CLAIRE: an UHF Wind Profiler Radar for turbulence and precipitation studies

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Abstract—**Due to diverse and extreme weather conditions, the Peruvian population is vulnerable to high-impact natural disasters. A continuous monitoring of all weather conditions is necessary for accurate weather models, forecast, and nowcast along the territory. To cope with this problem, the Jicamarca Radio Observatory (JRO) is developing a low-cost, portable CLear AIr and Rainfall Estimations (CLAIRE) Radar that will provide tropospheric winds, turbulence, and rainfall estimations that will help analyze and quantify meteorological phenomena.**

CLAIRE consists of four Yagi-Uda antenna phased arrays, one for transmission and three for reception, arranged in a quasi-monostatic system. The 445-MHz CLAIRE system is sensitive to both clear-air and precipitation echoes. The aim is to separate the two types of echoes through spectral analysis and process them independently. For the wind and turbulence measurements, Spaced Antenna technique will be applied, while precipitation measurements will be obtained by analyzing the corresponding radar reflectivity factor (Z_e).

I. INTRODUCTION

Floods caused by intense rain in the Peruvian territory have reduced the life quality of thousands of people and burdened the sustainable development of the country [1]. For example, in 1982-83 and 1997-98, El Niño Southern Oscillation (ENSO) caused extreme climate events, such as intense rains and floods in the northern Peru. The damages were estimated to be 11.6% and 6.2% for both events of the national Gross Domestic Product (GDP) respectively [2].

Wind information is crucial at airports for very short range forecasting or nowcasting of weather conditions. Indeed, proper monitoring of the vertical structure of the atmospheric boundary layer can prevent accidents by providing important information, such as early warnings of wind shears or keeping track of the evolution of the inversion layer in the vicinity of the airport [3].

The proper monitoring of meteorological conditions along the Peruvian territory is not only a matter of scientific concern, but a political, economic, and social concern as well. A proper database of atmospheric phenomena would considerably improve the accuracy of current climate models, which will help prevent or reduce the impact of natural disasters.

One of the most important instruments for remote sensing the atmosphere is the RADAR (RAdio Detection And Raging) [4]. Doppler radars can detect tracers of wind and measure their radial velocities, both in clear-air and within regions of precipitation. This type of radars have been successfully applied to map wind and rain within storms in real time, which is valuable information for weather forecasters and researchers that seek to understand the life cycle and dynamics of storms [4].

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The Jicamarca Radio Observatory (JRO), funded by INNÓVATE Perú, has started the construction of the CLear AIr and Rainfall Estimations (CLAIRE) system, a portable, low-cost radar that will provide real-time estimation of winds, turbulence, and precipitations with high spatial and temporal resolution. The project aims to build an easy-to-replicate system that might be the beginning of the Peruvian radar network. This network would provide key information for monitoring and future prediction of climate conditions to national government agencies.

CLAIRE is currently under construction and is planned to be installed in the Huancayo Observatory (Junin, Peru), scientific facility of Instituto Geofísico del Perú by the end of 2016 for test and operation. The remaining sections of this paper are organized as follows. Section II is a brief introduction to atmospheric radars. Then, Section III makes a general description of the radar system. Next, Section IV describes the antenna arrays design. Section V presents the design and considerations of the electronic system. Finally, a summary of the paper and the acknowledgements are presented.

II. RADARS FOR ATMOSPHERIC STUDIES

Radar signals are the contribution from scatters like hydrometeors (rain, snow or hail), or refractive index irregularities in clear air (turbulence) [4]. These Atmospheric radars are mainly Doppler pulsed radars, which detect frequency shifts in order to obtain information about the motion of the phenomenon [5].

Power signal is a function of radar parameters and backscattering cross section of the scatter. Consider a volume that contains scatters inside a transmission pulse of width τ_w. The radar equation [5] can be re-written in four terms [4]:

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi)^3 R_0^2 l^2} \times \frac{c\tau_w}{2} \times \frac{\pi \theta_{1t} \theta_{1r}}{8 \ln 2} \times \eta, \tag{1}$$

where P_t is the instant transmission power, G_t is antenna transmission gain, G_r is antenna reception gain, R_0 is the center volume point distance between radar pulses and transmission antena, and l is attenuation losses. The second term represents range resolution volume. The third term is the beam angle width, where θ_{1t} is the transmission antenna beam angle and θ_{1r} is the reception antenna beam angle, both measured at -3 dB, in radians.

At last, the radar reflectivity, η, is a measure of the scatters dispersion in units per m^{-1}. Following, η can be calculated independently for clear-air and for precipitation.

A. Clear-air Wind Profile Radars

Clear air wind profiler are Doppler pulsed radars that emits radio waves vertically and detect signals originated by clear air refractive index. These variations are generated due to air temperature and humidity fluctuations [6], [5].

Clear-air radar reflectivity η is a measurement of variations on refractive index inside the radar resolution volume. If refractive index fluctuations is within the inertial range, reflectivity can be represented as [4]:

$$\eta = 0.379 C_n^2 \lambda^{-1/3}, \tag{2}$$

where C_n^2 is the structure function parameter of refractive index (in m$^{-2/3}$). Table I shows some examples of C_n^2 values [4].

