Characterization of Some L-Band Signals Visible at Arecibo

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1 Introduction

This report (updated from a previous version to include more data) provides an analysis of several L-band signals visible at Arecibo Observatory. The data sets were captured during the daylight hours of Sunday, April 8, 2001. Five signals were recorded:

- An air traffic control radar at 1350 MHz (Dataset 8).
- An Aerostat L-88A radar at 1261.2 MHz (Dataset 13).
- An AN/FPS-117 radar at 1232.75 MHz (Dataset 16).
- An unidentified pulsed signal at 1269.0 MHz (Dataset 19).
- An unidentified pulsed signal (not necessarily a radar) at 1106 MHz (Dataset 22).

Phil Perillat of NAIC as already done a formidable amount of study of these signals; [1] serves as a useful reference.

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Figure 1: Receiver used to capture data. From [2].

2 Instrumentation

Rick Fisher (NRAO) has provided a detailed description of the method used to make the measurements [2]; some of that information is repeated here for convenience.

The system used in these measurements is shown in Figure 1. The front end was Arecibo’s 1.1–1.8 GHz radio astronomy receiver; i.e., the “L-Wide” receiver used for HI and OH astronomical observations at the Gregorian focus of the Arecibo telescope. The Gregorian reflector/receiver system was parked at azimuth 450°, zenith distance 10°. The Arecibo planetary radar baseband system was used for data acquisition. A/D full scale was ±2.5 V (20 mV digitization level spacing), and the RMS noise level was usually set to about 70 mV. The sample period was 0.3 µs (~3.3 MSPS).

The format of the recorded data is as follows: Each dataset consists of a single file of about 100 MB representing about 15 s of contiguous observation. Datasets consist
of records, each 60,792 bytes in length, organized as a 792-byte header followed by 30,000 complex samples (8-bit “I” plus 8-bit “Q”) representing 9 ms of observation.

In addition to received signals, we also recorded two diagnostic datasets in order to characterize the baseband recording system. In both cases, we injected test signals directly into the 260 MHz IF input to the I-Q mixer. In one case, we injected white noise, and in the other, a test tone at \( \sim 260.8 \) MHz. Using the noise measurements, biases of about \(-0.2\%\) and \(-0.5\%\) of the full-scale output of the A/Ds were identified for the “I” and “Q” channels respectively. These biases were observed to vary slightly over time, even within a single record. The result is a narrow spectral line centered at DC. In the analysis to follow, the biases are measured on a record-by-record basis and removed. However, the intra-record variation makes it difficult to remove it completely and therefore there is always some spectral residue near DC.

Using both the noise and tone measurements, it was determined that the I-Q balance was \( \sim 0.36 \) dB and very stable. This has a negligible effect on the results presented here and so no attempt was made to correct it. For studies of RFI mitigation (as opposed to simply characterization), however, this imbalance may need to be taken into account. For example, the effect on the test tone is the generation of an undesired image \( \sim 29 \) dB weaker than the test tone and reflected around the frequency origin.

Also, it appears that “I” and “Q” have been swapped at some point; possibly in the author’s software for reading recorded samples. Thus, all frequency spectra are probably shown reversed from their correct orientations. This should have no consequence for the present effort.

3 Dataset 8: FAA Radar at 1350 MHz

Lots of clipping.

In this section we analyze dataset 8, which is the 1350 MHz emission of an FAA air traffic control radar. The geographic coordinates of the radar are 18° 16’ 14.3” N, 65° 45’ 31.2” W. It is believed to transmit at 1330 MHz as well. Figure 2 shows the total power measured per record (9 ms interval) relative to the total power measured when no signal is detected. A transmit of the main beam appears to occur at about
5.5 s. This radar is believed to have a rotation rate of $\sim 12$ s [1], which is difficult to confirm from this data set.

One of the stronger pulses recorded from the radar is shown in Figure 3. This, like many of the stronger pulses in this dataset, exhibit some clipping. Nevertheless, this figure is useful to show the length of the pulse; $\sim 7$ $\mu$s. Among those pulses that were not clipped is shown in Figure 4. It is interesting to note that the pulse waveform begins with a strong impulse and then varies somewhat before turning off. The spectrum of the pulse in Figure 4 is shown in Figure 5.

