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VHF-band RFI in Geographically Remote Areas

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The Experiment to Detect the Global EoR Signature (EDGES) is a radio spectrometer operating between 90 and 205 MHz using a single broadband dipole. The instrument recently completed a deep, three-month continuous measurement campaign in the Murchison Radio-astronomy Observatory (MRO) where it reached sufficient sensitivity to constrain the cosmological epoch of reionization (EoR). EDGES has also been used to conduct short, shallow RFI surveys in remote regions in the United States, including northern Maine and the Catlow Valley in southeast Oregon. Here, we show results on the RFI spectrum seen by EDGES at each of these locations and implications for upcoming low-frequency arrays such as MWA, LWA, LOFAR, and PAPER.

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1. Introduction

Radio frequency interference (RFI) in the VHF band between 30 and 300 MHz is a serious concern for several major new low-frequency radio telescopes presently under construction, including LOFAR, LWA, MWA, PAPER, and 21CMA. The sources of intereference in the VHF band include some of the most ubiquitous forms of telecommunication: FM radio, television (analog and digital), aircraft and marine navigation beacons, and low-earth orbit satelites. These signals can propagate for hundreds of kilometers under typical conditions, hence most of the new telescopes plan to be located in very remote sites that are sparsely populated such as the Murchison Radio-astronomy Observatory (MRO) in Western Australia or northern China. But even in remote locations, the extent to which distant transmitters will interfere with radio astronomy observations has yet to be well characterized, particularly at the extremely sensitive levels that long integrations by the new facilities will achieve.

In this paper, we report observations with the Experiment to Detect the Global EoR Signature (EDGES). EDGES[1] is a standalone, compact, and easily transportable single dipole broadband radio spectrometer that operates between 95 and 205 MHz [1-2]. It is designed to study the cosmological epoch of reionization (EoR)—the era in the history of the Universe when the first stars, galaxies, and black holes exerted radiative feedback on the primoridal hydrogen gas from which the formed. Here, however, we will not focus on the science performed by the instrument, but rather on a brief overview of the qualatative and quantitative properties of RFI that the experiment has measured at several geographically remote regions. In Section 2, we discuss properties of RFI observed by EDGES at the MRO during a long, deep science integration lasting three months. In Section 3, we show the results of several short, shallow surveys performed at mulitple locations in the Unites States that were selected based on estimates of their radio-quietness in the VHF band.

2. Murchison Radio-astronomy Observatory (MRO)

EDGES was deployed at the MRO from 20 Aug 2009 through 12 Nov 2009. During the deployment period, the instrument observed the sky continuously for its primary science objective, recording a spectrum approximately once every minute. Each spectrum was calibrated internally using a comparison-switched scheme that cycled between the antenna port and two internal noise sources for reference in order to achieve high dynamic range and minimize instrumental systematic artifacts. The nominal duty cycle resulting from this scheme is 33%, but the digital backend of the spectrometer suffered additional data flow restrictions that lowered the overall duty-cycle to <5%. The instrument is sky-noise dominated, however, thus in each 1-minute spectrum the sensitivity reached 1% of the sky noise (e.g. ~3 K at 150 MHz since the sky noise is 250 K when high-Galactic latitudes are overhead).

Figure 1 shows a "waterfall" plot of one 24-hour period during the observation. The band observed by EDGES is very clear of RFI, with fewer than 3% of the spectral channels exhibiting detectable levels of RFI typically at any one time. In Figure 1, however, an

[1] Technical memoranda describing EDGES can be found at: http://www.haystack.mit.edu/ast/arrays/Edges

anomalous propagation event is shown starting at 16:00 UTC that lasted for about 10 hours. Seven comparable events were detected during the entire observation, although most lasted for shorter durations. During these events, FM and digital TV stations are easily detectable from distant cities, including Perth and Geraldton [3].

A variety of propagation mechanisms can cause very distant VFH-band transmissions to be received for short periods of time, as observed by EDGES. Reflections from aircraft and ionized meteor trails regularly scatter FM and TV signals over the horizon for durations of seconds up to minutes. Certain atmospheric conditions, including sporadic E progagation through the ionosphere, and tropospheric scattering and ducting can cause rare, but extreme periods lasting hours or days when transmissions can propagate up to about 2500 km. The statistics of these events and the amount of RFI they propagate are dependent on the properties of the site and the surrounding distribution of transmitters. In the event shown in Figure 1 and several other events detected by EDGES, the anomalous propagation is most likely due to tropospheric bending which results in signals following the earth's curvature. Tropospheric bending is likely since the events appear to follow strong rain storm activity when low lying water vapor increases the atmospheric refraction near the ground.

