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# The REACH Digital Backend

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## Abstract

The Radio Experiment for the Analysis of Cosmic Hydrogen (REACH) is a sky-averaged 21-cm experiment consisting of an ultra-wideband spectrometer that aims to improve current observations through in-field calibration of the receiver and by using a novel Bayesian data analysis system to fully parameterise the signal, foregrounds and instrument noise. The system is currently in the final stages of assembly and will be deployed on site in the first half of 2023. This paper focuses on the digital backend and management software of REACH, providing a description of the receiver and digital hardware, signal processing chain, and supporting instrument and observation management software.

## 1 Introduction

REACH is an ultra-wideband radiometer experiment designed to detect radio signatures of hydrogen at redshifts (z) between 7.5 and 28. At these redshifts the hydrogen (H1) signal is expected to be extremely weak, which makes its detection in the presence of strong sources such as the galaxy and bright point sources particularly challenging. To overcome these systematics, REACH is designed to average the hydrogen signal over the instrument's field-of-view and one of the main challenges of this approach is the calibration and foreground subtraction methods that are required to isolate the hydrogen signal. REACH uses a novel Bayesian data analysis system to fully parameterise the signal, foregrounds and instrument noise. To achieve this, it includes various calibration sources that can be used to calibrate the instrument noise and particular instrument effects that can appear in the data. The REACH system is described in [1].

This paper describes the REACH digital system that digitises the radio streams and processes the signals to produce a clean sky signal. The digital system also controls various calibration sources that can be coupled into the signal such that instrumental effects can be deduced and subtracted. The paper is structured as follows. Section 2 provides a general description of the REACH system, whilst Section 2 delves deeper into the digital backend and management software. Section 4 provides some results from running the REACH receiver through several calibration runs to model the instrument, and finally Section 5 concludes the paper.

## 2 The REACH System

REACH will feature two independent radiometers with different antenna designs, each connected to a Radio Frequency (RF) receiver that incorporates a switched calibrator system used to optimize calibration of the receiver electronics, relying on field-gathered data that are fully autonomous such that calibration and observation can happen concurrently. The receiver, a schematic of which shown in Figure 1, incorporates many calibration sources as well as several temperature sensors. The calibration system uses mechanical switches as well as a Vector Network Analyser (VNA) to measure the reflection coefficients of the sources and Low Noise Amplifier (LNA). An on-board microcontroller interfaces with the switches, providing the control software the capability of switching in or out the calibration sources, as well as routing the RF signal to either the VNA or spectrometer. During normal operation, Dicke switching will be used to observe the sky, an ambient load and a noise source on regular intervals. By using these three power spectral densities measured with the spectrometer, the effects of the receiver system can be calibrated out. Both receiver systems are connected through RF fibre to the digital system that includes the spectrometer, the processing server and the communication system. This setup is housed in an RF-shielded enclosure and is connected to a solar power system and a satellite data link. Power and control are propagated from this node to the receivers in the field.

## 3 Digital Backend

The digital backend (or REACH spectrometer) is based on the digital board developed for the Square Kilometer Array (SKA) Low Frequency Aperture Array [2], known as the Tile Processing Module (TPM) which hosts 16 dual-channel analgue-to-digital converters (ADCs), two Xilinx Ultrascale field programmable gate arrays (FPGAs) and 40 GbE interconnects. The board has been used both for verification of a SKA1 station [3] as well as the signal processing backend of other instruments [4, 5, 6]. For REACH, auxiliary functions such as monitoring control and data acquisition were reused, while the FPGA firmware was cus-