Another way to try shed light on the the nature of the waveform is to plot it’s “I-Q trajectory”, as shown as in Figure 6. In this plot, each sample is plot as a point whose coordinates are given by it’s “I” and “Q” values. Although the limited bandwidth of the measurement system makes it difficult to be sure, Figure 6 suggests that this is a simple CW (tone) modulation. The amplitude modulation remains unexplained; this may simply be a limitation of the radar transmitter.
Next, the timing of pulses was considered. To do this, a simple pulse detector was implemented as follows. Each sample is converted to a real value equal to $I^2 + Q^2$ and input to a detection filter. The impulse response of the detection filter is a triangular pulse (maximum at the middle, going to zero at the ends) of length 7 $\mu$s, which is the length of the pulse shown in Figure 3. It should be noted that this filter is inferior to the optimal filter, whose impulse response is the inverse Fourier transform of the pulse spectrum. Nevertheless, this detector is quite satisfactory for the present application and has the advantages of being very robust and waveform-independent. The latter may be an important consideration since we cannot be sure at this point that all pulses in the dataset have the same spectral or temporal characteristics as the two pulses shown above.

To detect pulses, the (nominally) signal-free output of the detection filter is first characterized by computing the mean and variance ($\sigma^2$) of the smallest 50% of the filter outputs over a 9 ms record. (Note that this assumes that the transmit duty cycle

Figure 3: 1350 MHz FAA Radar (8, record 577, $t \sim 5.2$ s), single pulse in time domain. Strong pulse exhibiting some clipping.
of the radar is much less than 50%, which appears to be true for all signals observed in this report.) Then, a pulse onset is declared when the filter output crosses above $12\sigma$, and the pulse length is determined using the time at which the filter output crosses back across the $12\sigma$ threshold. To account for the “smearing” of the pulse through the detector, an arbitrarily-determined correction of one-half the filter length (3.5 $\mu$s in this case) is subtracted from the time between threshold crossings. The result is shown in Figure 7. Note that most of the pulses appear to be in the 5 $\mu$s to 10 $\mu$s range, consistent with the 7 $\mu$s value obtained above. Note that the estimated pulse length has a tendency to be shorter or longer in response to the received power (compare to Figure 2). This is an unavoidable consequence of this method of pulse length detection when applied to pulses with relatively low signal-to-noise ratio. Thus, the apparent lengthening of pulses at the time of the main beam transit around 5.5 s should be disregarded.
Figure 5: 1350 MHz FAA Radar (8, record 576, $t \sim 5.2$ s), spectrum of the pulse shown in Figure 4.
Figure 6: 1350 MHz FAA Radar (8, record 576, \( t \sim 5.2 \) s), I-Q trajectory of pulse in Figure 4.
Figure 7: 1350 MHz FAA Radar (8) pulse length distribution. Each point represents the estimated length of a single pulse occurring at the indicated time.
Finally, the pulse inter-arrival times are shown in Figure 8, with a zoom along the vertical axis in Figure 9. It is clear that the pulses are being transmitted in a pattern with spacings selected from a set of five values between 2.6 ms and 3.3 ms. This has also been noted in [1]. The clusters of interarrival times under 0.2 ms may or may not be multipath components of other pulses; for example, some fraction of these may represent multiple detections of the same pulses. More work is required to sort these out.

4 Dataset 13: Aerostat Radar

In this section we analyze dataset 13, which is the 1261.2 MHz emission of an L-88A radar on an Aerostat balloon tethered at 17°58′45″ N, 67°04′55″ W. Figure 10 shows the total power measured per record (9 ms interval) relative to the total power measured when no signal is detected. This radar is believed to have a rotation rate
Figure 9: Same as Figure 8, zooming in on the vertical axis.

of 12 s [1], which is consistent with the data. Note the \( \sim 1.5 \) period shortly after the 10 s mark during which the radar appears to be off. This is consistent with the \( \sim 45^\circ \) range, centered on Arecibo, over which the radar is supposed to be off in accordance with a special agreement between the observatory and the radar operators [1]. This is clearly beneficial during the “off” period, but certainly does not prevent the radar from dominating the system noise elsewhere.

A single pulse from the radar is shown in Figure 11, and it’s spectrum is shown in Figure 12. The pulse has an unusual jagged waveform and spectrum which is difficult to explain. The I-Q trajectory is shown in Figure 13. Note that no characteristic modulation-induced pattern is apparent.

