Using the 21-cm Hydrogen Line to Probe the History of the Intergalactic Medium

by

Tabitha Christine Voytek

Submitted in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy
at
Carnegie Mellon University
Department of Physics
Pittsburgh, Pennsylvania

Advised by Professor Jeffrey Peterson

November 4, 2014

Abstract

This thesis describes measurements of the 21-cm line as it is used to study the history and content of the universe by focusing on the evolution of the Inter-Galactic Medium.

Contents

List of Tables

List of Figures

Chapter 1

Radio Frequency Interference (RFI) and Site Testing

1.1 Overview

One of the challenges of radio astronomy is locating sites that meet the environmental requirements of a particular set of observations. Potential sites must be assessed for their viability prior to observation at those sites. I am going to focus here on a specific subset of requirements that are particularly significant for 21-cm observations.

First, does the site have any nearby man-made sources of regular radio frequency interference (RFI) in the frequency band of the observations. Evaluation of this requirement can be done using a simple broadband antenna and spectrum analyzer on site at multiple locations. Deployment of an identical system at multiple sites is key in doing comparisons between them.

Second, are there sources of intermittent or highly time-variable RFI visible from the site. This can be more difficult to evaluate as it requires a long period of data collection. In cases where time-variable RFI is expected to play a significant role in the data collection, semi-permanent systems may need to be installed to track the RFI environment over time.

Third, is the site logistically accessible for the type of equipment needed for a set of observations. Some important considerations include the availability of power, transport into/out of the location, housing and other observer requirements and site access permissions (such as permits). Assessment of these considerations often requires an in-person visit and careful documentation.

Fourth, are there atmospheric effects that must be considered in assessing the viability of a site (eg meteor scatter, thickness of ionosphere, inclement weather). Tracking data may be available from external sources such weather surveys, but it is often limited to broad trends instead of local details.

In the following sections, I am going to evaluate both existing telescope sites and new sites based upon the requirements listed above. I will set a baseline using

Pittsburgh, Pennsylvania; which as a major metropolitan area is not expected to be a suitable radio astronomy site. I will then look at several existing radio telescope sites and examine their strengths and weaknesses. Finally, I will report on several new radio sites, comparing them to the existing sites to demonstrate viability.

1.2 Existing Site Evaluations

Figure 1.1: Map of evaluated sites in North America.

One major element of site evaluations was a measurement of the RFI over a wide frequency band at each site. This was measured using a kit composed of a broadband antenna, amplifiers, and a portable spectrum analyzer for data collection.

By using the same kit at all the sites, the systematic noise contribution to the signal is the same in all datasets. The kit is also highly portable, packing up into a small suitcase and poster tube for easy transport.

Add in photos of system both in suitcases and assembled on the lawn. Can use Algonquin picture for assembled picture.

Add in section about calibrating the instrument using Kevin's notes.

1.2.1 Carnegie Mellon University Pittsburgh, PA, USA

Carnegie Mellon University is located in the city of Pittsburgh, home to several such universities and possessing a population of over 300,000. As should be expected, the radio environment in Pittsburgh is full of RFI with signals of such magnitude that they overload test equipment. Figure 1.2 shows the RFI environment in Pittsburgh as measured with the site testing kit. In order to not overload the spectrum analyzer with the high RFI levels at some frequencies, it was necessary to remove one stage of amplification from the system.