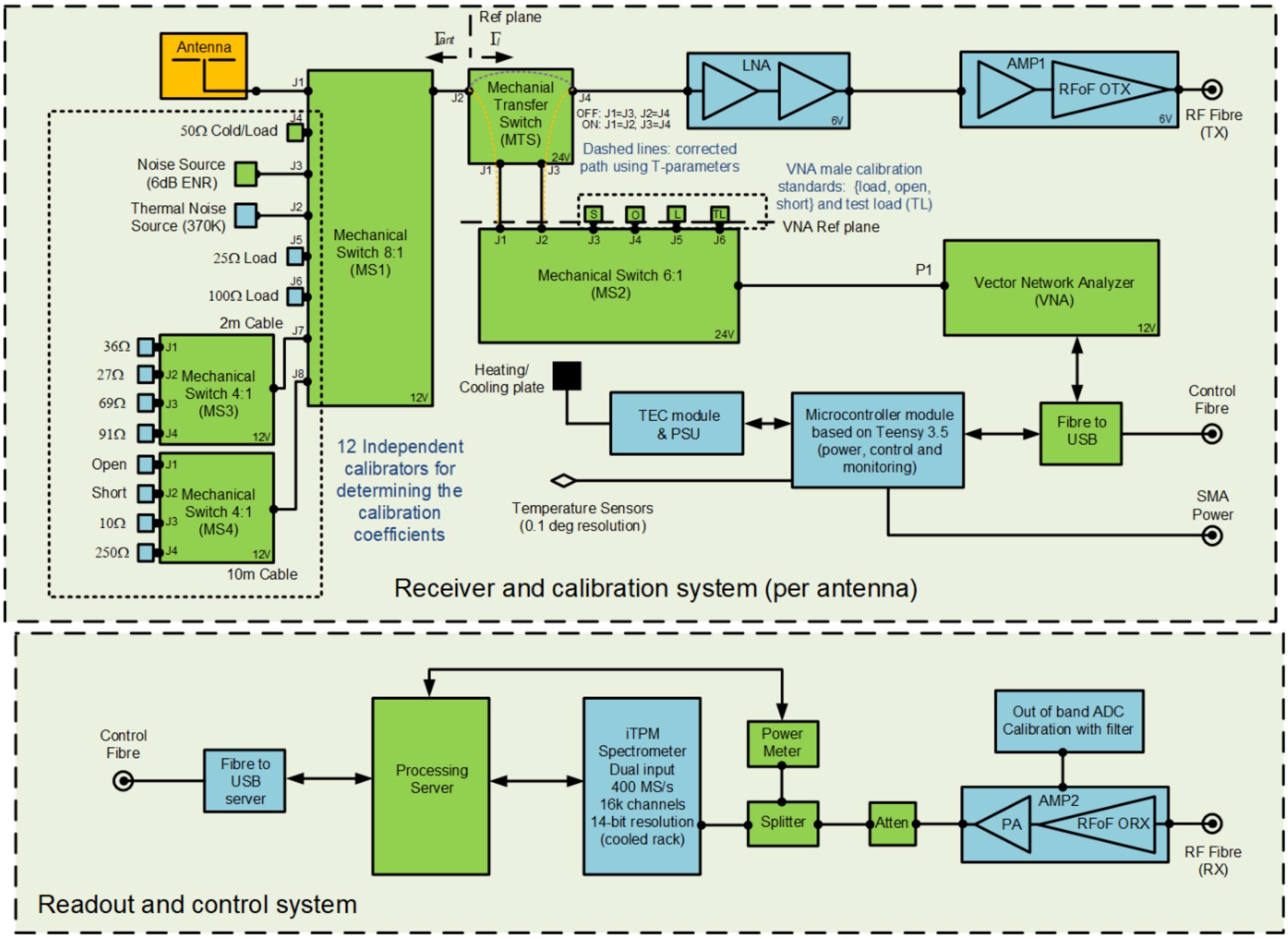


**Figure 1.** Schematic showing the components of the REACH receiver and digital backend. The receiver is composed of the LNA, to which the antenna is connected, a VNA that can measure the reflection coefficients of all the calibration sources (and LNA) in the field, several mechanical switches to determine which RF source will be used, a TEC module to stabilise the temperature of the receiver and a microcontroller that provides monitoring and control of the receiver. The digital backend is composed of the TPM and processing server. Temperature sensors are present throughout the system, whilst a power meter is attached to the incoming RF signal in the digital backend through a RF splitter.

tomised to include a high-performance, full floating-point digital spectrometer that includes a polyphase filterbank and a power integrator. A single TPM can fully process two RF signals, one per FPGA. See [1] for details on the spectrometer implementation for REACH.