One final analysis method that can be applied is to generate a time-frequency representation (TFR) of the pulse. To do this, the record is partitioned into contiguous blocks of 64 samples each, and block is individually FFTed to obtain the power spectrum over a 19.2 \( \mu s \) period with about \( \sim 52 \text{ kHz} \) resolution. Concatenating the
Figure 10: Aerostat (13), time domain total power.

Figure 11: Aerostat (13, record 264, $t \sim 2.4$ s), single pulse in time domain.
Figure 12: Aerostat (13, record 264, $t \sim 2.4$ s), single pulse spectrum.

Figure 13: Aerostat (13, record 264, $t \sim 2.4$ s), I-Q trajectory.
results yields the TFR plot in Figure 14. Finally, we can see some evidence of modulation: The pulse appears to consist of a narrowband (perhaps sinusoidal) signal that is rapidly swept over a span of $\sim 1$ MHz, with a little bit of dwell at the ends. However, it remains unclear as to why there is a time-domain variation in the magnitude.

The pulse length and inter-arrival statistics were determined using the same method described in Section 3. In this case, the detection filter has length 61 $\mu$s, which is the length of the shortest pulse which the Areostat radar is known to emit [1]. The pulse length estimates are shown in Figure 15. Note that most of the pulses are estimated to be about 160 $\mu$s, which is the size of the Aerostat “long pulse” [1] and is consistent with Figure 11. Few if any 61 $\mu$s “short pulses” are detected. As in the previous section, note that the estimated pulse length has a tendency to be shorter or longer in response to the received power (compare to Figure 10).

Finally, the pulse inter-arrival times are shown in Figure 16. It is clear that the pulses are being transmitted in a pattern with spacings selected from a set of seven values between 2.8 ms and 3.8 ms. This has also been noted in [1].
Figure 15: Aerostat (13) pulse length distribution. Each point represents the estimated length of a single pulse occurring at the indicated time.
Figure 16: Aerostat (13) inter-arrival times. Each point represents the time between the estimated onset of the current pulse and the previous pulse, for the pulse occurring at the indicated time.
In this section we analyze dataset 16, which is the 1232.75 MHz emission of an FPS-117 radar located at Punta Salinas [1]. Figure 17 shows the total power measured per record (9 ms interval) relative to the total power measured when no signal is detected. This radar is believed to have a rotation rate of 12 s [1], which is consistent with the data. Note that the radar appears to be turned off at three times over the length of this dataset. It is possible that the off periods are synchronous with the rotation, as is the case for the Aerostat radar.

This radar emits pulses of two different lengths. The long pulse is shown in Figure 18, its spectrum is shown in Figure 19, the I-Q trajectory is shown in Figure 20, and TFR is shown in Figure 21. It is obvious that the long pulse is a swept-frequency modulation (sometimes known as “chirp” or “linear frequency modulation”) with a span of about 600 kHz.
Figure 18: FPS-117 long pulse (16, record 1472, \( t \sim 13.3 \) s).

Figure 19: FPS-117 long pulse (16, record 1472, \( t \sim 13.3 \) s), spectrum.
Figure 20: FPS-117 long pulse (16, record 1472, $t \sim 13.3$ s), I-Q trajectory.

Figure 21: FPS-117 long pulse (16, Record 1472 ($t \sim 13.3$ s), time-frequency representation.
Figure 22: FPS-117 short pulse (at 4.5 ms); Note weaker long pulse at about 0.7 ms for comparison. (16, Record 144 (t ∼ 1.3 s))

An example of the FPS-117 short pulse is shown in Figure 22, it’s spectrum is shown in Figure 23, the I-Q trajectory is shown in Figure 24, and TFR is shown in Figure 25. It appears that the modulation of the short pulse is very similar to that of the long pulse.

Pulses were detected and measured using the technique discussed in the previous section, except the length of the detection filter was set to 51.2 µs, equal to the length of the short pulse. The measured pulse length distribution is shown in Figure 26. It is clear that the data consists primarily (perhaps entirely) of the short and long pulses identified above.

Next, all detected pulses were classified as either short or long pulses, and their inter-arrival times were computed separately. Figures 27 and 28 show the results for short and long pulses, respectively. In each case it is evident that there is some pattern in the pulse spacings. The short pulse exhibits many repeatable spacings.
Figure 23: FPS-117 short pulse (16, Record 144 ($t \sim 1.3$ s)), spectrum.

