SDR Cloud Radar development with reused Radio Telescope Components

Felipe Toledo, Rafael Rodríguez, Roberto Rondanelli, Roberto Aguirre, Marcos Díaz

Abstract— **The ongoing implementation of a fog observatory in a coastal fog forest in northern Chile is expected to provide valuable information to improve our comprehension of these ecosystems alongside retrieving valuable data to fog scientists. Observing this opportunity and the increase on radio astronomy instrumental it is proposed to develop a low-cost Cloud Radar reutilizing obsolete but operative radio telescope components and software defined radios for modulation. Only preliminary tests have been conducted so far to test the viability of this approach. These tests show that it is in fact possible to build an emitter and receiver operating at 35 GHz using radio telescope components as a Radio Frequency front-end, and that the detected echo coming from the signal is affected by the presence of liquid water droplets in the air. Further development is being carried on the prototype to enable the detection of fog droplets in the boundary layer up to 2 km of height.**

Index Terms—— **Cloud Radar, Millimeter wave radar, Recycling, Software Defined Radios**

I. Introduction

COASTAL fog forests are a common occurrence along the eastern border of the northern Chilean coast. The main places of occurrence are usually coastal slopes facing the ocean down to 32°S. Associated to these locations there is the sprout of vegetation ranging from small plants to full forests. It is believed that water to sustain these forests comes from the liquid water transported by the fog when it intercepts the existing vegetation [1] and that it also reduces the drought stress during dry months by reducing the amount of direct solar radiation that reaches the surface [2]. An important example of this type of ecosystem is the relic forest of Fray Jorge, in northern Chile.

The fact that these fog events intercept the topography motivates the establishment of an in-situ regional fog monitoring laboratory to obtain continuous measurements of cloud properties. The products obtained would provide a valuable input for fog physics researchers. Specialized meteorological observatories take advantage of continuous measurements to improve the comprehension of the physical interactions that drive the fog life cycle, improving the quality of fog forecast models [3]. These models have a wide range of applications in aeronautics[4] and climate[5], and can also be extended to solar energy studies due to the effect of clouds in the radiation budget[6].

An instrument of interest for these observatories is the Cloud Radar. These instruments can make remote profiles of cloud properties, such as its reflectivity, scatterers Doppler speed, among others. They have proven useful in the characterization of cloud and rain, and it is expected that more applications of this technology in geophysical research should appear in the future [7, 8]. However, Cloud Radars remain an exceptionally costly instrument, thus we propose a less expensive alternative to retrieve these measurements, exploiting millimeter wave astronomy components.

Over a hundred radio telescopes are currently operating in the Chilean Atacama Desert soil, due to the exceptionally favorable climatic conditions for millimetric and sub millimetric wave observations [9]. These instruments usually have a use span that is limited by either scientific constrains, such as a fixed extension of time for their associated projects, or due to replacements with upgraded instrumental. Most of the obsolete components usually remain operative, and due to their quality, we think they are suitable for use in fields that do not have the same delicate precision constrains found in state-of-the-art radio astronomy but could benefit from the same technologies.

The presented situation and the absence of Cloud Radars in Chile motivated the development of this instrument at the Millimetric Wave laboratory of the University of Chile, in collaboration with the Space and Planetary Exploration Laboratory and the Department of Geophysics of the same university and the Institut Pierre-Simon Laplace in France.

In this work, we publish a summary of the operating principles that we want to achieve with our instrument and the preliminary results of the technological tests carried on with a proof of concept radar prototype. The objective was to verify that the reutilized radio telescope components are suitable for

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F. Toledo is with the Electrical Engineering Department of the University of Chile, Santiago, Chile (e-mail: felipe.toledo@ing.uchile.cl).

R. Rodríguez is with the Millimetric-Wave Laboratory of the University of Chile, Santiago, Chile (e-mail: rrodrigu@ing.uchile.cl).

R. Rondanelli is with the Geophysics Department of the University of Chile and the Center for Climate and Resilience Research, Santiago, Chile (e-mail: ronda@dgf.uchile.cl).

