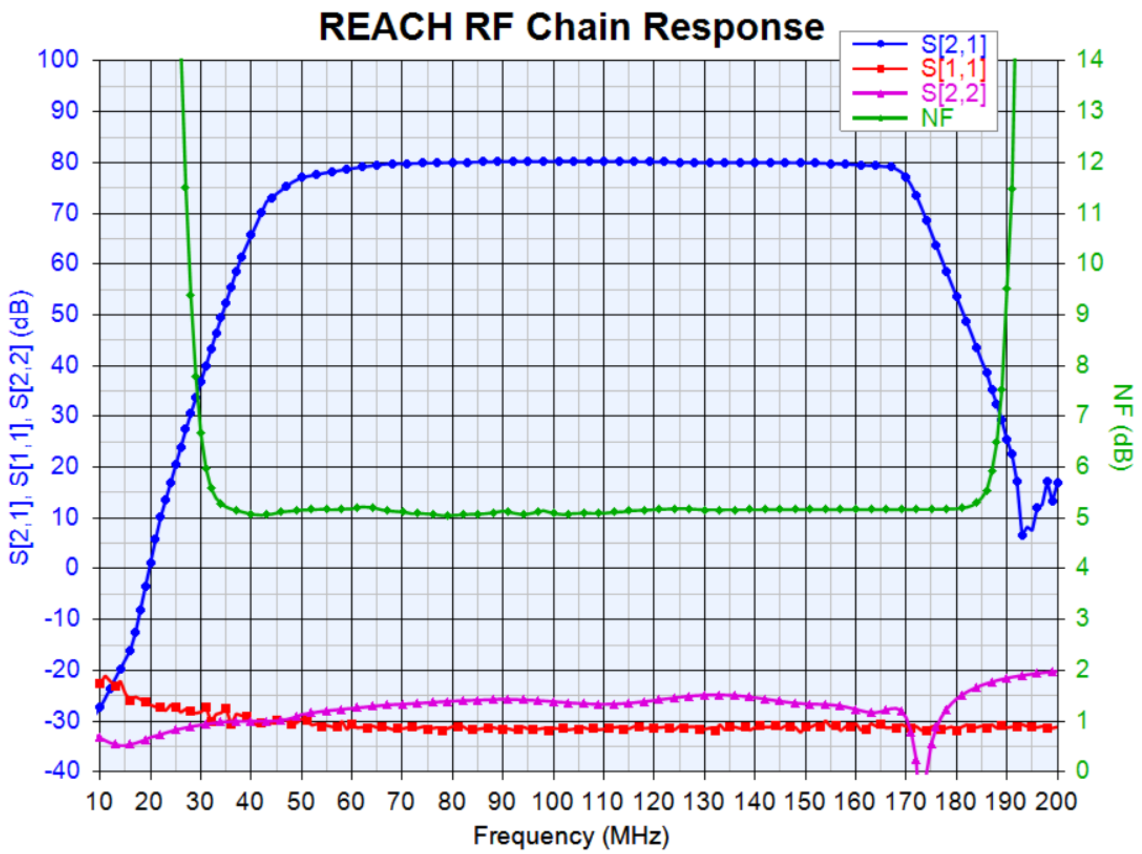

Measured S parameters
Mixture of measurement and modelling
Ji: small semi rigid coax
2m/10m: the long coax cables
MS1
J2
MTS
J4
RF chain
J1/2/3
MS1
J2
MTS
J4
RF chain
MS3
2m
MS1
J2
MTS
J4
RF chain
MS4
10m
MS1
J2
MTS
J4
RF chain

- Block diagram of RF chain (analogue part)
- Note that the LNA is based on S parameter measurement done in Cambridge