The receivers and digital backend are controlled and monitored by the management software running on the processing server. This software is responsible for the correct, timely and safe operation of the instrument, including configuring, controlling and monitoring all hardware components, as well as observation and data management. Figure 2 presents a high-level overview of the management software architecture. The bottom layer shows monitorable and controllable hardware components that are distributed across the enclosure and receivers. A variety of communication protocols are used, including: the Python FPGA Board Interface Layer (PyFABIL) [7] for the TPM, SCPI for the VNA, a command-line serial interface to the uController, and proprietary USB and serial-based protocols for the temperature and power probes. New PyFABIL plugins were implemented to match the customised functionality of the FPGA firmware. The digital backend transmits integrated spectra as SPEAD [8] UDP packets over the 1 GbE network, which are in turn received by the associated spectrometer software module.

There are two primary modes of operation: calibration and sky observation. During calibration the reflection coefficients and spectral densities of all the calibrator sources and LNAs are measured, the result of which go through the calibration pipeline that generates calibration coefficients that can be applied to observation data. During sky observation the power spectra of the sky, an ambient load and a noise source are measured regularly. Both scenarios are managed by the scheduler that is configured through YAML config-

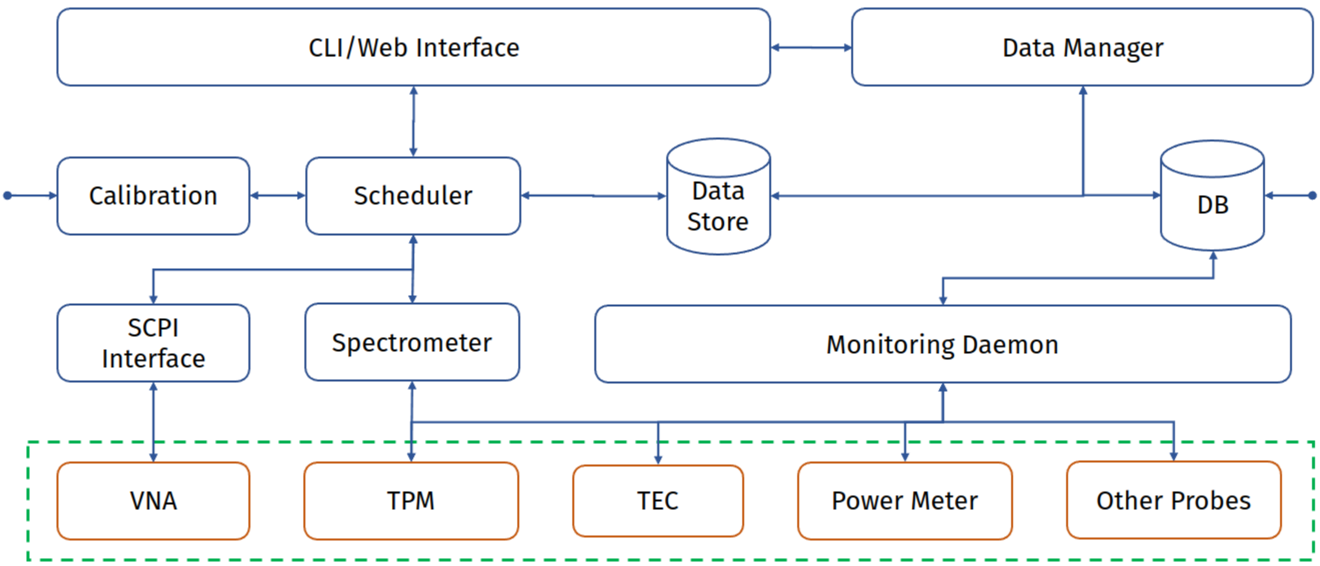


**Figure 2.** An overview of the management software architecture running on the processing server. Blocks in orange represent hardware components that are monitored and controlled, whilst blocks in blue are software components. Output from the VNA and TPM (through the spectrometer module) are forwarded to the Scheduler that acts as an observation manager. The Calibration block generates calibration coefficients and stores them in a database which is also used to store temperature and power metrics gathered by the Monitoring Daemon. The system can be interface through a command-line interface (CLI), with the aim of providing a Web Interface in the near future. The Data Manager handles observation data.

uration files. These files allow an operator to specify a sequential list of operations that need to be performed which can include source switching, reflection coefficient measurement, spectrum measurement, VNA calibration, hardware initialisation and several lower-level commands that can be used for fine adjustments and debugging of the system.

