The REACH Global 21cm Experiment Instrument

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on behalf of REACH collaboration
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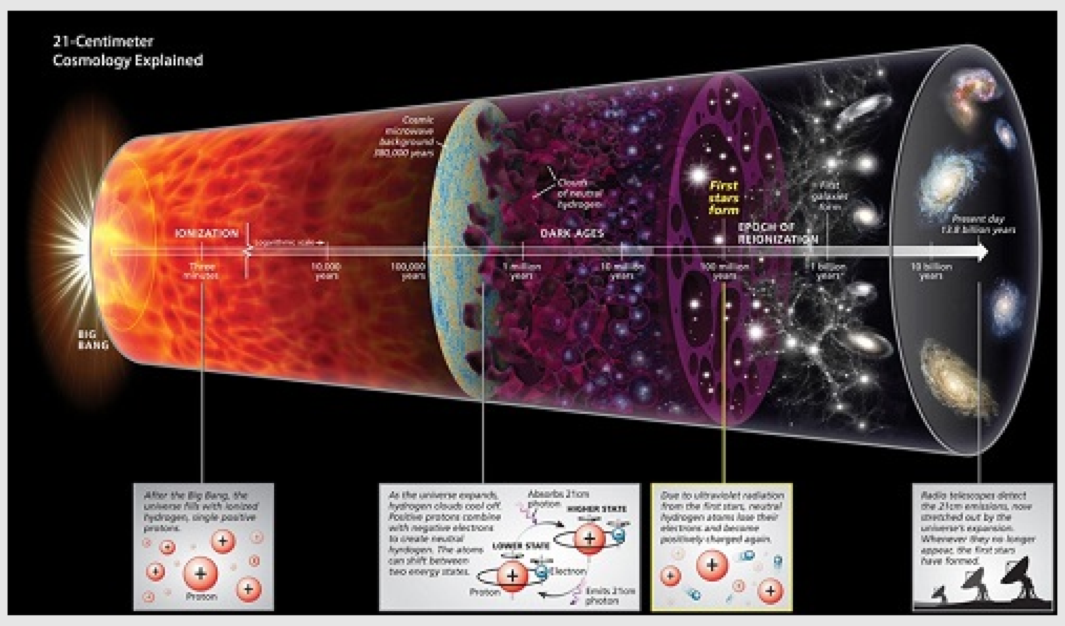
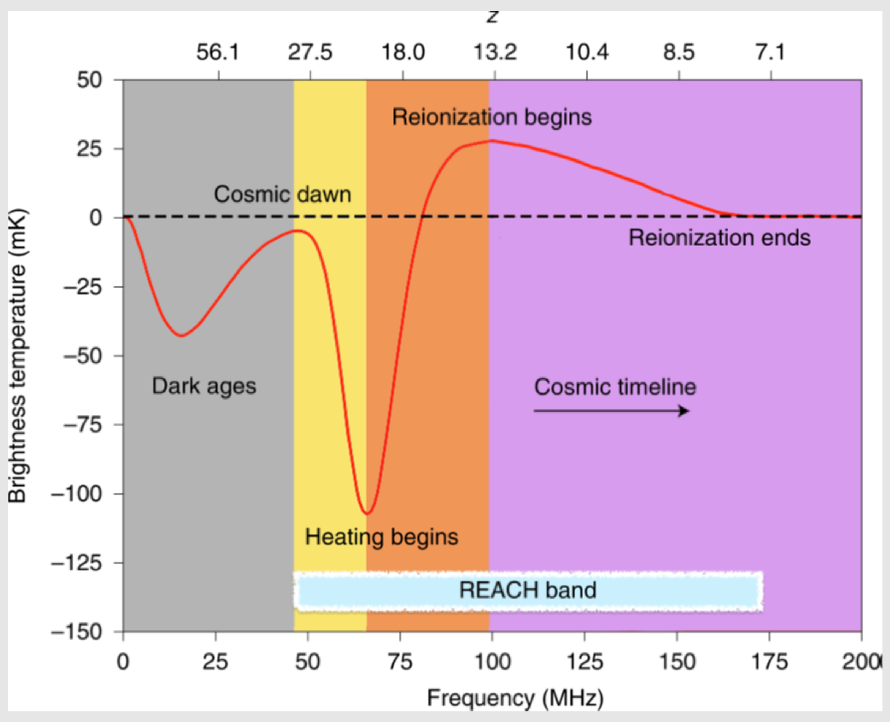
Scientific Goals of REACH



(a) Cosmological epochs. The REACH instrument is focussing on the Cosmic dawn and epoch of reionization.