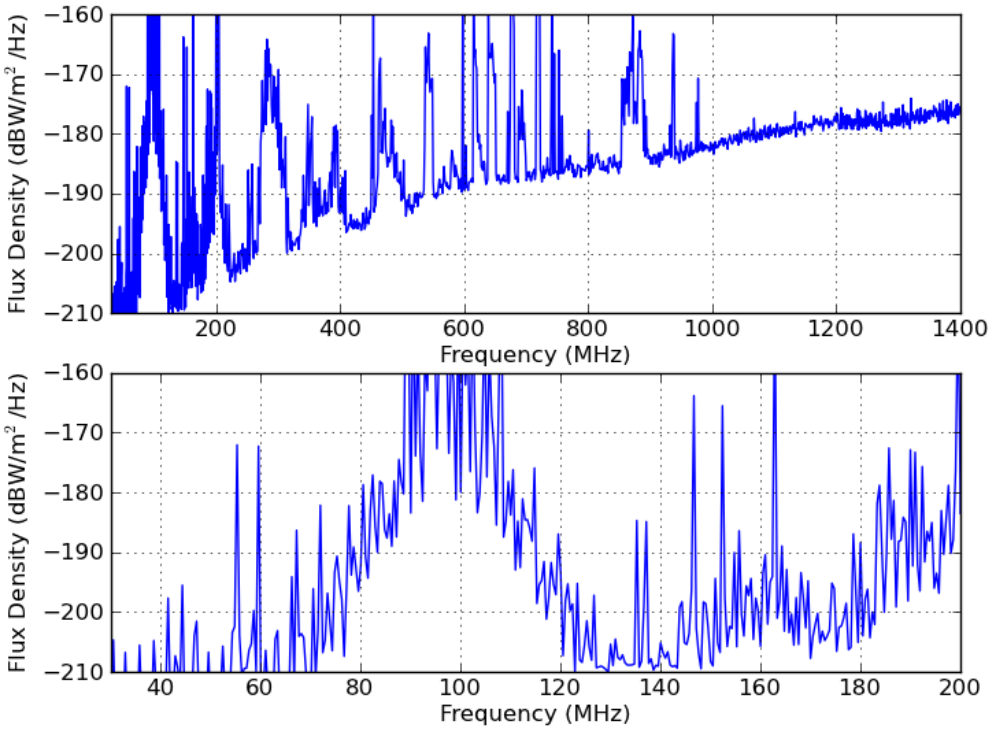

Figure 1.2: RFI measurement at Carnegie Mellon University in Pittsburgh, Pennsylvania

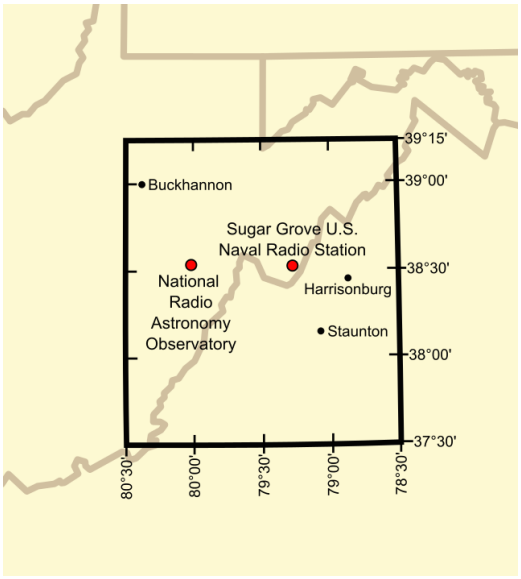

Figure 1.3: Extent of the US National Radio Quiet Zone around the Green Bank Site.

Add picture of Green Bank here. Still building a composite image.

1.2.2 National Radio Astronomy Observatory (NRAO) Green Bank, WV, USA

The National Radio Astronomy Observatory (NRAO) is a research center funded by the United States National Science Foundation (NSF). It maintains several telesopes in radio quiet locations. One of these locations is in Green Bank, West Virginia inside the United States National Radio Quiet Zone in Virginia and West Virginia (see Figure 1.3). Within this zone radio broadcasts at all frequencies are extremely limited, allowing for a relatively quiet RFI environment.

The size of the radio quiet zone (about 34,000 km^2) is sufficient for higher frequencies. However, as you go to lower frequencies the size of the zone needed for sufficient shielding becomes larger. As you can see in Figure 1.4, there are specific bands low freqencies This means that the site becomes less ideal for observations as you go to frequencies below 600 MHz (see Figure 1.4). The FM band is still significantly contaminated at this site.

1.2.3 Dominion Radio Astrophysical Observatory (DRAO)

The Dominion Radio Astrophysical Observatory (DRAO) is a Canadian radio astronomy site located near Penticton, British Columbia in the south-central part of the province. It has a number of radio telescopes on site and the Canadian Hydrogen Intensity Mapping Experiment (CHIME) system is currently being built there. Figure