Figure 24: FPS-117 short pulse (16, Record 144 ($t \sim 1.3$ s)), I-Q trajectory.
Figure 25: FPS-117 short pulse (16, Record 144 \((t \sim 1.3 \text{ s})\)), time-frequency representation.

Figure 26: FPS-117 (16) pulse length distribution.
Figure 27: FPS-117 (16), inter-arrival times for short pulses.

ranging from 1 ms to 27 ms. The long pulse exhibits at least 4 repeatable spacings between 4 ms and 75 ms.
Figure 28: FPS-117 (16), inter-arrival times for long pulses.
6 Dataset 19: Unknown Transmitter

In this section we analyze dataset 19, which is the 1269.0 MHz emission of an unidentified transmitter. Figure 29 shows the total power measured per record (9 ms interval) relative to the total power measured when no signal is detected. Note the peak around 3 s, which may be the transit of a rotating narrow-beam antenna, as observed in the previous sections.

This emission consists of pulses as shown in Figure 30. The pulse spectrum is shown in Figure 31, and the I-Q trajectory is shown in Figure 32. Because the pulses are so short with respect to the sample rate, it is difficult to discern any modulation in these pulses.

Pulses were detected and measured using the technique discussed in the Section 3, except the length of the detection filter was set to 7 $\mu$s, roughly equal to the length of one of the pulse shown in Figure 30. The measured pulse length distribution is
Figure 30: Unknown transmitter (19, Record 330), time domain.

Figure 31: Unidentified transmitter (19, Record 330), Spectrum.
Figure 32: Unidentified transmitter (19, Record 330), I-Q trajectory.

shown in Figure 33. Note that all the pulses seem to have about the same length as the one studied above.

Figure 34 shows the pulse inter-arrival times. Here we note that many of the pulses are spaced about 3 ms apart, although four other spacings between 5.5 ms and 14 ms are apparent.
Figure 33: Unidentified transmitter (19), pulse length distribution.

Figure 34: Unidentified transmitter (19), inter-arrival times.
In this section we analyze dataset 22, which is the 1106.0 MHz emission of an unidentified transmitter. Figure 35 shows the total power measured per record (9 ms interval) relative to the total power measured when no signal is detected. Here, it is interesting to note that the signal appears in nearly every record without much variation in strength. This argues against a rotating narrow-beam antenna, as most radars use.

This emission consists of pulses that come in pairs, as shown in Figure 36. For this pulse-pair, the spectrum is shown in Figure 37, the I-Q trajectory is shown in Figure 38, and TFR is shown in Figure 39. Because the pulses are so short with respect to the sample rate, it is difficult to discern any modulation in these pulses.

Pulses were detected and measured using the technique discussed in the previous section, except the length of the detection filter was set to 7 \( \mu \text{s} \), roughly equal to the length of one of the pulses in a pulse pair. The measured pulse length distribution
Figure 36: Unidentified transmitter (22, Record 16), time domain.

Figure 37: Unidentified transmitter (22, Record 16), Spectrum.
Figure 38: Unidentified transmitter (22, Record 16), I-Q trajectory. Solid: First pulse. Dashed: Second pulse.
Figure 39: Unidentified transmitter (22, Record 16), Time-frequency representation. Note that length-16 FFTs were used in this case to help resolve the short pulse.

is shown in Figure 40. Note that all the pulses seem to have the same length as the one studied above; the second dispersed cluster of estimates around 25 $\mu$s seconds are simply cases where the pulse pair was mis-estimated as a single pulse.

Figures 41 and 42 show the pulse inter-arrival times. The only consistently repeating spacing appears to be that of the the pulse pair itself, visible as the 12 $\mu$s line in Figure 42.

8 Summary

The table in Figure 43 summarizes the features of the signals analyzed in the previous sections.
Figure 40: Unidentified transmitter (22), pulse length distribution.

Figure 41: Unidentified transmitter (22), inter-arrival times.
Figure 42: Same as Figure 41, zooming in along the vertical axis.

Figure 43: Summary.

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<td>161 µs</td>
<td>2.8-3.8 ms (7)</td>
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<td>Linear Chirp</td>
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<td>∼7 µs</td>
<td>3-14 ms (5)</td>
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<td>Probably CW</td>
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<td>(∼7 µs/pair)</td>
<td>none repeatible</td>
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Acknowledgments

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References
