Searching for cosmic dawn: Marion 2017 takeover report

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1 Scientific background

Observations of redshifted 21-cm emission of neutral hydrogen at radio frequencies are a rapidly growing area of cosmology research that can potentially shed light on numerous epochs in the universe's history. Measurements at low frequencies (below 200 MHz) probe the era known as "cosmic dawn," a period roughly a few hundred million years after the big bang, when the first stars ignited in the universe. The formation of these first stars heated the intergalactic medium, imparting characteristic structure in the brightness of the globally averaged 21-cm sky signal as a function of frequency. The detailed frequency structure of the global 21-cm signal captures the heating processes of the first stars and is expected to have a ~ 100 mK dip around 70 MHz (corresponding to a redshift of about 20), as shown in Figure 1. This signature is undetected to date, and a number of international experiments are working to make the first measurement of the universe in this slice of its history, an epoch that is ripe for new exploration.

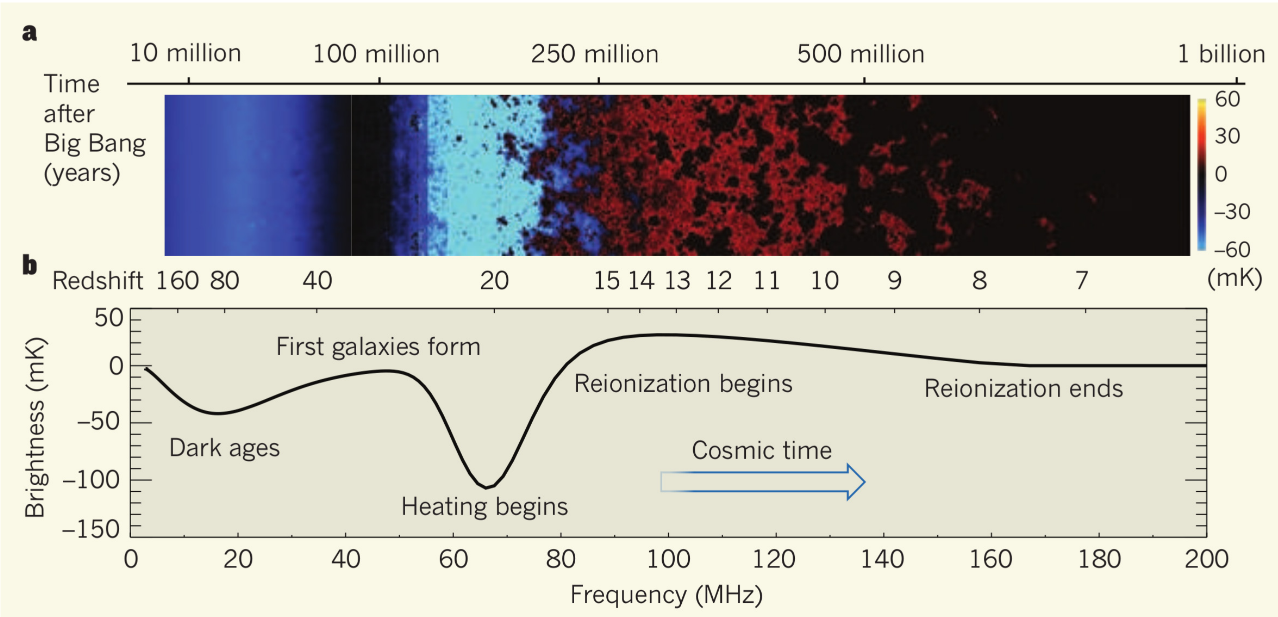

Figure 1: A model prediction of globally averaged 21-cm emission at low frequencies. The birth of the first stars in the universe is expected to produce an absorption feature around 70 MHz. (Image courtesy Pritchard and Loeb, 2010.)