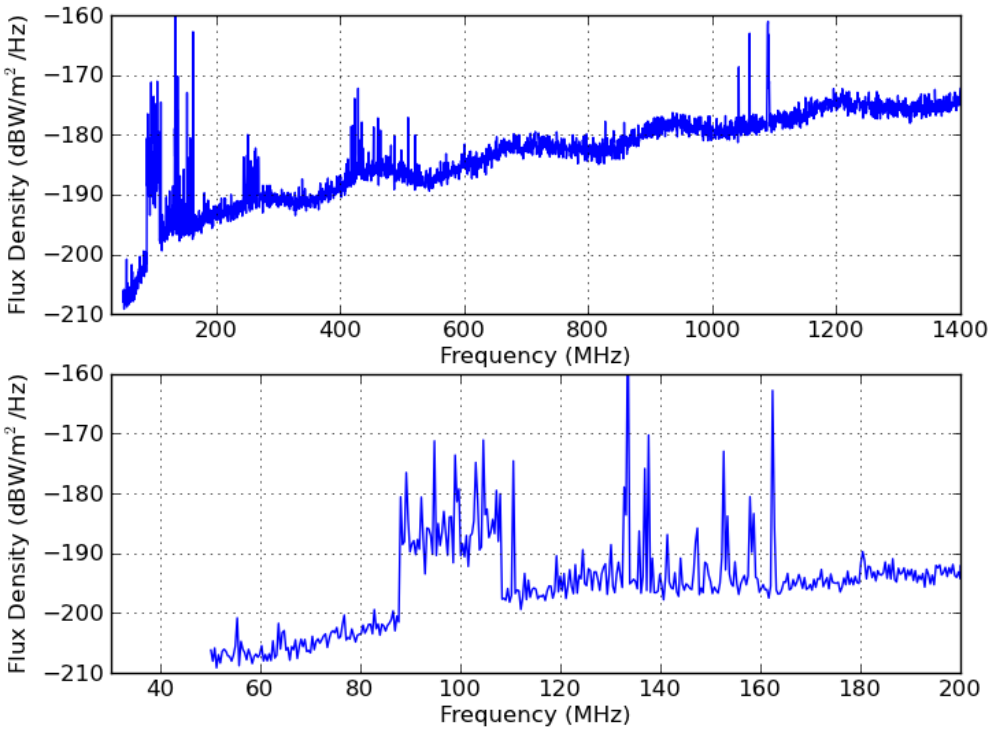

Figure 1.4: RFI measurement at the NRAO Green Bank site.

1.6 shows some of the facilities at DRAO including part of the CHIME pathfinder in the foreground.

Like the NRAO Green Bank site, the DRAO site has insufficient isolation from civilization to provide a radio quiet environment at the lower frequencies. There is significant RFI contamination for most frequencies below 500 MHz at this site (see Figure 1.5).

1.2.4 Algonquin Radio Observatory (ARO)

The Algonquin Radio Observatory (ARO) is a single instrument Canadian radio astronomy site located in the center of Algonquin Provincial Park in Ontario, Canada. Accessible only by logging roads, this is a fairly remote site with excellent radio quiet properties. However, Algonquin is still relatively close (about 200-250 km) to the major Canadian metropolitan areas of Toronto and Ottawa. When we set up our site test at ARO (see Figure 1.8, we found that although the rest of the spectrum is quite clean there is still significant RFI below 300 MHz (see Figure 1.8).