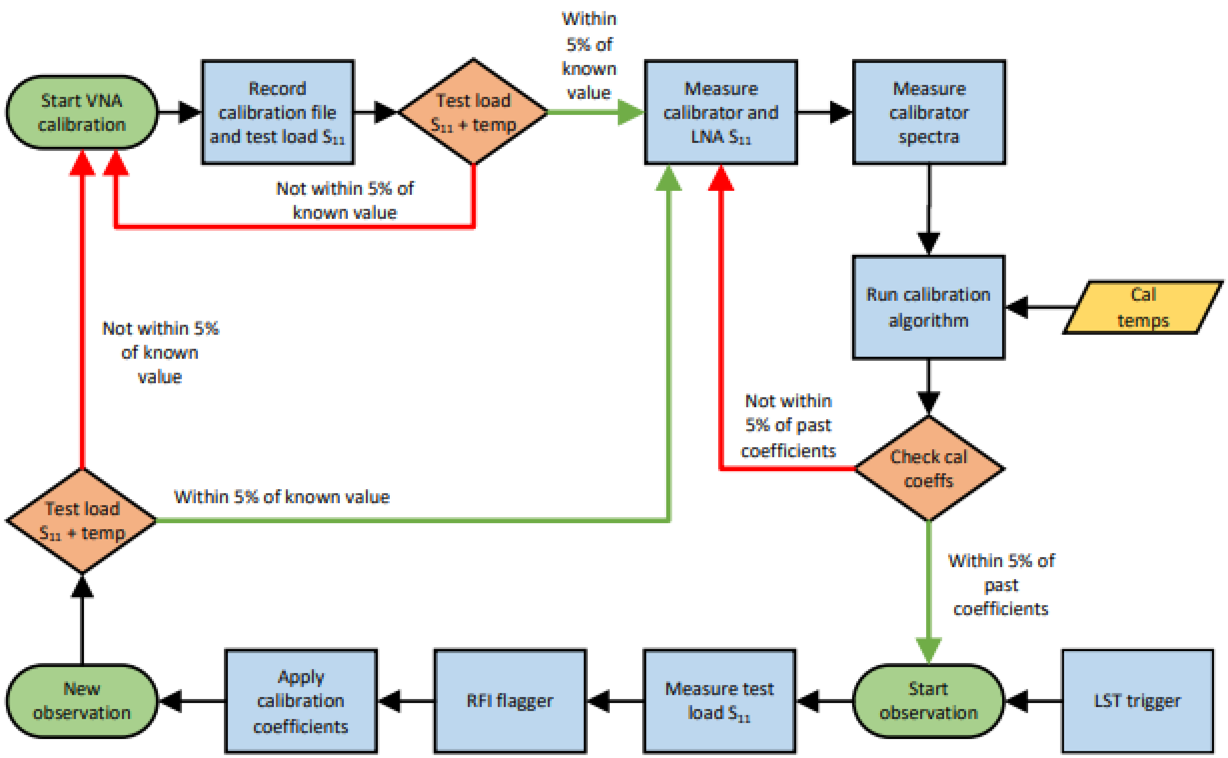
RF chain response

- Simulation by Nima
- LNA: measured, the other components are simulation based

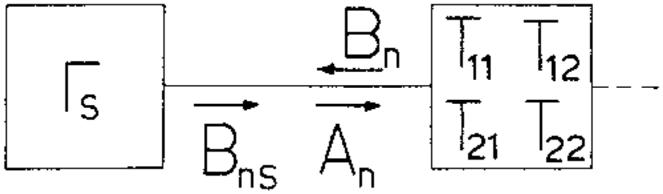


Cable current

- 10m cable is 10.1m; **model LBC195**
  2m cable is 2.02m; **model: not sure could be LMC195 or LBC195**
- **New cables: 2m and 10m LCOM200**


Start VNA calibration
Record calibration file and test load S_{11}
Test load S_{11} + temp
Within 5% of known value
Measure calibrator and LNA S_{11}
Measure calibrator spectra
Not within 5% of known value
Run calibration algorithm
Cal temps
Not within 5% of known value
Not within 5% of past coefficients
Check cal coeffs
Test load S_{11} + temp
Within 5% of known value
Within 5% of past coefficients
New observation
Apply calibration coefficients
RFI flagger
Measure test load S_{11}
Start observation
LST trigger