Our team has constructed a radio astronomy experiment that has been specifically designed to study cosmic dawn in the universe using 50–200 MHz observations of globally averaged 21-cm emission. The experiment consists of two compact, modified four-square antennas that operate at central observing frequencies of 70 and 100 MHz. One of the greatest challenges for low-frequency radio observations is terrestrial radio-frequency interference (RFI), which overwhelms the cosmological signal even when the nearest RFI sources are hundreds of kilometers away. Because our system observes total power, the required level of RFI control is far more stringent than for most radio telescope arrays, which benefit from crosscorrelations. The first incarnation of the antennas, known as Sonda Cosmologica de las Islas para la deteccion de HIdrogeno neutro (SCI-HI), deployed to Guadalupe Island (200 km off the coast of Mexico) in 2013, and the experiment established upper limits on the global 21-cm signal at redshift ~ 20 (~ 70 MHz) that provided the most stringent published results for several years. The residual RFI levels were about an order of magnitude larger than the expected cosmological signal, and it is likely that RFI contamination could be reduced further by moving to an even more remote observing location.

In 2014, our team was funded by the NRF/SANAP to perform radio observations from Marion Island: the 2000 km separation from the nearest continental land masses represents an order-of-magnitude distance isolation improvement over Guadalupe. During our first engineering run at Marion in the 2016 takeover period, we set up the original SCI-HI 100 MHz antenna at Rooks. From a modest amount of data taken during the takeover period, we determined that Marion provides an exceptionally clean RFI environment, with almost no visible RFI within the FM band. Remarkably, Marion even outperforms the Square Kilometre Array site in the Karoo desert, which is one of the premier radio astronomy observing locations worldwide. In preparation for the 2017 takeover period, we completely rebuilt both the 70 and 100 MHz antennas, and we upgraded the back-end electronics to operate both antennas simultaneously, with dual-polarization readout. Because our system no longer shares any common hardware with the original SCI-HI antennas, we have renamed our experiment to be **P**robing **R**adio **I**ntensity at high-**Z** from **M**arion, or **PRI^{Z}M**. The following sections describe our detailed activities for the 2017 takeover period and preparations for continued observing throughout the 2017 Austral winter.

2 2017 takeover period activities

The primary goals for the 2017 Marion takeover period were to identify a suitable observing location for PRI^{Z}M, install the equipment, verify end-to-end functionality, test survival in the harsh environmental conditions, and ensure sufficient robustness of the system for winter-long operation. The takeover team members were H. Cynthia Chiang (group leader and senior lecturer at UKZN), UKZN PhD students Liju Philip and Heiko Heilgendorff, and Rhodes PhD student Ridhima Nunhokee.

2.1 Site selection

Because we intended to leave the PRI^{Z}M system operating during the Austral winter, we needed to select a new observing site that balanced two competing requirements: 1) ease of regular accessibility from the base, and 2) sufficient distance from the base to minimize the impact of locally generated RFI. (Rooks, the original site used during our engineering run in 2016, was too far from the base to be feasible for regular winter maintenance and operations.) During the first several days of the takeover period, we surveyed RFI levels and examined terrain quality at three different locations:

- Elevated area near the old hydro shack (Figure 2)
- Three Sisters (between second and third)
- Between Junior's and Fister's kop (Figure 3)

Figure 2: RFI surveying a candidate site near the old hydro shack.

Figure 3: RFI surveying the area between Junior's and Fister's kop. We ultimately selected this site for the installation of the PRI^{Z}M hardware.

Although the area near the hydro shack was the most convenient in terms of ease of access, we found that the level of RFI shielding between the hydro shack and the base was insufficient.

In particular, the 400 MHz DORIS beacon was clearly visible from the hydro shack location, and the level of attenuation was only ~ 20 dB. The candidate location between the Second and Third Sister provided better shielding than the hydro shack location; however, the long hiking distance (including Hoppie's Hell) made this site unfeasible. We ultimately selected the third site, between Junior's and Fister's kop, for both the reasonable hiking time and for the excellent RFI shielding. By good fortune, we surveyed the site on a day when the helicopters were flying and broadcasting radio signals, and we were able to use the helicopter transmission to approximately calibrate the level of RFI shielding from Junior's kop, which we determined to be roughly 60 dB. Furthermore, there is ample terrain that is flat, elevated, and free of rocks (for easier equipment anchoring). We confirmed with the ECOs that there are no specific environmental concerns associated with our site, and several people inspected our setup after all equipment was installed. The GPS coordinates of our equipment are as follows:

- Three containers (M5, M19, S44), central point: S 46° 53′ 13.0″, E 037° 49′ 10.7″
- 70 MHz antenna: S 46° 53′ 13.7″, E 037° 49′ 09.1″
- 100 MHz antenna: S 46° 53′ 14.0″, E 037° 49′ 12.1″

2.2 Remote RFI surveying

In addition to surveying and selecting the PRI$^{\mathrm{Z}}$M observing site near the base, we also surveyed two remote locations at Kildalkey and Swartkop in order to assess the level of improved RFI shielding at far distances from the base. Team member Heiko Heilgendorff led the surveying effort. The original plan was for Heiko to join another group on a round-island walk and survey as many hut locations as possible. However, due to schedule changes and reprioritization of tasks, we descoped our remote RFI surveying plan to include only Kildalkey and Swartkop. Heiko assisted with the hut restocking operations for these two locations, and he completed the surveying measurements at the same time. We found that combining the RFI surveying with hut restocking operations and flights was an efficient way of completing these measurements, and we will likely pursue this option again for future surveying. Both Kildalkey and Swartkop have exceptionally low RFI levels and are suitable as future radio astronomy observing sites.

Figure 4: The Ultimate Heli team slinging the final container to the PRI$^{\mathrm{Z}}$M observing site.

2.3 Equipment setup

Each of the two PRI$^{\mathrm{Z}}$M antennas consists of a fiberglass mounting structure (square platform, central column, and angled struts) and black powder-coated aluminum petals. The antennas are placed on top of 10 m $\times 10$ m wire mesh sheets, which serve as reflective ground planes; there are also 16 radial wires that extend beyond the perimeter of the ground planes by about 5 m in length. The front-end electronics are enclosed inside the central fiberglass columns, and 50-m cable bundles (two LMR-400 coaxial cables for the antenna signals, plus doubled Ethernet cable for power distribution) run from the antennas to the central "command module" container, which lies near the midpoint of the two antennas and houses the readout electronics. The command module also houses eight lead crystal batteries that power the system, as well as the battery chargers. The battery charging is performed with a Honda EU30i generator that is housed in a separate container.

Figure 5: *Left:* assembly of the 100 MHz antenna on April 20. *Right:* completed 100 MHz antenna.

Following the selection of the PRI$^{\mathrm{Z}}$M observing location between Junior's and Fister's kop, our three containers (M5, M19, S44) were slung to the site on April 19 (Figure 4). The containers were placed end-to-end along the north-south direction, with the open sides facing approximately east so that the container interiors are sheltered from the prevailing winds. We began by surveying and marking our antenna locations relative to the command module container (southernmost of the three). We completed the 100 MHz antenna assembly within one day (Figure 5), and we configured the command module and achieved first light on the 100 MHz system another day later on April 21. On April 22, we completed the assembly of the 70 MHz antenna and successfully demonstrated end-to-end functionality of the full PRI$^{\mathrm{Z}}$M experiment.

Despite the initial success of the PRI$^{\mathrm{Z}}$M setup, we encountered a few days of setback after the equipment was operational: to quote Marius Rossouw, "Marion hates equipment." The island attacks hardware on three fronts: wind, water, and mice. Although we were adequately prepared for the first two of these attacks[1], we soon discovered that the mice had developed a fond taste for our coaxial cable sealant, self-amalgamating tape, electrical tape, wire insulation, etc. We spent a few days repairing superficial mouse damage and applying several mouseproofing measures, which included wrapping cables in wire mesh cloth, stuffing cable penetrations with metal scouring pad material, and selective use of silicone sealant. These mouseproofing measures proved effective, and we were back online and observing again by April 27. The remainder of the takeover period was devoted to continued observations, calibration measurements, and preparing the hardware and software for winter operations. The final, completed PRI$^{\mathrm{Z}}$M system is shown in Figure 6.