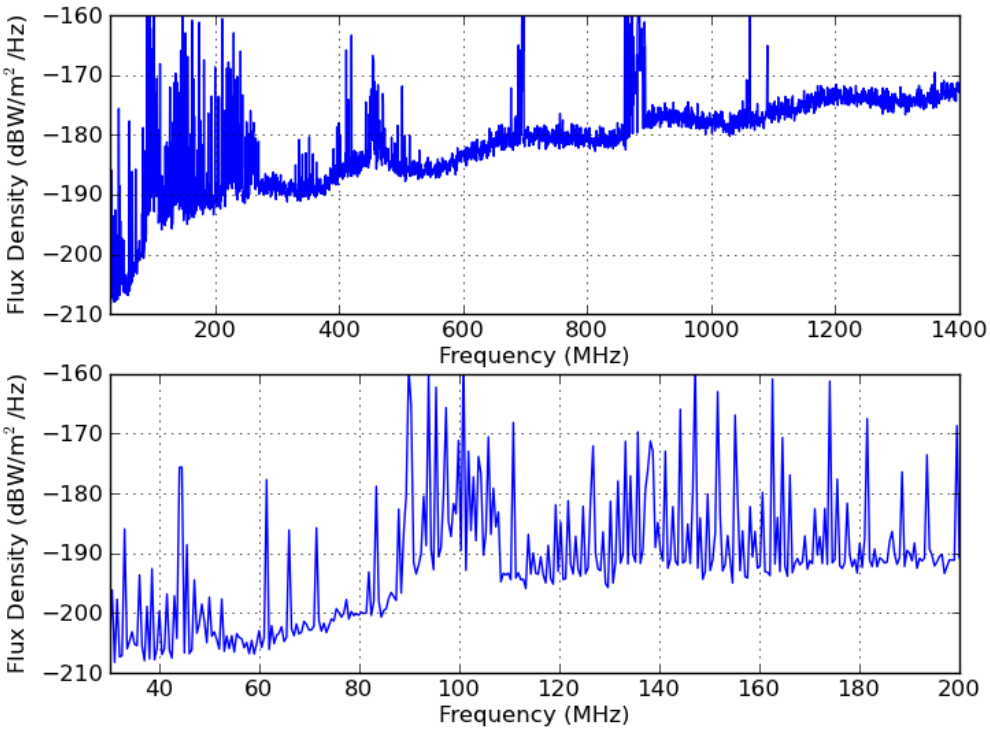

Figure 1.5: RFI measurement at the DRAO Penticton site.

1.3 New Site Evaluations

Evaluation of these existing radio quiet sites demonstrates a clear need for sites whose RFI environments are clean to lower frequencies. However, locating such sites can be difficult as the distances required begin to grow large. I will report on a couple of potential sites in Mexico that have significant improvement in their low frequency RFI strength compared to the existing sites.

1.3.1 La Zona de Silencio Mapimi, Mexico

″Zona del Silencio″ is a radio quiet region in the Mapimi part of the Chihuahuan desert in Northern Mexico. Its current radio quiet status is a feature of geography as it is surrounded by mountains and has no major metropolitan areas in the local region. It is also a protected biosphere reserve maintaned by Mexcio's ″Comisión Nacional de Áreas Naturales Protegidas″ (CONANP).

Figure 1.6: Some of the facilities at DRAO.

Figure 1.7: Collecting data with the site testing equipment at the ARO site.

Logistics and Current Infrastructure

While major highways can be found along the outside of the region, the only roads in and out of the site are poorly maintained dirt roads that require 4-wheel drive at a minimum.

Permanent settlements are not allowed within the biosphere reserve. However, at the center of the site is a camp for ecologists studying the reserve. This site has minimal housing with solar cells charging batteries for power but all water on site has to be brough in from outside.

For our site test, we got special permission to stay at the ecologist's camp called ″Laboratorio del Desierto″, shown in Figure 1.9.

Environmental Impacts

During the site testing, we were able to observe the general climate of the site as a consideration for future deployments. One of the challenges we observed was the prevalence of dust due to the arid climate. All our equipment had to be well protected from dust, especially during transport to and from the site. If not properly shielded, dust can cause electronic equipment to malfunction.

Another potential challenge is the temperature variation associated with the cli-