R. Aguirre is with the Electrical Engineering Department of the University of Chile, Santiago, Chile (e-mail: roberto.aguirre@ing.uchile.cl).

M. Díaz is with the Space and Planetary Exploration Laboratory and the Department of Electrical Engineering of the University of Chile, Santiago, Chile (e-mail: mdiazq@ing.uchile.cl).

implementations in this field, and discover the underlying limitations that could appear following this approach to size correctly the investment needed to obtain a fully operative Cloud Radar.

II. Description of the Instrument

The cloud radar is a remote sensing instrument that enables the retrieval of physical parameters related with the droplet properties of fog and clouds. Due to its relatively low attenuation when compared with optical devices such as ceilometers, it enables the spatial profiling of properties in its line of sight, providing internal information and even the top boundary altitude of the cloud.

In the following sections, we explain the principles that we want to implement in our prototype, after the technological tests and component characterization is finished.

A. Measurement principle

A radar main components are the transmitter, the antennas and the receiver. The transmitter generates a signal that is directed by the outgoing antenna. If the transmitted signal interacts with an object or "target" part of the power will be reflected to the receiver. The reflected power is a function of the properties of the target, the atmospheric path and its range.

The power budget analysis required for deriving the weather radar equation (1) is explained in Butterworth Heinemann [10].

$$10\log P_r = 10\log Z - 20\log r - 10\log L(r,\lambda) + C \qquad (1)$$

In this equation P_r is the instantaneous received power, $10\log Z$ is the target reflectivity in dBZ, r is the target distance, $L(r,\lambda)$ is the attenuation caused by the atmospheric gasses and C the radar constant. $L(r,\lambda)$ mostly depends on both the range and the wavelength [11] and C is related with both radar design properties, such as the antenna gains and beam width, and the target refraction properties for the used wavelength. In this case, we only consider liquid water droplets. Equation (1) is considered valid for droplet sizes under $0.1\,\lambda$. Typically, the fog droplets have a size under 20 μm and the prototype wavelength is close to 9 mm, so we consider this a good approximation for our study.

1) Frequency Modulated Continuous Wave (FMCW) Distance Estimation

As expressed in equation (1), it is necessary to know the distance from which the reflected power is coming to accurately measure the reflectivity. The speed of an electromagnetic wave propagating through the air can be approximated by its vacuum velocity, so the delay between an emitted and received signal is related to the range following relationship (3).

$$r = c \cdot \frac{t}{2} \qquad (3)$$

Most meteorological radars emit strong and short pulses and measure the delay of the reflected signal. That way they can determine the range directly using (3).

The later approach usually requires very expensive and specialized electronics. Since we desire to assemble the radar using available components we decide to implement it using the Frequency-Modulated Continuous Wave (FMCW) principle. It consists in the emission of a continuous signal modulated in frequency. The modulation induces a periodic linear variation, called chirp, that enables the target distance estimation comparing the emitted and received frequency at a given instant. Further details are explained in Figure 1.

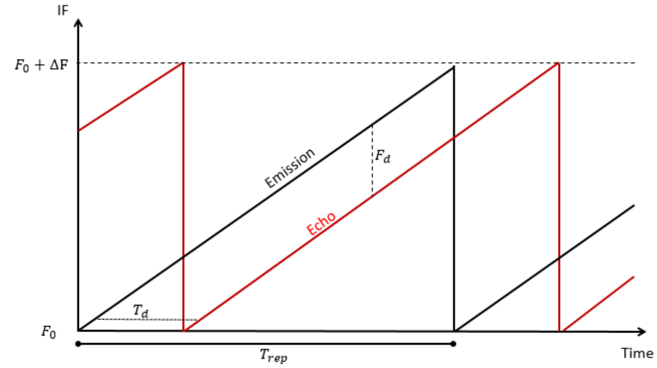

Figure 1: Diagram illustrating the main variables involved in the FMCW principle. F_0 is the chirp starting frequency, ΔF is its bandwidth, T_{rep} is the repetition frequency and T_d, F_d are the time delay and frequency delay between the two signals.