2.4 Preliminary data

We successfully obtained several days' worth of data on both antennas during the takeover period, and a preliminary look suggests that the data quality is outstanding. There is nearly zero RFI contamination from our selected site, and and rebuilt PRI$^{\mathrm{Z}}$M system is vastly more stable than the hardware that was deployed in 2016. Figure 7 shows a portion of data taken during 2016 (only one polarization at 100 MHz), and Figures 8 and 9 show some representative data from the 2017 takeover period—using two antennas and two polarizations (with both auto- and cross-spectra recorded by the readout system). We greatly look forward to seeing the data from the forthcoming winter observations.

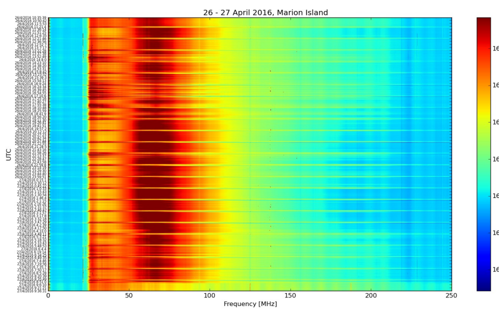

Figure 7: Single-polarization 100 MHz data from the previous takeover (2016). A comparison with Figures 8 and 9 shows the improved 2017 data quality.

[1]We were present during a storm with 90 knot gusts, and there were no detectable vibrations in the antenna structures.