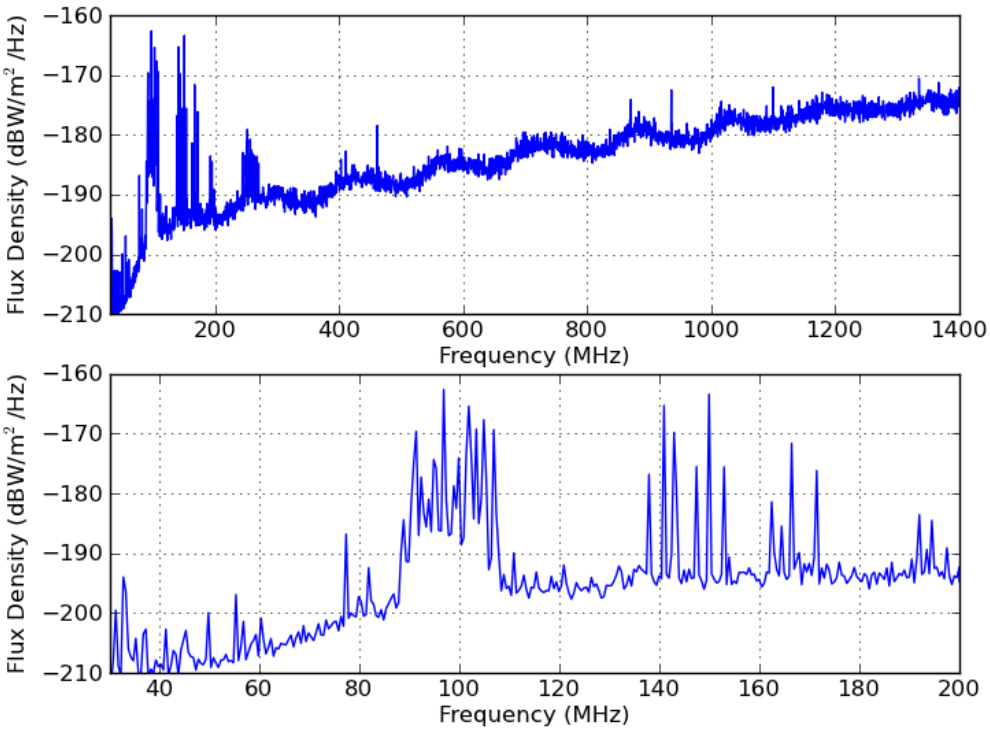

Figure 1.8: RFI measurement at the ARO Algonquin site.

mate. Even within a single day we saw a strong difference between night and and day temperatures. Temperature variation can create variance in collected data from a telescope, making the desired signals more difficult to detect.

Measurements

On this first site test, we chose to measure the site quality at a specific location around the center of the zone where RFI was expected to be at a miniumum. Setting up near the ecology camp but far enough away to prevent contamination by the local electronics, we measured extremely low RFI levels as is shown in Figure 1.10.

There is still some noise at lower frequencies, but the FM band is considerably quieter than at any of the existing radio quiet sites that we had tested.

1.3.2 Isla Guadalupe Baja California, Mexico

Isla Guadalupe is a small volcanic island located about 250 km west of Baja California in Mexico. The island is about 250 km^2, with two significant peaks along the

Figure 1.9: View of the Zona del Silencio from one of the nearby peaks. The ecologist's camp where we ran our testing is in the center of the picture.

north-south axis of the island. A biosphere reserve, access to Guadalupe is limited to a few groups; namely the Mexican government and Navy (″Secretaría de Gobernación″ and ″Secretaría de Marina″), ecologists studying the land and marine life such as the ″Grupo de Ecología y Conservación de Islas A.C.″ (GECI) and CONANP, and the local fishing cooperative (″Sociedad Cooperativa d Producción Pesquera de Participación Estatal Abuloneros y Langosteros, S.C.L.″). We were able to travel to Isla Guadalupe with support from these organizations.

Logistics and Current Infrastructure

Access to Isla Guadalupe can requires one of two transport methods. First, small planes such as the one shown in Figure 1.13 can fly from the city of Ensenada in Baja California to the island, where there is a small landing strip. This flight takes 1-2 hours and can only be made during good weather. On several of our visits to Isla Guadalupe, this was our method of transport.

A much cheaper alternative is transport with the supply ship that the Mexican Navy uses to support its base on Guadalupe. This supply ship, shown in Figures 1.15 and 1.16, deploys once a month from the port of Ensenada; stopping first at Isla Guadalupe, then Isla Cedros, then returning to Ensenada with a total travel time of about three days. Travel via this route is much longer and requires passengers