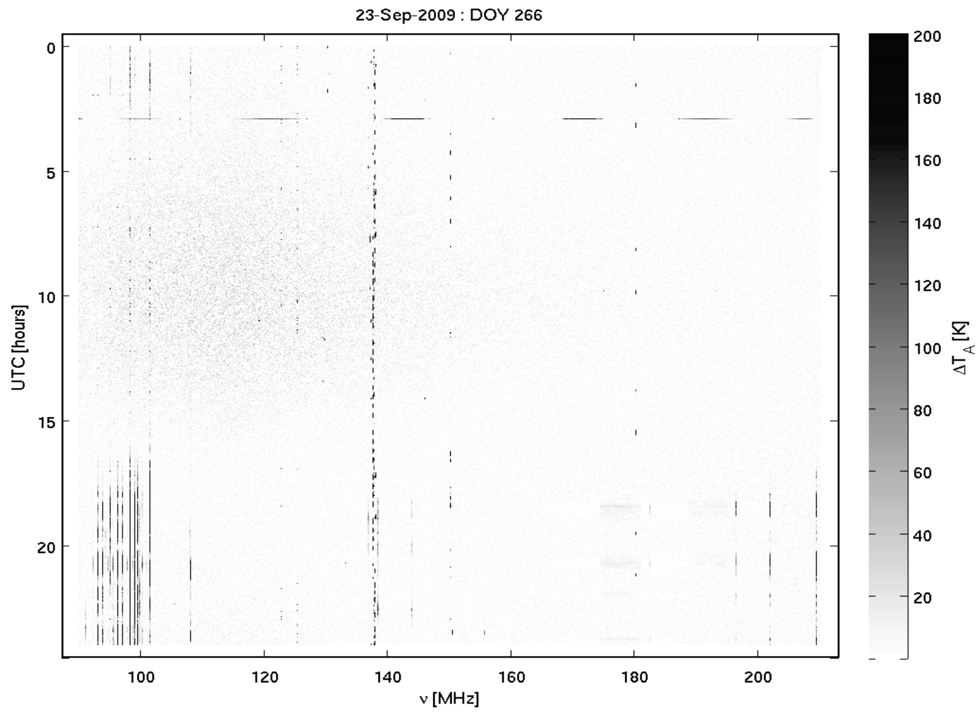

Figure 1: *Waterfall plot of RFI following subtraction of the sky noise background for a 24-hour period at the MRO. The consistent stream of RFI pulses around 138 MHz is from the Orbcomm constellation of low-earth orbit satelites and the intermittent, quasi-periodic bursts at 150 MHz are from a satellite beacon. Aircraft transmissions are observed between 120 and 130 MHz. A rare event is seen starting at approximately 16:00 UTC that greatly increased the observable RFI for several hours, lasting until 02:00 UTC the following day. The signals below 108 MHz are FM stations from Perth, Geraldton and other cities in Western Australia, most of which are hundreds of kilometers distant. Broadband (6 MHz) digital TV signals are visible at 175 MHz and continuing out of the band above 200 MHz. Analog TV carriers are also interspersed. The extremely wideband event at approximately 03:00 UTC is likely due to lightning associated with a severe storm in the region.*