(b) The REACH band frequency band [Lera Acedo et al. 2022]

Figure 1. Scientific background and motivation for REACH

The Radio Experiment for the Analysis of Cosmic Hydrogen (REACH) is a pioneering experiment that aims to detect the global 21 cm signal from the cosmic dawn and the epoch of reionization [Lera Acedo et al. 2022]. REACH covers a redshift range of approximately 7.5 to 28. The innovative features are expected to provide percent-level constraints on astrophysical parameters, potentially opening up a new window to the infant Universe.

The REACH Measurement System

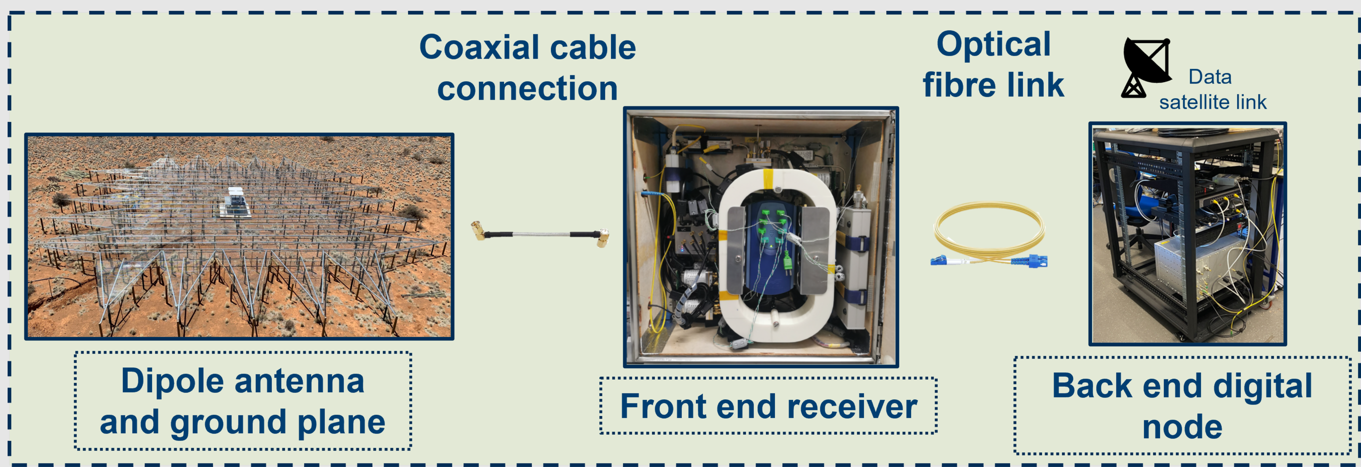


Figure 2. Schematic diagram of the REACH antenna, receiver and digital systems on site

- **Based on single dish dipole antenna**
- **Receiver front end system is located under the dipole blades**
- **Data is transmitted through a satellite link**
- **Data analysis is a based on a fully Bayesian pipeline and advanced foreground removal techniques**