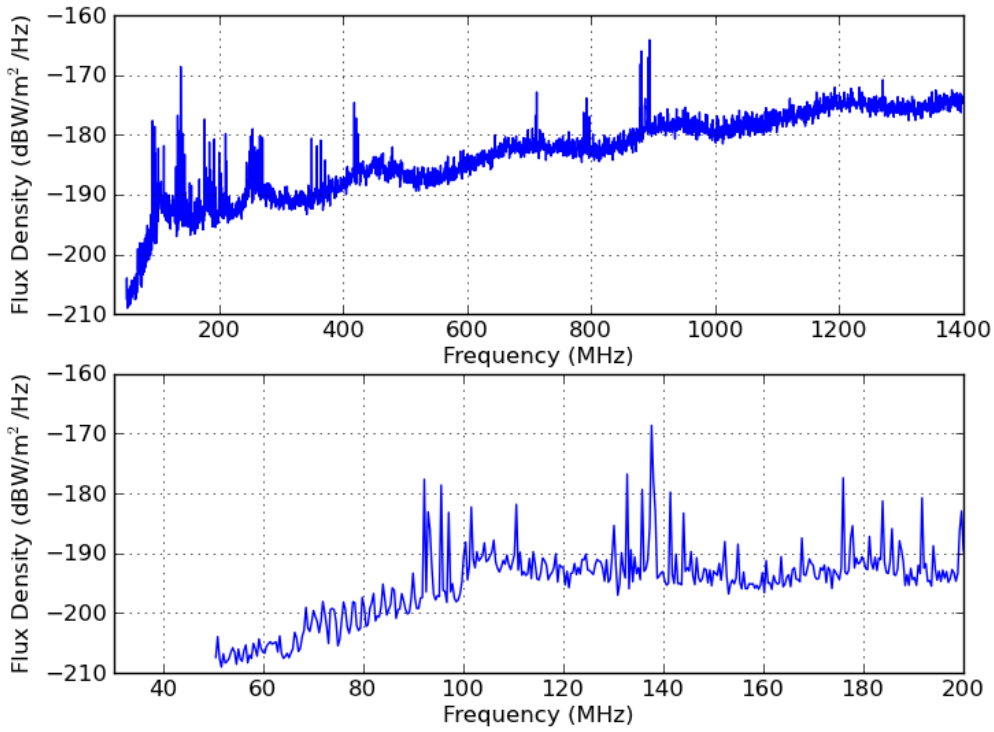

Figure 1.10: RFI measurement at the ecologist's camp in the Zona del Silencio.

to ″camp out″ by sleeping on the deck of the ship during transit. In addition, since passengers are hitching a ride with the ship they have no control over changes in ship deployment (eg delays or re-routing) that may change the departure or arrival schedule. This places strictures on any deployments to Isla Guadalupe that must be accounted for in planning the trip.

While on Guadalupe we could stay with the ecologists, the fishing village or the navy base. Each provided some level of logistical support, but were limited in a significant way.

The ecology camp is a small camp with about 5-15 researchers in residence at any given time. Housing, including running water, is available at the site for the researchers and their visitors but there is little to no plumbing, so the bathroom is a dry toilet. Since power is supplied by solar panels and batteries, it is pretty limited, especially at night. However, during the day there is regular internet access via satellite. Since it is a small camp, food is served communally, with everyone taking turns for cooking and cleaning responsibilities.

In contrast, the fishing village has a semi-permanent population of about 100 people and can be seen in Figure 1.14. In the village there are a number of houses,

Figure 1.11: Map of Isla Guadalupe with the relevant sites indicated.

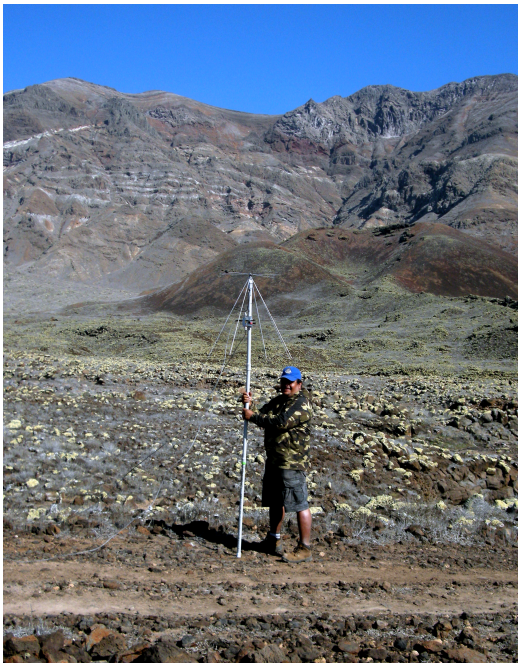

Figure 1.12: Collecting data with the site testing equipment on Isla Guadalupe.

Figure 1.13: Airplane used for access to Isla Guadalupe after landing on the island.

Figure 1.14: View of the plateau with the fishing village from the airplane.

one for each family currently on site on the island. Furnishings in the houses are haphazard since all of it had to be brought in on boats. There is a sewage plant for the village, but no running water (so flushing the toilet means dumping sea water into the bowl). Instead, water is supplied by a desalination plant and each family has barrels of clean and sea water at their homes. Power in the village is supplied

by a large generator that runs throughout the day except for a few hour siesta in the mid-afternoon and in the middle of the night. Food supplies are brought in via the supply boat and stored at a community store, where each family will ″purchase″. When we stayed in the fishing village we were given use of one of the houses that was currently unoccupied, while food was provided by paying one of the fishermen's wives to cook for us.