TABLE I: Examples of the magnitude and intensity for C_n^2 [4]

C_n^2	Turbulence intensity
6×10^{-17} m$^{-2/3}$	weak
2×10^{-15} m$^{-2/3}$	intermediate
3×10^{-13} m$^{-2/3}$	strong

B. Precipitation Radar

Doppler pulsed radars are also used to detect hydrometeors. The η for precipitations can be described as

$$\eta = \sum_{i=1}^{N} \sigma_i, \tag{3}$$

where N is the number of scatters number per volume and σ_i is the backscatter cross section of the ith scatter.

To obtain useful η, [4] describes a method to calculate the target return signal starting from plane waves that reach spheric water drops. This signal depends on radar wavelength, the complex refraction index and $2\pi\alpha/\lambda$ ratio, where α is the spheric particle radius and λ is the radar wavelength.

When the ratio $2\pi\alpha/\lambda << 1$, then the process is approximated by Rayleigh scattering. In this case, σ_i is

$$\sigma_i = \frac{\pi^5}{\lambda^4} |K|^2 D_i^6, \tag{4}$$

where D_i is the ith drop diameter, and

$$|K|^2 = \left| \frac{m^2 - 1}{m^2 + 2} \right|^2, \tag{5}$$

where m is the complex dielectric index of water. For instance, with temperatures between 0 y 20ºC and for wavelength of the order of cm, liquid water has $|K|^2 \simeq 0.93$ and ice $|K|^2 \simeq 0.20$.

Therefore, (3) can be re-written as

$$\eta = \frac{\pi^5}{\lambda^4} |K|^2 Z, \tag{6}$$

and the reflectivity factor Z can be defined as

$$Z = \int_0^\infty N(D) D^6 dD. \tag{7}$$

Z is mainly represented in logarithmic scale, dBZ, and it is used by meteorologists to estimate the rain or snow intensity. It is proportional to the number of drops per unit volume and the sixth power of drops diameter. Some examples of this values are shown on Table II [4].

TABLE II: Z value examples

Z value	Type of precipitation
0 dBZ	cumulus clouds
20 dBZ	light rain
60 dBZ	heavy rainfall and hail

Meteorologic radars usually works with Z values between 10 and 60 dBZ, while research radars works in wider dynamic range between -10 and 80 dBZ [5].

III. CLAIRE RADAR

CLAIRE is a 445-MHz quasi-monostatic radar that consists of one transmitting antenna and three receiving antenna arrays. A general block diagram can be seen at Figure 1, while the general specifications are summarized Table III.

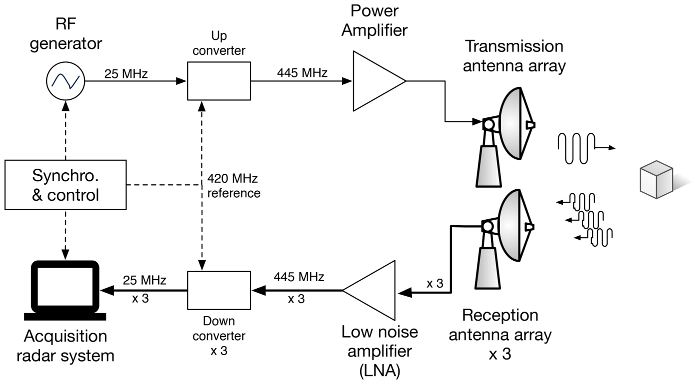


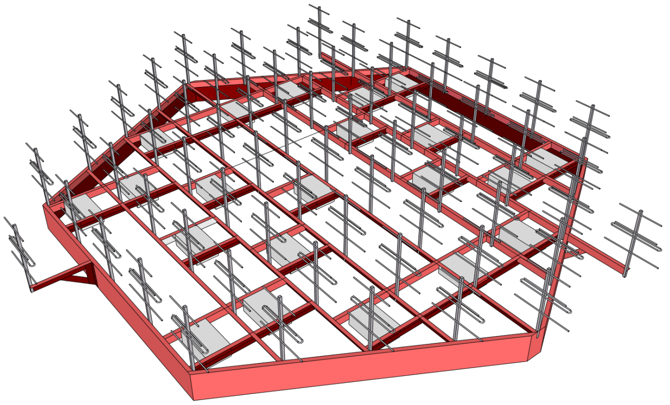
Fig. 1: CLAIRE radar general block diagram

Wind profilers typically operate at VHF or UHF frequencies from 40 to 915 MHz [7]. Frequencies around 50 MHz are more sensitive to clear-air echoes from temperature and humidity fluctuations, while higher frequencies, such as 915 MHz, are more sensitive to Rayleigh scatter from precipitation [8]. The radar operation frequency was set to 445 MHz ($\lambda = 67.4$ cm) to be sensitive to both clear-air and hydrometeor echoes.

