Design of a Small, Low Cost, P-band Airborne Polarimetric Synthetic Aperture Radar

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***Abstract* — A preliminary study of the design of a small, low cost, P-band airborne, polarimetric Synthetic Aperture Radar desired by the Wageningen University and the Borneo Orangutan Survival Foundation (BOS) to carry out forest biomass monitoring in Indonesia is presented. The requirements of the application are established and the main radar parameters are derived from them. A preliminary design of the system, based on commercial off-the-shelf components is also presented. Some novelties of the system are the use of Direct Digital Synthesis to perform the modulation, the use of dual-polarized microstrip square patch antennas and the reduced size and power consumption of the system. To assist in the calculations and comparisons of SAR systems a general Matlab based program, SARCAL, has been developed. Its philosophy and main functions are described.**

I. INTRODUCTION

Within the European Space Agency Earth Explorer Opportunity Mission (EEOM) program BIOMASCA P-band SAR has been proposed for worldwide forest biomass monitoring. The poor availability of P-band data has prevented the development of robust biomass estimation algorithms. Especially the lack of data in the tropics and the general lack of multi-temporal data are considered as a major problem. The Wageningen University, together with BOS, has requested IRCTR to design a small, low cost, P-band SAR intended to acquire observations over long time periods to capture seasonal variations in the Indonesian peat swamp forest. Thus, a unique and very meaningful scientific data set will be collected.

Section II of this paper gives an overview of the requirements of the radar. Section III describes the radar architecture and parameters derived from these requirements. An initial system design is shown in section IV, presenting the main novelties of the system. Among them, the use of Direct Digital Synthesis to perform the modulation, the use of dual-polarized microstrip squared patch antennas or the combination of frequency modulated continuous wave (FM-CW) radar architecture with synthetic aperture techniques. Section V describes SARCAL, a general Matlab-based program developed to enable performance calculations and comparisons of SAR systems.

Fig. 1 Ultralight aircraft used as platform for the radar

II. REQUIREMENTS OF THE SYSTEM

Since in the forest study area there are no airport facilities the radar system should be mounted on one of the ultralight aircraft that are already in use in the area. Therefore the main constraints of the whole design will be the limited weight, volume and electrical power that these aircraft can carry. Fig. 1 shows a picture of the aircraft.

The lack of technicians in the area, together with the difficulties to carry out complex operations while flying, makes simplicity of use recommendable. In order to reduce costs the system should be based on commercial off-the-shelf (COTS) components whenever possible.

The radar should be fully polarimetric for better land use classification capabilities. In order to penetrate the forest canopy the radar will operate at low frequencies, (P-band 430 MHz) [1].

Since the area under observation is quite homogeneous and the measurements are mended to investigate future satellite missions, a high resolution will not be necessary. A maximum of 30 meters in ground range resolution is considered sufficient, but 15 meters is desired. Multiple looks will be used in order to reduce speckle noise.

Considering the increasing interest in developing a spaceborne P-band SAR, small angles of incidence are preferred. The reflectivity of the areas under study is expected to vary from -5 dBm^2 to -35 dBm^2. Table I summarizes the requirements of the system.

Ground range resolution	<15 m (<30 m max)
Azimuth resolution	<1 m (<15 m multilook)
Number of looks	>15
Swath width	800 m
Angle of incidence	25^o to 65^o
CNR^{SAR}	>15 dB
Altitude of the platform	500 to 600 m
Velocity of the platform	75 km/hr

Table I Summary of the specifications for the radar

III. Radar Architecture and Parameters

An FM-CW radar architecture, rather than a pulse one, was preferred for its low power consumption, minor requirements in the sampling frequency of the receiver and simplicity of design. Although SAR algorithms were initially applied in pulse radars, their use in FM-CW has been studied recently [2]-[3].

FM-CW radars transmit continuously a signal the frequency of which is a function of time. Well known modulation schemes are the triangular or the sawtooth modulation. In the receiver the echo is mixed with the transmitted signal producing a signal with beat frequency f_b, which for linear modulations is proportional to range:

$$f_b = \frac{2R}{c} \Delta f \alpha \quad (1)$$

where R is the range, c is the speed of light, Δf is the frequency sweep and α is the sweep rate [4].

The size of the antenna must be proportional to the wavelength, thus at low frequencies the antenna has considerable dimensions. On the other hand in polarimetric FM-CW radars four antennas are necessary. Therefore a dual-polarized microstrip squared patch has been chosen as antenna. This kind of antenna has several advantages: they are compact, they have a reasonable fabrication cost and, since they are dual-polarized, the number of antennas required reduces to two. On the other hand they have several shortcomings [5]: They have a narrow bandwidth (roughly 5% of the central frequency), a low gain (5 dB typically), and a wide beamwidth (approximately 65^o). Therefore the antennas will constrain the parameters of the system. Table II summarizes the parameters of the system. All these parameters have been calculated using SARCAL, the Matlab based program described in section V.