Using (3) and the geometric relationship shown in Figure 1, the range is now provided by:

$$r = \frac{F_d T_{rep} c}{2\Delta F} \qquad (4)$$

Where F_d is obtained using the emitter and receptor measurements. Here ΔF and T_{rep} are design parameters. ΔF is set to get a certain range resolution and T_{rep} is set depending on the maximum range measurable by the radar. The range resolution is estimated using equation (5). This provides an estimation of the minimum distance discernible between targets, and usually determines the radar gate size.

$$res = \frac{c}{2\Delta F} \qquad (5)$$

B. The Proof of concept Prototype

The RF components of the radar prototype consist mainly of former parts of the CBI telescope which worked between 26-36 GHz and had 13 receivers [12]. The Millimeter Wave Laboratory has only some components of two receivers. The suitable components for the prototype are WR22 waveguides, feedhorns, filters, isolators and oscillators. A scheme of the prototype is presented in Figure 2.

The Local Oscillator (LO), which is a GUNN oscillator of 38 GHz biased at 5 V, feeds the two mixers simultaneously. For flexibility, transitions of the WR-28 waveguide to 2.92 mm coaxial are used in the connections of the LO to the power splitter and mixers. Since in the implementation the LO is not being driven by a PLL, it has a width of nearly 1 MHz.

For the Front-end (FE) of the receiver we included a Low Noise Amplifier (LNA) designed to operate in the frequencies of 33-50 GHz. The following low pass filter the USB part of the signal to avoid superposition of the image band.

Modulation and demodulation of the wave is made using open hardware HackRF One Software Defined Radios (SDR). These enable the modulation of signals in the band comprehended between 1 MHz and 6 GHz using a computer processor rather than an analogic circuit.

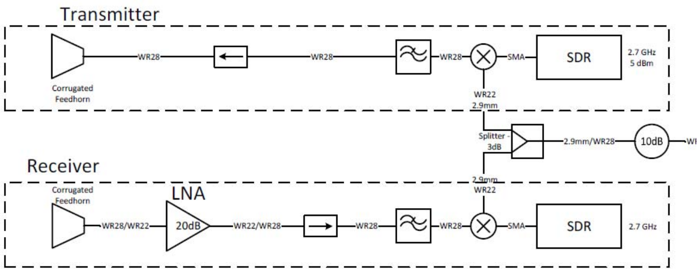

Figure 2: Prototype RF circuit schematic.

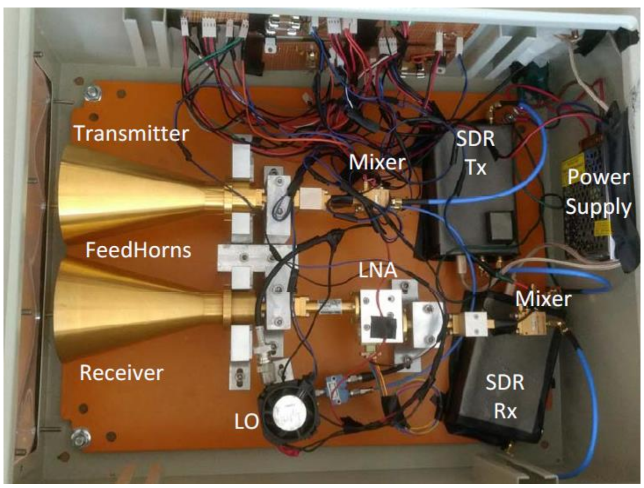

Figure 3: Radar prototype. Includes labels for the RF schematic components.

SDR emitted and received signals are fixed in the band of 2.7 GHz, being this signal is upconverted up to 35 GHz and the reflection down converted to SDR operating range using the described frontend. Figure 3, shows the prototype with the most important parts labelled. The SDR are cover by a layer of an absorber to diminish any cross talk between the SDR.

The main constraint of using these SDRs in the radar prototype is the expected range resolution. The maximum available bandwidth of the chosen SDRs is of approximately 9 MHz, providing a theoretical maximum range resolution of 17 meters.