Temperature stability of the receiver is an important factor that needs to be considered during both calibration and sky observations. Temperature sensors are distributed throughout the receiver boxes and allow accurate temperature measurements to be taken of the several loads, LNA, digital backend and the environment. A TEC module is also included to stabilize the internal temperature to within 0.1 degrees. The software monitoring daemon collects temperature and power information every minute and stores them in a metric database. After a calibration or observation run is completed these metrics are included in the generated data files as metadata, which are in turn used by the calibration procedure.

Data generated during calibration and observation runs are stored as HDF5 [9] files and include all the spectra and reflection coefficients generated during the run with associated timestamps, all temperature sensor readings, and general metadata. The HDF5 files are self-describing, such that they contain all the necessary information required to process them in the future, without having to refer to any observation schedule or documents. These files will then be transferred off-site to a centralised storage system through the dedicated satellite network link.

## 4 Verification

A REACH receiver and the digital backend have been assembled, with the receiver going through several iterations to increase thermal stability and reduce radio interference. This was combined with incremental updates to the management software to include more powerful diagnostic features and improvements to the configuration infrastructure. Several measurements and improvements were performed in Q4 of 2022 to model the system and fine-tune the calibration procedure.

The digital system has been verified through passband measurements of the several calibrator sources. Figure 3 shows the passbands of 10 calibrator sources, having a clean frequency response across the processable REACH band, with small RFI spikes at the lower frequencies that are visible upon magnification. Figure 4 shows the temperature variation during a calibration run from several probes placed next to various components in the receiver, including cables connecting the mechanical switches and a selection of calibrator sources. The first 1.5 hours represents mechanical switch stabilization and VNA calibration, after which the temperature variation stays within $\pm$ 0.1 K. The absolute value of the hot source is around 370 K, whilst the other sources have a stabilised temperature in the range 296 K to 304 K. This shows that both the TEC module and the monitoring component of the management software are functioning as expected. All the runs were performed through

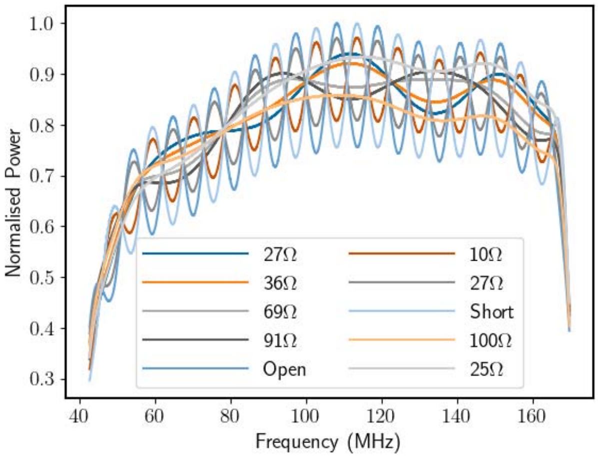


**Figure 3.** Frequency response of several calibrators.

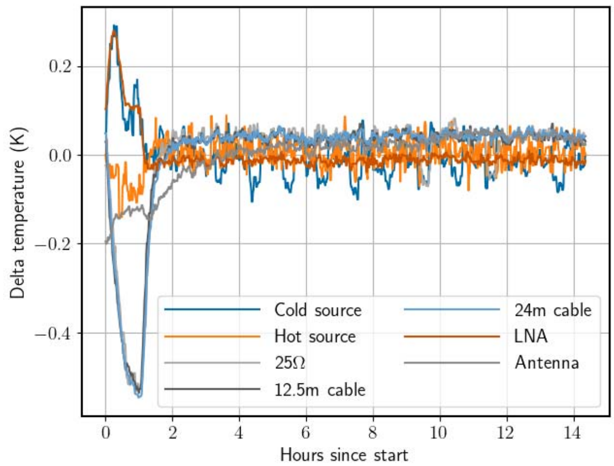


**Figure 4.** Temperature variation during a calibration run of 14 hours.

the observation scheduling and management system.

## 5 Conclusion

In this paper, we have described the digital backend and management software for the REACH instrument, whilst presenting some results for lab measurements conducted to model the instrument. Articles describing the final receiver system, calibration pipeline mechanism and verification results are forthcoming. Both the receiver and digital system have been shipped to South Africa in January 2023 for deployment to the SKA site in the Karoo desert.


## Acknowledgements

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