- Noise waves from Meys paper
- Supposed to have a uncorrelated noise from receiver Tunc and describing the correlated part by Tsin and Tcos



(b)

Additional temp sensors

- There's a possibility to extend the 8 existing ones

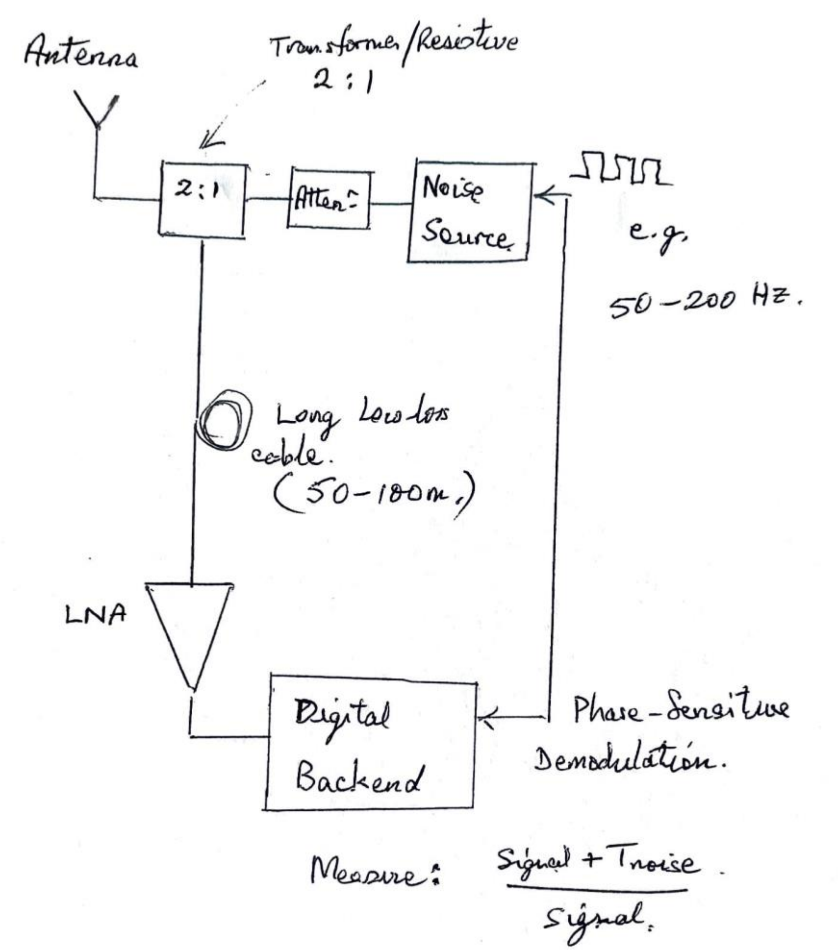
Fig. 9: The bottom and top layers of the stacked

Pros

1. Direct comparison of Antenna Power with a Noise source, using calibrated, passive components.
2. Using a long cable between the antenna and the LNA, the period of any standing waves (SWs) can be put outside the range of structure expected in the HI spectrum.
3. The SWs can either be fitted to a model or the spectrum convolved with a narrow bandstop filter. [Because the amplitude of the SWs will vary across the spectrum, fitting to a constant amplitude sine-wave is not appropriate.] Note that it is NOT necessary to know the phase of the SWs.
4. Measurements can be repeated with the 2:1 inputs interchanged if thought necessary.
5. Test measurements can easily be made with the Antenna replaced by alternative Noise sources for diagnostic purposes.

Cons

1. The effective system temperature is increased due to the loss in the 2:1 and the long cable. However the sky temperature is likely to be a significant factor in *any* receiving system.
2. The long cable will be bulky! However, it does mean that the active part of the receiving system can be a long way from the antenna (and the cable could also carry the drive signal for the noise source, if required).
3. There do not appear to be any requirements for temperature control anywhere in the system.
4. Because the calibration signal is relatively small e.g. ~10 to 20 K, a longer integration time will be required to reduce the noise level in the chosen spectral resolution bandwidth. These numbers need to be quantified !