III. Experiments

The first stage objective is to test the viability of using radio telescope components in the cloud radar prototype. To do this, two tests are deployed. The first one consists on the verification of remote emission and reception capability using a metallic high reflectivity target. After this test, it is studied if the prototype signal reacts to the presence of suspended water droplets.

A. *Target Measurement*

The first experiment to validate the correct emission and power receiving from the instrument was to measure a well-known target with high reflectivity. This test was done at the SIRTA atmospheric observatory [13], which provided the trihedral target in addition to continuous monitoring of the atmospheric conditions.

Figure 4: Picture illustrating the target measurement experiment. The prototype (on the right) emits a sinusoidal wave to the trihedral corner reflector (on the left) and registers the resulting echo power.

For the test a trihedral target with side length of 20 cm is located at 7.84 m of distance from the prototype. At that distance, it has an effective reflectivity of 103.8 dBZ. The prototype is aimed to obtain maximum reflected power from the target and then it is slowly misaligned to check if the power reflected is coherent with this behavior. After some time, the radar is returned to the position of maximum retrieved power to verify consistency with the first step. The results are shown in Figure 5.

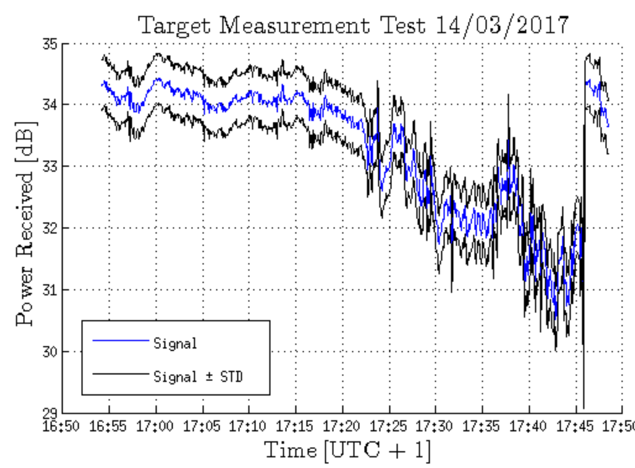

Figure 5: The prototype is aligned until 17:15. After this time it is slowly misaligned until 17:46, when it is aligned again to recover the original signal. It is possible to see the passing through a secondary antenna lobe around 17:38.

This test also enabled the acquisition of a first calibration constant. Using a sample of six hours of aligned target measurements we obtained $C = -111 \pm 1$ dBZ. To calculate it we used equation (1) with a known target Z and ignoring the L attenuation term due to the short distance and absence of LWC in the ray path. Another result is that the target was not detected at distances further than approximately 10 m. Because of this, and considering the expected distance resolution due to the SDR´s bandwidth, it is determined to postpone the chirp implementation due to the impossibility of discriminating between targets reachable by the instrument.

B. Fog formation inside a closed box

After successfully verifying the reception of remote reflections an experiment to measure sensitivity of the instrument to suspended liquid water droplets is prepared. Our approach was to create a controlled closed environment to generate suspended liquid water droplets using evaporated water coming from a boiler. The chamber was continuously monitored with an in-situ droplet spectrometer (Fog Monitor) available in the department of Geophysics of the University of Chile.

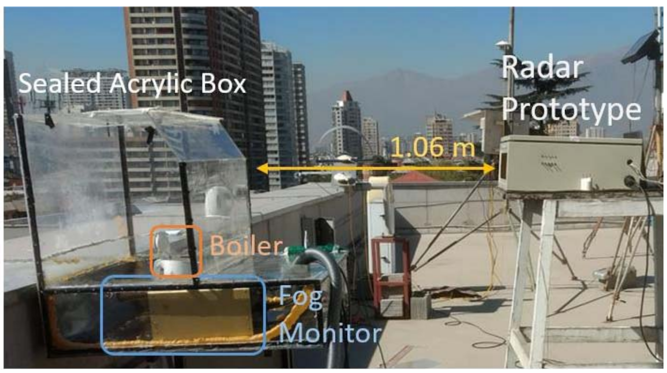

Figure 6: Experimental setting for the enclosed box fog experiment.