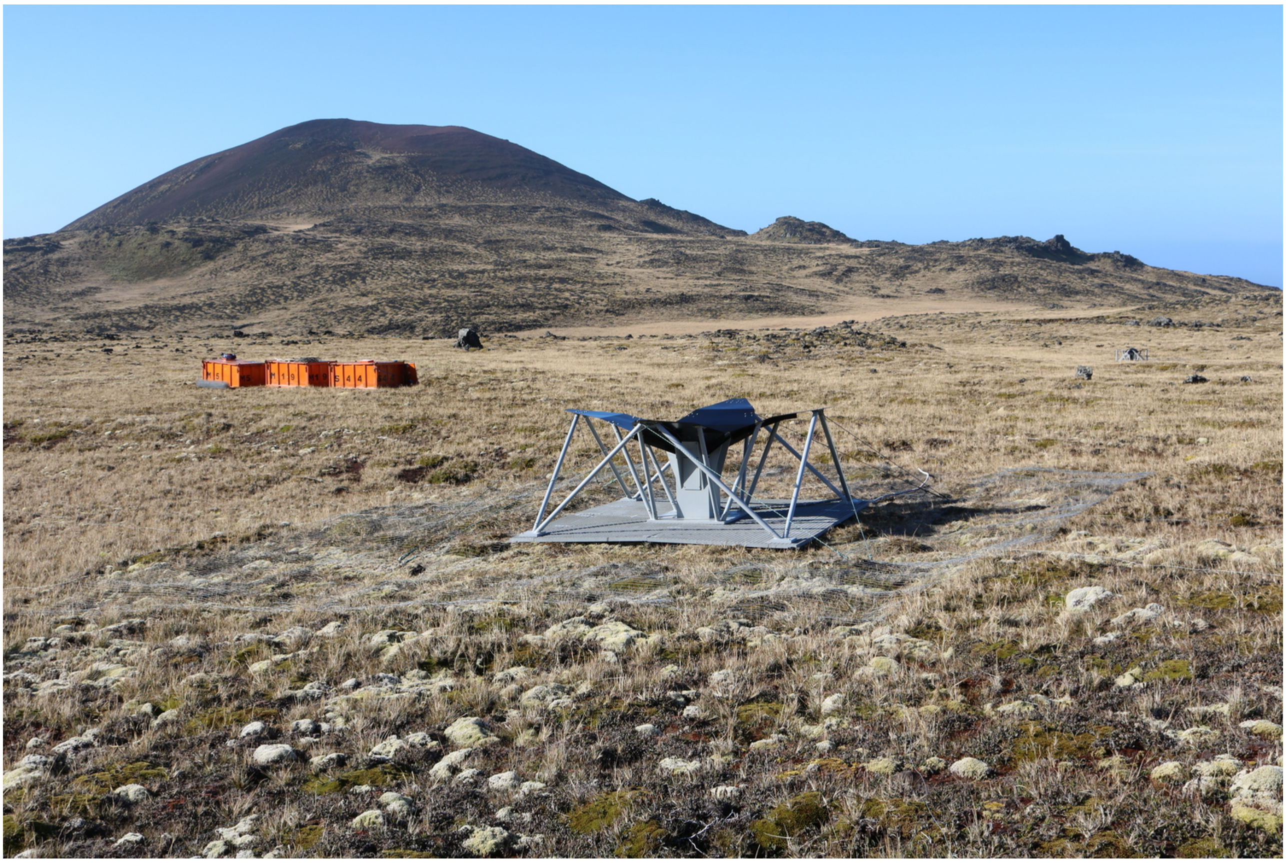

Figure 6: The completed PRI^{Z}M system as of May 4, 2017. The 70 MHz antenna is in the foreground, and the 100 MHz antenna is in the background (toward the right edge of the image). The rightmost of the three containers is the "command module" that houses the readout electronics. The photo perspective is roughly northeast, with Junior's kop in the far background (and the base lying farther behind, out of sight).

3 Acknowledgments

We extend our sincere gratitude to Adriaan Dreyer and Errol Julies for general logistics support and coordination, Thomas Mufanadzo for answering our environmental impact questions, the Ultimate Heli team for delivering us and our cargo safe and sound to our site, Werner Nel for science support and island wisdom, Nico de Bruyn for mouse warfare tips, and Marius Rossouw for lab support at the base. Many thanks for emergency hardware loans and hacking support from the PWD team, the base engineers, Diesel John, and Comms David. Lastly, but certainly not least, we gratefully acknowledge the SANSA team—Travis Duck, Pierre Joubert, and Kagiso Malepe—for helping us with site selection and countless other tasks that were critical for making the experiment a success. In particular, many advance thanks to Kagiso for making the long walks to check on our equipment and keeping the system happy throughout the winter!