Radically new ideas are also being looked at too, an idea by Paul Scott-> advantage very simple, but perhaps too simple …..

TC08 stability

Specifications

Hardware	
Number of channels (single unit)	8
Maximum number of channels (using up to 20 units)	160
Conversion time	100 ms per thermocouple channel + 100 ms for CJC (this can be disabled if all channels are used as voltage inputs)
Temperature accuracy	Sum of ±0.2% of reading and ±0.5 °C
Voltage accuracy	Sum of ±0.2% of reading and ±10 μV
Overvoltage protection	±30 V
Maximum common-mode voltage	±7.5 V
Input impedance	2 MΩ
Input range (voltage)	±70 mV
Resolution	20 bits
Noise-free resolution	16.25 bits
Thermocouple types supported	B, E, J, K, N, R, S, T
Input connectors	Miniature thermocouple

General	
Connectivity	USB 2.0
Device connector type	USB 2.0, Type B
Power requirements	USB port
Dimensions	201 x 104 x 34 mm (7.91 x 4.09 x 1.34 in)
Temperature range, operating	0 °C to 50 °C
Temperature range, operating, for quoted accuracy	20 °C to 30 °C
Temperature range, storage	–20 °C to 60 °C
Humidity range, operating	5 to 80 % RH non-condensing
Humidity range, storage	5 to 95 % RH non-condensing
Altitude	Up to 2000 m
Pollution degree	Pollution degree 2
Water resistance	Not water-resistant
Safety approvals	Designed to 2014/35/EU: Low Voltage Directive
EMC approvals	Tested to 2014/30/EU: Electromagnetic Compatibility Directive
Environmental approvals	RoHS and WEEE compliant
Software	PicoLog Cloud, PicoSDK (available from www.picotech.com/downloads) Example code (available from Pico's GitHub organization page, github.com/picotech)

VNA operating conditions

Operating temperature	+5 °C to +40 °C (41 °F to 104 °F)
Storage temperature	-50 °C to +70 °C (-58 °F to 158 °F)
Humidity	90 % at 25 °C (77 °F)
Atmospheric pressure	70.0 kPa to 106.7 kPa

Measurement Accuracy[3]

Accuracy of transmission measurements[4]	Magnitude / Phase ($S_{11} = S_{22} = 0$)	Magnitude / Phase ($S_{11} = S_{22} = 0.1$)
+10 dB to +13 dB	±0.2 dB / ±2°	±0.2 dB / ±2°
-50 dB to +10 dB	±0.1 dB / ±1°	±0.15 dB / ±1.5°
-70 dB to -50 dB	±0.2 dB / ±2°	±0.2 dB / ±2°
-85 dB to -70 dB	±1.0 dB / ±6°	±1.0 dB / ±6°
Accuracy of reflection measurements[5]	Magnitude / Phase	
-15 dB to 0 dB	±0.4 dB / ±4°	
-25 dB to -15 dB	±1.5 dB / ±7°	
-35 dB to -25 dB	±4.0 dB / ±22°	
Trace noise magnitude (IF bandwidth 3 kHz)	0.002 dB rms	
Temperature dependence	0.02 dB/°C	

Noise waves for LNA

- What are the noise waves for our LNA?
- That can be got from the NF and 4 noise parameters
- Meys worked these out:

- Meys: $T_{nS} = T_a + |\Gamma_s|^2 T_b + 2T_c|\Gamma_s|cos(\Phi_s + \Phi_c) + (T_s(1 - |\Gamma_s|^2))$

  converting between noise description:

  $T_d = 4T_0 \frac{R_n}{Z_0|1+\Gamma_{opt}|^2}$

  $T_a = T_{nmin} + T_d|\Gamma_{opt}|^2$

  $T_b = T_d - Tnmin$

  $T_c = T_d|\Gamma_{opt}|$

  $\Phi_c = \pi - \Phi_0$, where $\Phi_0 = arg(\Gamma_{opt})$

- 4 noise waves of Meys