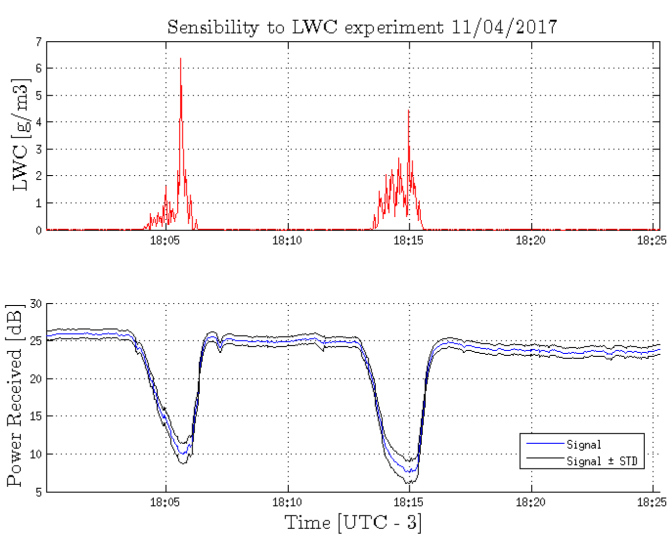

Figure 7: Time series for the LWC inside the box and the associated detected reflected power.

When air saturation is achieved the Fog Monitor starts to measure the liquid water droplet size distribution on the air inside the chamber. The time series for the liquid water content (LWC) inside the box and the simultaneous radar reflected power are shown in Figure 7. Plotting the retrieved reflectivity versus the LWC it is possible to see that the prototype at its current state can detect the presence of water droplets in the medium.

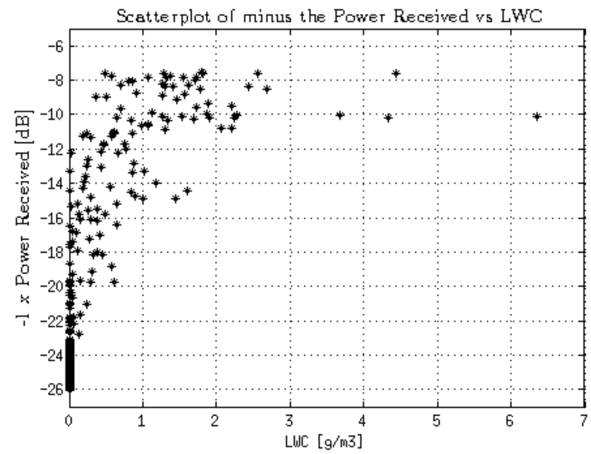

Figure 8: Scatterplot of the negative of the radar retrieved power versus LWC. Since this is a continuous wave radar, it continuously detects the power reflected from the first and second walls of the box. This curve indicates that part of the received power is absorbed in a way correlated with the amount of suspended liquid water inside the box.

IV. CONCLUSIONS

The development carried out so far proves that it is in fact possible to reutilize obsolete radio telescope components in other applications, including suspended liquid water detection.

Figure 8 indicates a relationship that indicates the detection of absorption correlated with the detected LWC. We hypothesise that the received wave power loss is related with the water absorption of power reflected from the further box wall. Nevertheless, the detected behavior is not yet fully explained due to the difficulties assessing all the power budget variability introduced by the surrounding environment, the box and the water condensation in its walls. This introduces the necessity of quickly implement the distance detection to enable long time series of reflected power measurements alongside in-situ instrumentation in a less cluttered setting.

Regarding the other RF components, most of them are well suited for this application. It may be necessary to include a PLL to reduce the LO frequency width which may decrease the distance resolution due to its comparable size to the chirp, but this can also be solved using radios with a higher bandwidth so there are still possibilities that must be evaluated. To complete the radar functionality, it is also necessary to acquire extra components not commonly used in radio astronomy, such as power amplifiers, to increase the emitted wave reach.

A problem we faced when assembling the current prototype is the lack of information about many minor components. Fortunately, The Millimeter Wave Laboratory is equipped with Ka band characterization equipment. It is highly recommendable to have access to this instrumentation if reutilization of microwave components is intended.

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