We chose not to explore staying at the navy base, as the site was not expected to be good for RFI mitigation. Ask Jeff if he knows what the logistical situation is like there.

Figure 1.15: Mexican naval vessel as it arrived at Isla Guadalupe to deliver supplies.

Figure 1.16: Onboard the Mexican naval vessel during trip back to the Port of Ensenada.

Environmental Impacts

Located in the Pacific Ocean in the midst of the California current, Isla Guadalupe is quite temperate for its latitude. The high elevation of its peaks (nearly 1300 meters) means that there are two distinct microclimates (one near sea level and one at high elevations). One reason for this contrast is that the island's peaks sit above the low cloud layer, making the higher altitudes warmer and generally clearer. Additional impacts include flash flooding in the lower areas of the island during the wet season and wind and dust interfering with system at any time.

Guadalupe's location puts it north of the main Pacific hurricane impact zone, but during the hurricane season the storms can pass over the island. In addition, the naval supply vessel often has its schedule changed during this season due rough seas from the storms. As an example, we had to change our deployment strategy from boat transit to plane in October 2012 due to Hurricane Paul, which did hit the island but only as a weak tropical depression. This means that the optimal time to visit Isla Guadalupe is during the off-season (November to June).

Measurements

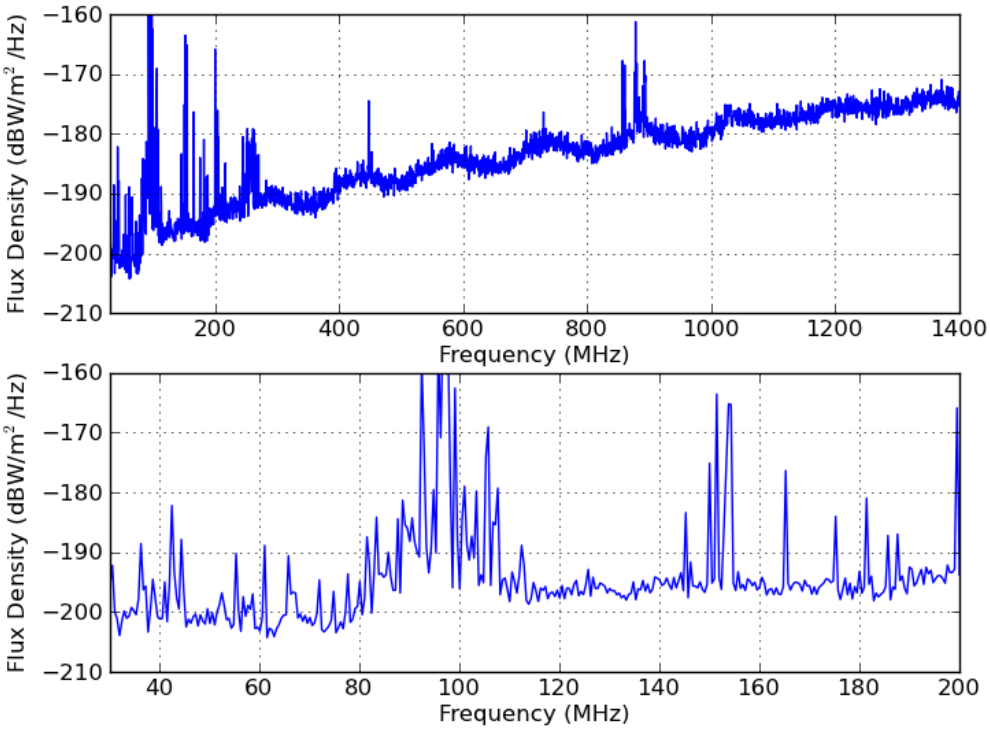

Figure 1.17: RFI measurement from the ecology camp at the summit of Isla Guadalupe.

Upon arrival on Guadalupe, several sites were studied for potential deployment. Site 1 was the ecology camp at the summit of the northern peak of the island, site 2 was the fishing village on the western side of the island and site 3 was the military base on the southern tip of the island. The exact positions of these sites are shown in Figure 1.11. RFI from the military base made it a less than optimal site for testing, so we focused on the other two sites.