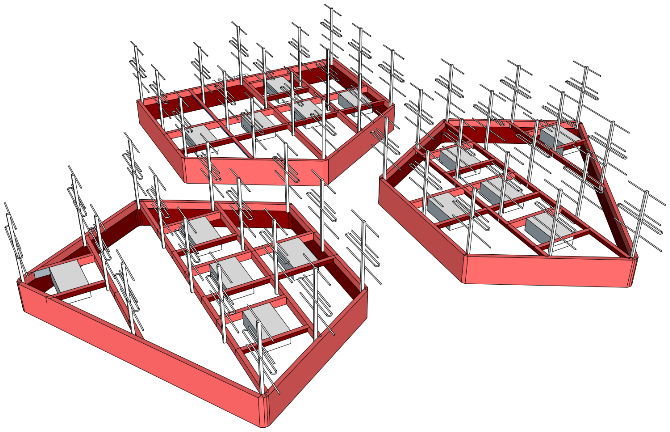
The goal is to separate the clear-air and precipitation signals through spectral analysis techniques, and process them separately afterwards. With the clear-air echoes, wind and turbulence estimations will be obtained through the Spaced

Antenna (SA) technique [9]. SA will be implemented in the frequency domain (FSA)[10]. While rainfall rate will be estimated from the hydrometeor echos with the Reflectivity Factor Z [4].

The antennas distribution to apply SA requires one transmitter and three or more closely spaced receivers [6]. CLAIRE has one array for transmission and three equidistant arrays for reception. The 3D design of the arrays can be seen in Figure 2.



(a) Transmitting antenna array



(b) Receiving antenna array

Fig. 2: CLAIRE radar 3D antennas design

TABLE III: CLAIRE Radar Specifications

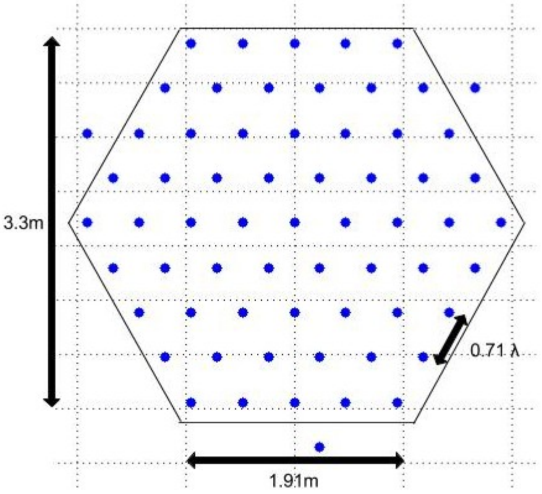
Specification	Value
Operation frequency	445 MHz
Transmission power	5 kW
Wind Profiling method	Spaced Antenna
Antenna Arrays	01 transmitter, 03 receivers
Transmisor Antenna Gain	24.7 dB
Receiver Antenna Gain	18.5 dB
Range resolution	37.5 m
Bandwith	4 MHz
Maximum Range	10 km

IV. ANTENNA DESIGN

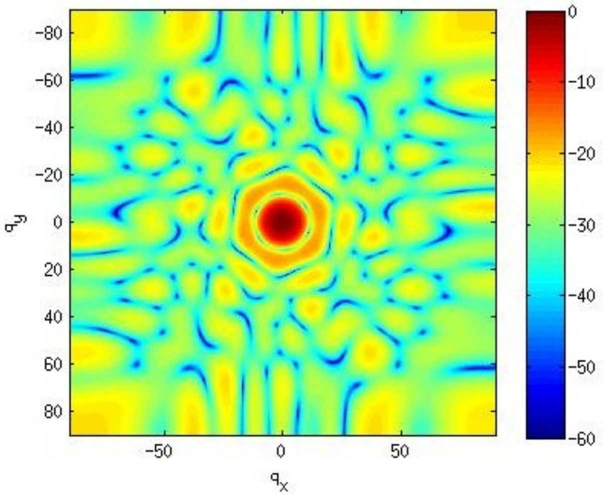
A. *Transmitter Array*

The transmitting antenna consists of a 64-element quasi-hexagonal array. The antenna distribution can be seen in Figure 3a, where the blue spots represent the locations of the Yagi-Uda antennas.

The hexagonal shape was selected due to its better performance in the simulations with FEKO ®electromagnetic simulation software (https://www.feko.info/). Array pattern simulation can be seen at Figure 3b. The transmitter has a simulated total gain of 24.7 dB. Furthermore, the beam-width is 9.49° and the side-lobe level 17.55 dB.



(a) Antenna Distribution. The antennas are equally spaced by 0.71λ, which makes the total array extension approximately 3.3m×3.3m



(b) Antenna pattern simulation. Antenna pattern view from the top. The beam-width is 9.49° and the side-lobe level 17.55 dB

Fig. 3: Transmitter array distribution and simulated pattern.

B. *Receiver Arrays*

The three receiving arrays and their spatial distribution can be seen at Figure 4a. Each of the three receiving antennas was