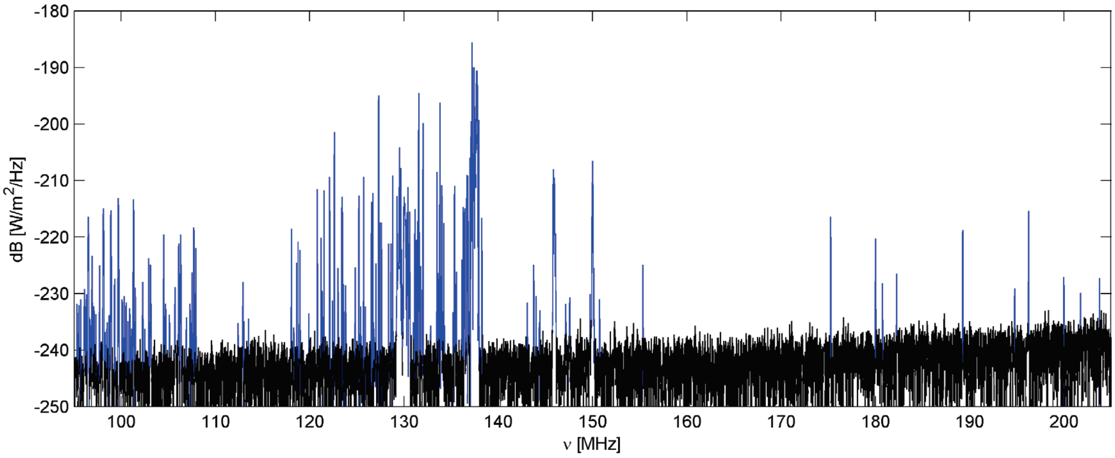

Figure 2: *Integrated residual spectrum following subtraction of the sky noise background for a three-month long observation at MRO. The thermal noise limit is approximately -240 dB [W/m^2/Hz], equivalent to ~30 mK in antenna temperature units for 13 kHz spectral channels. The blue line indicates the 11% of spectral channels that contained narrow-band RFI at least once during the long integration. The black line plots channels that never exhibited detectable RFI.*

EDGES also provides the first ability to look at RFI in a very deep integration at the MRO that reaches the extreme sensitivity levels of order 10 mK that will be required by all future low-frequency arrays to study the reionization epoch. Figure 2 shows the deep EDGES spectrum resulting from approximately 1500 wall-clock hours of observations (50 hours of effective integration). The spectrum reaches a thermal sensitivity of -240 dB [W/m^2/Hz], which is equivalent to an RMS noise of ~30 mK in the native 13 kHz channels. The instrumental systematic noise in the spectrum is estimated at approximately 5 mK. Because high dynamic range is crucial for the primary science of the EDGES instrument, temporal excision was applied to the spectrum in Figure 2 by filtering out entire 1-minute spectra using a total power threshold to remove times when the Orbcomm signal dominated the total power in the observed band and when FM or TV bands were extremely strong due to anomalous propagation periods. This filter removed 30% of the individual temporal samples, but otherwise did not remove any specific frequency channels. Other instruments, such as the MWA, should be able to tolerate the periods when Orbcomm dominates the power in the band much better than EDGES, hence we expect this temporal excision to be much less critical during their science observations.

The black line in Figure 2 illustrates the final spectrum after a very aggressive spectral filter has been applied. The spectral filter removes any channel from the final integrated spectrum that was *ever* observed to have narrow-band RFI during the integration (even in only a single 1-minute spectrum). Only 11% of the spectral channels were flagged in the mask after three months of integration.

3. Shallow Surveys at Remote Sites in the United States

The EDGES instrument has also been operated at several sites in the United States for purposes of instrument testing and also to directly characterize the RFI for future science observations. The sites were chosen based on a prediction of the total power from FM and TV transmission derived from the FCC national catalog of transmitters and a propagation model that utilized a digital elevation terrain map. We commissioned Radio-Locator.com[2] to produce the derived map of the integrated received power as a function of latitude and longitude in the U.S. This map, shown in Figure 3, predicts a minimum integrated signal strength in the region of the Catlow Valley in southeast Oregon. In the New England region nearby Haystack Observatory, the map predicts that a small valley near West Forks, Maine, will be radio quiet in the VHF band. We performed shallow surveys at both of these locations.

The West Forks region was significantly more radio-quiet than Haystack Observatory in northern Massachusetts or the VLBA site in Hancock, New Hampshire [4-5], but the FM band remained fully populated with stations typically 10 dB above the sky background and one station more than 40 dB above the sky. A number of additional transmitters were also observed throughout the spectrum, possibly originating in the local community. A plot of the West Forks spectrum can be found in [5].