Figure 1.17 shows the RFI signals from site 1 at the northern summit. Just as at existing radio quiet sites the spectrum is quite clean at high frequencies. However, as we move to low frequencies there is still some significant RFI, particularly in the FM radio band. Much of this noise is coming from the radio stations in San Diego and Ensenada, including some channels which can actually be heard with a hand-held radio. In this case, the elevation is actually a detriment as the height extends the line of sight for the RFI testing antenna.

In contrast, Figure 1.18 shows the RFI signals from site 2 near the fishing village.

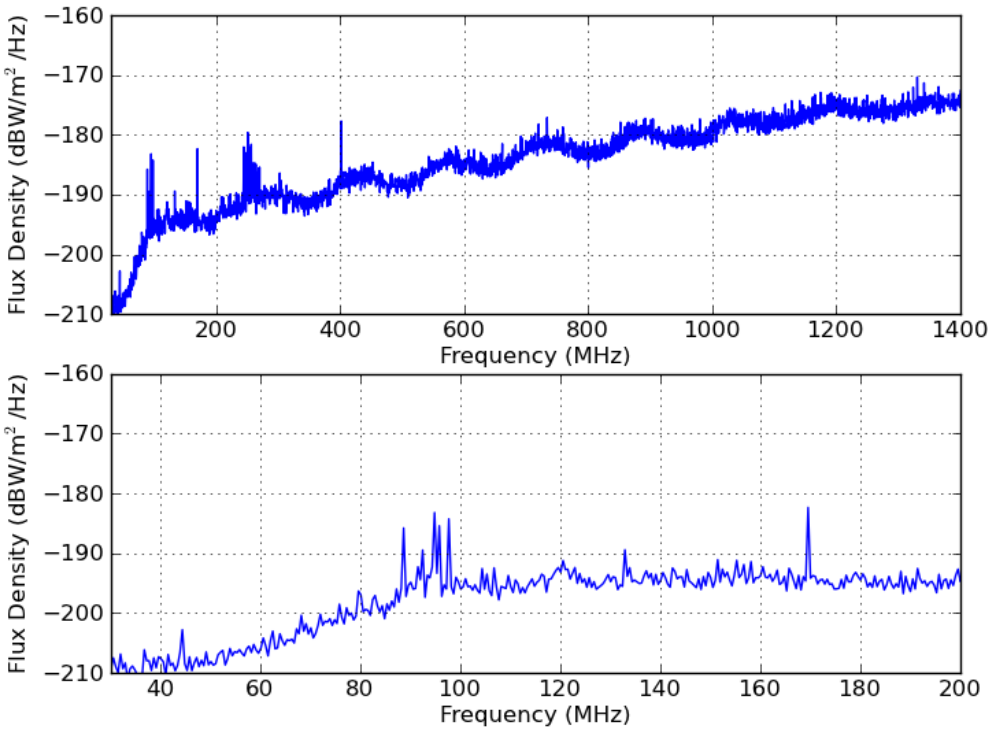

Figure 1.18: RFI measurement from the plateau near the fishing village at Isla Guadalupe.

Here the combination of low elevation, distance from the mainland and the the peaks of Guadalupe act as an excellent shield to minimize the RFI in the FM band to nearly undetectable levels. As seen from the plane in Figure 1.14, this plateau has significant elevations to the north, south, and east shielding it from mainland Mexico and Baja California quite effectively.

1.4 Future Sites

Usage of Isla Guadalupe with the SCI-HI experiment (Add pointer to one of the SCI-HI chapters) demonstrated that while the island is quite good it is still not good enough in the FM band ($88MHz \leq f \leq 108MHz$) as there is some residual RFI present at all frequencies in this band. Several potential sites have been identified for future testing.

1.4.1 Isla Socorro and Isla Clarion, Mexico

In Mexico there are two islands further west of the mainland that may provide the additional RFI isolation necessary for the SCI-HI experiment.

Add a couple of paragraphs on the islands including logistical challenges. Depending on timing of future SCI-HI expeditions may be able to add data.

1.4.2 Marion and Gough Islands, South Africa

May add a whole section to this chapter on the earth's ionosphere, in which case these islands discussion will need significant write up. Additional research needed prior to writing this section.