REACH Services Node and Digital backend

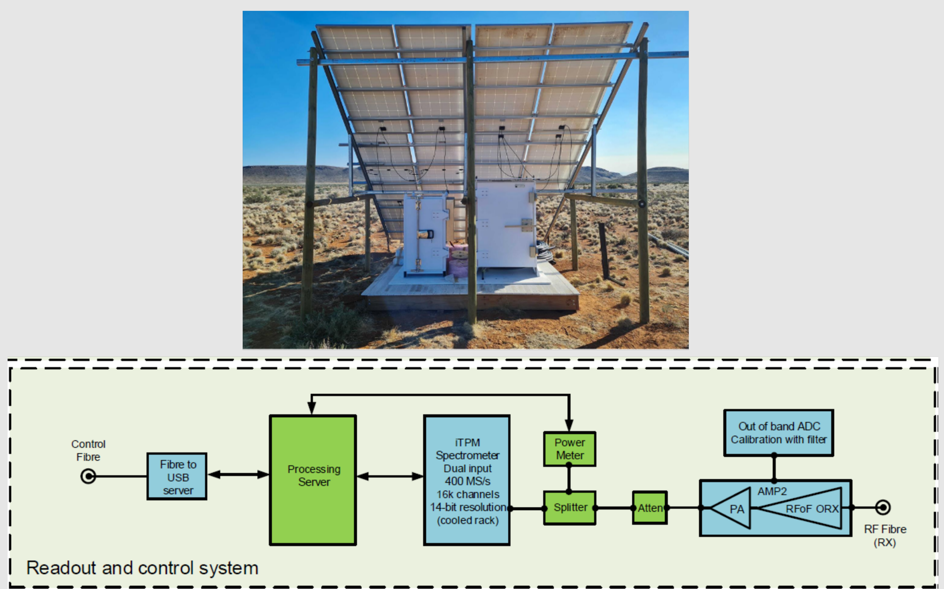


Figure 3. REACH services and digital back end node in RF shielded enclosures and the schematic of back end.

- **REACH is solar powered** and a battery is used for night observation
- **The digital backend** contains the ADC and the TPM spectrometer
- **Satellite link** for data transmission is also located at the services node

REACH Receiever System

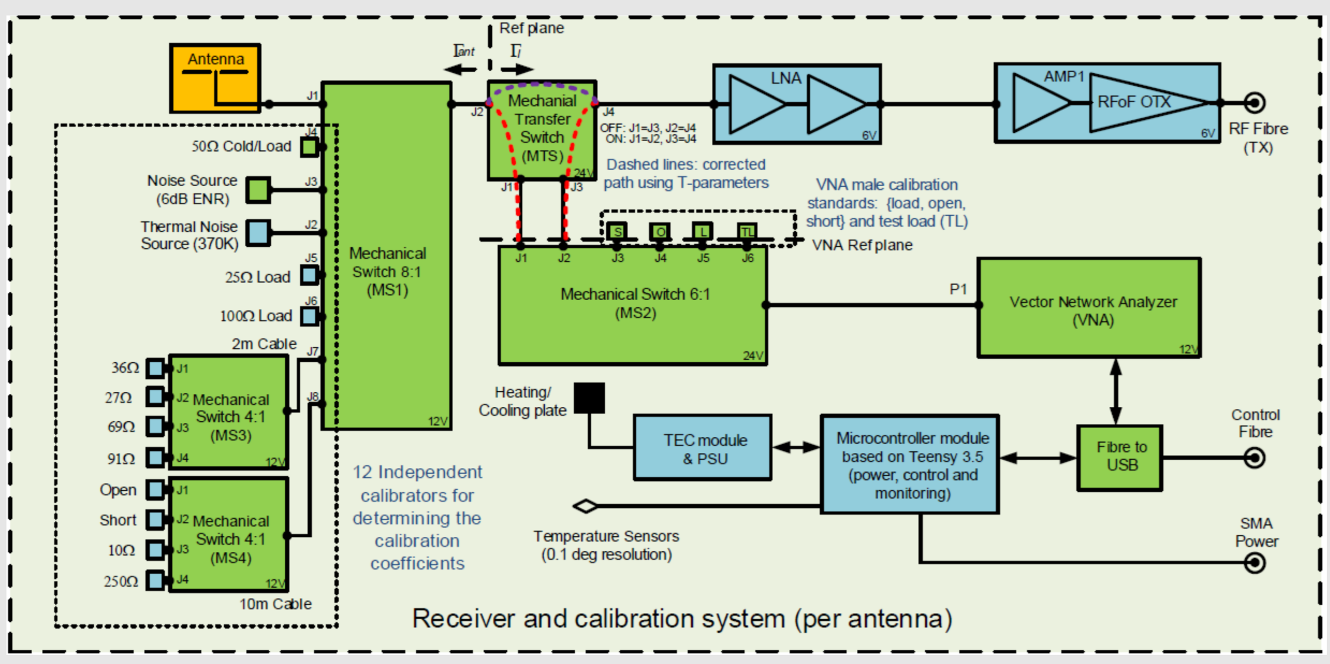


Figure 4. REACH receiver front end system schematic diagram.