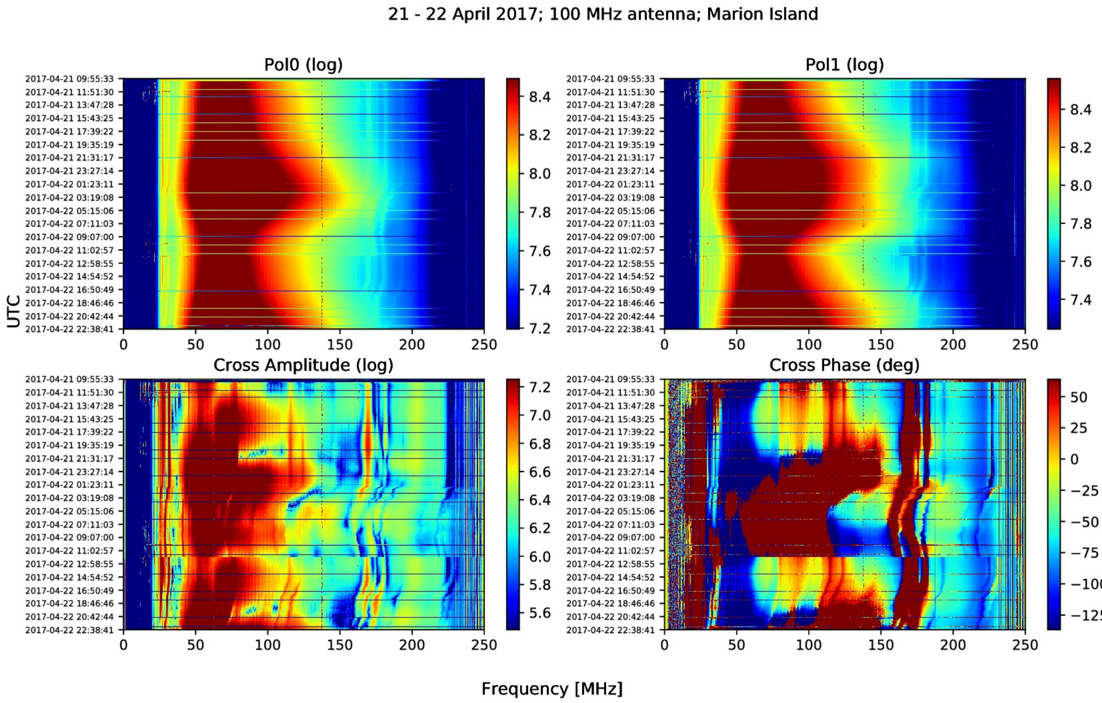

Figure 8: Representative 100 MHz PRI^{Z}M data from the 2017 takeover period. In each of the four panels, the horizontal axis is frequency in MHz, the vertical axis is time in UTC, and the color scale is signal intensity. The top two panels show the autospectra of each antenna polarization, and the bottom two panels show the amplitude and phase of the cross-correlation between the two polarizations. The large-scale structure in the autospectra arises from the Milky Way galaxy, which drifts in and out of the antenna field of view as the sky rotates overhead. The narrow features around 140 MHz arise from the ORBCOMM satellites. The faint horizontal lines in all of the panels correspond to hourly calibration measurements that are automatically performed by the control system.

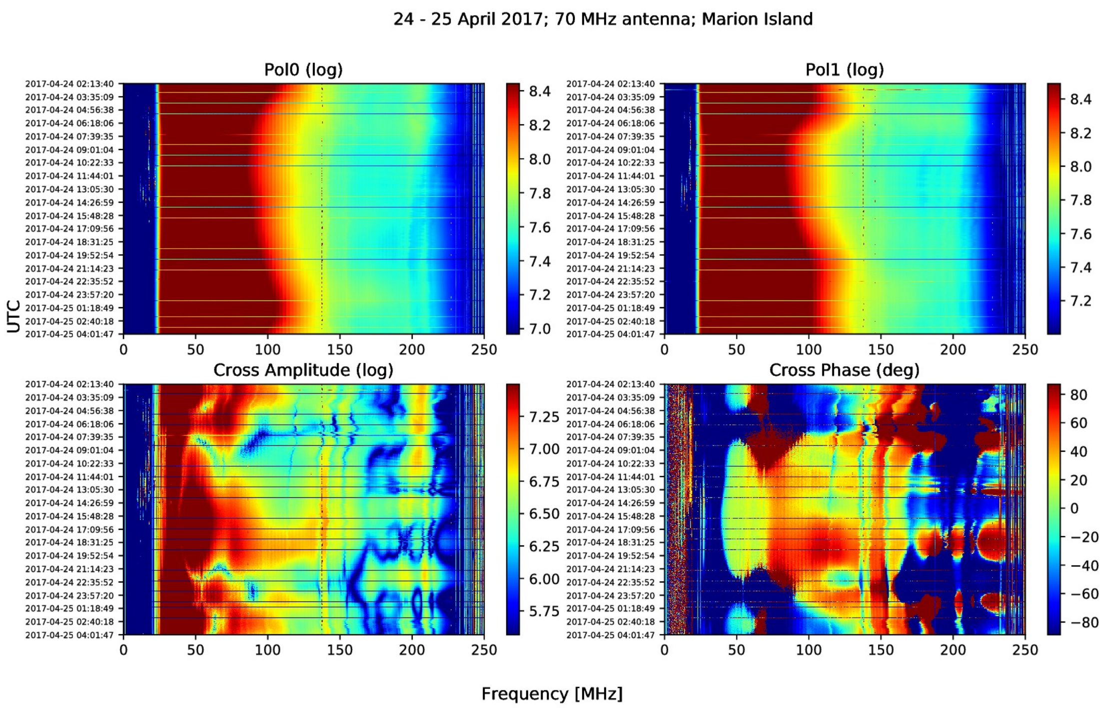

Figure 9: Representative 70 MHz PRI^{Z}M data from 2017; see Figure 8 for details.