The Catlow Valley is even more radio-quiet that West Forks due to terrain shielding by surrounding mountains, but received RFI power was found to vary considerably with both time and location in the valley. FM radio stations were only sporadically received at the 10 dB level and we judged this reception to be the result of several diffracted and reflected paths with total strength varying on time scales of seconds as the refraction along the paths changed. Sometimes, the signals were stronger for timescales of order a few minutes. In these cases, we were often able to identify aircraft flying overhead that were likely to be adding more significant propagation paths as they became mutually visible to both EDGES and the FM transmitter. Even less frequently, there were short bursts of greatly increased signal on time scales of less than half a second. These events were separated by many tens of minutes. We speculate that they were due to micrometeors generating short lived ionized clouds from which the FM signals were being reflected.

Figure 4 shows spectra from six sites within the Catlow Valley distributed over a region ~30 km in diameter [6]. The best location in the valley was a "Canyon" site, which had steep walls surrounding a narrow gorge. The walls shielded the instrument from much of the sky below ~30 degrees elevation angle, providing a significant reduction in the reception of distant transmitters scattered from meteor or aircraft due to purely geometrical effects since the volume of atmosphere observed is greatly reduced when the horizon is occulted [7].

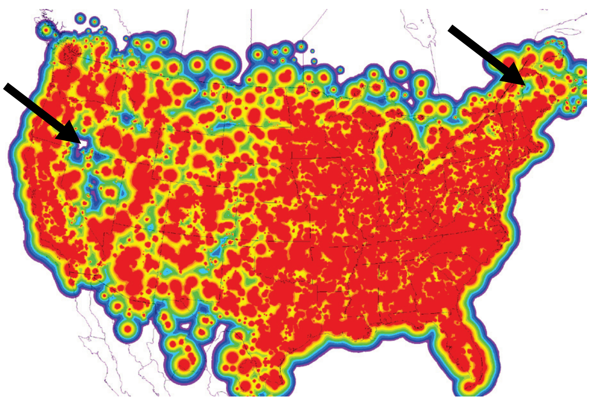

Figure 3: *Prediction of integrated VHF-band interferer power in the United States based on the FCC national database of TV and FM radio stations and a propagation model. West Forks, Maine, is marked by the black arrow on the right side of the map, and the Catlow Valley in southeast Oregon is marked by the arrow on the left side of the map. The color scale is linear. Red indicates areas of strong predicted total power, while blue and white areas indicate weak power.*

[2] http://www.radio-locator.com

4. Conclusion

Even remote sites will suffer some degree of RFI in the VHF band due to the nearly ubiquitous sources of interference. This is particularly evident in seemingly isolated regions of the United States, where even significant terrain shielding is not sufficient to block distant transmitters because the density of transmitters remains relatively high across the country and the constant bombardment of earth's atmosphere by meteors and busy air traffic lanes provide low-loss paths of reflection over the horizon. At the MRO, conditions are much better, and we have shown that the site is conducive to extremely sensitive radio astronomy observations with little or no RFI filtering over much of the VHF band sampled by EDGES. Nevertheless, rare conditions do propagate very distant signals to the site and meteor and aircraft reflections remain capable of reflecting even the relatively few regional transmissions to the site.

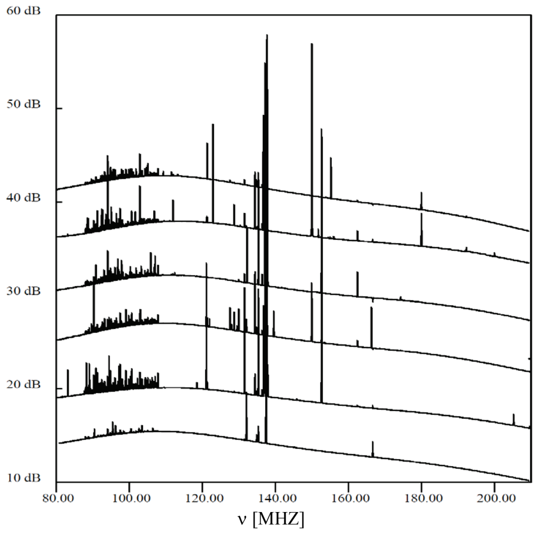

Figure 4: *RFI spectra from multiple sites in the Catlow Valley, Oregon. The spectra are offset by approximately 5 dB for comparison. The "Canyon" site is shown on the bottom and had significantly reduced RFI in the FM band due to geometrical effects from horizon blockage that limited the exposure of the antenna to distant transmitters reflected from aircraft and meteors.*

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