- **Based on 3-way Dicke switching** REACH relies on in-situ continuous calibration
- **Switching between reference load of 50 Ω, 6dB ENR noise source and calibrator source/ antenna continuously**
- **12 calibrators to accurately map the antenna Smith chart for LNA noise calibration**

Receiever Calibration

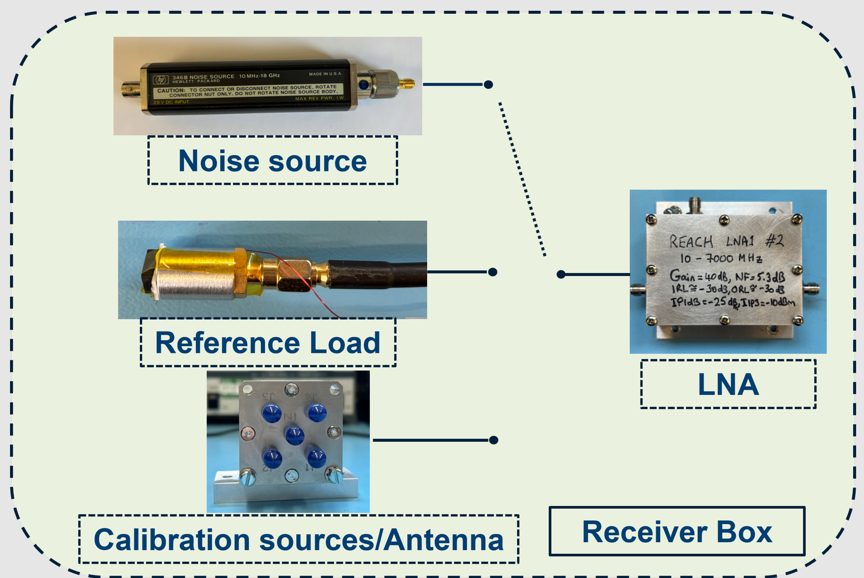


Figure 5. Calibration process schematic diagram with REACH components based on the 3-way Dicke switch.

- **Calibration is aimed at characterizing the 4 noise-parameters of the LNA**, and obtaining a calibrated antenna temperature with a few mK accuracy

$$T_n = T_{nmin} + T_d \frac{|\Gamma_s - \Gamma_{opt}|^2}{1 - |\Gamma_s|^2} \quad (1)$$

- PSDs are compared with physical temperatures to obtain uncalibrated source/antenna temperature.

$$T^*_{source} = T_{NS} \frac{P_s - P_L}{P_{NS} - P_L} + T_L \quad (2)$$

- **REACH description is based on the noise wave formulation** equivalent to eq. 1 describe the 4 noise parameters of the LNA [Meys 1978]
- **Detailed noise temperature modelling** of each element of the chain in fig 4 for the required few mK accuracy, for instance cable noise contribution needs to be modelled more accurately than with standard methods [Bucher et al. 2024],
- Reflections are taken into account at each RF plane to yield calibrated source/antenna temperature :

$$T_{source} = T_A(1 - |\Gamma_A|^2)|F|^2 + T_u|\Gamma_A|^2|F|^2 + |\Gamma_A||F|[T_c cos(\phi) + T_s sin(\phi)] + T_0 \quad (3)$$

- **REACH currently uses a fully Bayesian** based calibration method [Roque et al. 2021]
- **Various calibration strategies** are being tested at the moment, most notably polynomial fitting and machine learning based ones

Overview and Future Avenues

- **Improvements to the receiver**, → eg. thermal management, size reduction and VNA accuracy
- **Receiver calibration strategy selection** → from ML, Bayesian, Polynomial, Least squares fit select with lowest residual temperature
  - Implications beyond REACH use case
- **REACH phase 1 currently in commissioning** phase 1: one dipole antenna, phase 2: multiple antennae on site at the Karoo
- **Second identical system has been built at Cambridge** at Lord's Bridge Observatory near Cambridge → for test purposes and possible Northern Hemisphere observation

References

Bucher, M. and D. Molnar (2024). "Noise description of cables". In: *In preparation.*

Lera Acedo, E. de et al. (Aug. 2022). "The REACH radiometer for detecting the 21-cm hydrogen signal from redshift z ≈ 7.5–28". In: *Nature Astronomy* 6.8, pp. 984–998.

Roque, I. L. V., W. J. Handley, and N. Razavi-Ghods (May 2021). "Bayesian noise wave calibration for 21-cm global experiments". In: *Monthly Notices of the Royal Astronomical Society* 505.2, pp. 2638–2646. ISSN: 0035-8711. DOI: 10.1093/mnras/stab1453. eprint: https://academic.oup.com/mnras/article-pdf/505/2/2638/39680658/stab1453.pdf. URL: https://doi.org/10.1093/mnras/stab1453.

Meys, R. (1978). "A Wave Approach to the Noise Properties of Linear Microwave Devices". In: *IEEE Transactions on Microwave Theory and Techniques* 26.1, pp. 34–37. DOI: 10.1109/TMTT.1978.1129303.