Carrier frequency	430 MHz
Frequency sweep	20 MHz
Sweep rate	150 Hz
Transmission power	17 dBm
Sampling rate	100 kHz
Dynamic range in the receiver	32 dB
Antenna Gain	6 dB
Antenna beamwidth	65^o
Pointing angle	55^o

Table II Summary of the main parameters of the system

A. Scene

The altitude of the platform will be on average 600 m. The swath width will be 800 m. This width gives a sufficient view of the scene without increasing excessively the far range, which would increase the beat frequency and the dynamic range in the receiver. Only part of the antenna beamwidth will be used in the signal processing. The minimum incident angle will be 26.5^o and the maximum 63.5^o. Therefore, the near range and the far range will be 670 m and 1342 m respectively. The pointing angle of the antenna will be steered up to 55^o to reduce the dynamic range in the receiver.

B. Sweep Rate

The sweep rate should be sufficient to sample the Doppler shift caused by the relative movement between the scatterer and the platform. With an antenna beamwidth of 65^o, the minimum sweep rate required is 125 Hz (62.5 Hz each polarization), however the sweep rate used will be 150 Hz to account for undesired movements of the platform.

C. Frequency Sweep

The modulation used will be sawtooth with a frequency sweep 5% of the central frequency (20 MHz), which is the maximum bandwidth achieved with the chosen antenna. The range resolution depends on the frequency sweep [1] and can be written as:

$$\Delta R = \frac{c}{2\Delta f} \quad (2)$$

Therefore the slant range resolution obtained is 7.5 m and projecting the range resolution on the ground we get a worst case ground range resolution of 16.8 m, which is within the specifications.

D. Transmission power

The clutter-to-noise ratio (CNR) of an FM-CW SAR system after integration can be written as:

$$CNR = \frac{P_t G_t G_r \lambda^3 \sigma^o}{(4\pi)^3 R^3 K_B TFL} \frac{1}{2} \left(\frac{c}{2\Delta f \sin\theta_i} \right) \frac{1}{v_p} \quad (3)$$

Where P_t is the transmission power, G_t and G_r are the antenna gains in transmission and reception respectively, λ is the wavelength, σ^o is the reflectivity of the surface per square meter, K_B is the Boltzmann constant, T is the temperature of the medium, F is the noise factor, L stands for the different losses, θ_i is the angle of incidence and v_p is the velocity of the platform [6].

With the given parameters the minimum transmission power required to achieve the specifications is 10 dBm. However, in order to account for degradations due to the motion of the platform or imperfections on the circuitry 17 dBm will be used, which is the power that can be obtained with the available COTS components. With this power the minimum theoretical CNR obtained is 27 dB. However it is expected to be a bit lower due to non-perfectly coherence of the integration.

E. Sampling rate and dynamic range in the receiver

The sampling rate in the receiver must be sufficient to sample the beat frequency. At the given range and sweep rate, using (1) we obtain a minimum beat frequency of 13,5 kHz and a maximum of 26,9 kHz. The sampling rate should be at least twice the maximum beat frequency but 100 kHz will be used due to design considerations.

The received power in the antenna can be written as:

$$P_r = \frac{P_t G_t G_r \lambda^3 \sigma^o}{(4\pi)^3 R^3 L} \frac{1}{2} \left(\frac{c}{2\Delta f \sin\theta_i} \right) \frac{\alpha}{v_p} \qquad (4)$$

Therefore the power received by the system will be minimum -120 dBm and maximum -88 dBm. Thus, the dynamic range in the receiver will be 32 dB.

F. Synthetic aperture

In order to reduce the speckle noise multilook SAR processing will be used. This technique divides the azimuth beam in N different zones, which are separately processed and then averaged [7]. Using this technique a 15 looks image can be obtained dividing the total azimuth beam in 15 parts. Each part is the equivalent to a 1 look independent image with a resolution of 15 meters. Applying this technique the maximum integration time required reduces to 1.5 s.

IV. System Design

A preliminary design of the system has been made based on commercial off-the-shelf components that can fulfill the requirements of the application. A block diagram of the system can be seen in Fig. 2.

A. Transmitter

The core of the system is a direct digital synthesizer (DDS). This device synthesizes the chirp signal with a frequency sweep ranging from 30 to 50 MHz. Different modulations can be performed by simply programming several registers. The device can synthesize signals with a bandwidth up to 100 MHz, which gives a great flexibility when performing the modulation. A clock signal at a rate equal to the Sweep rate, *I/Oclock*, is available for external use. The DDS is controlled by a microcontroller.

The output signal of the DDS is then up-converted to the carrier frequency by using a 400 MHz crystal oscillator and a passive mixer. After being filtered, the resultant signal is amplified and sent to the antenna. A switch controlled by means of the I/O clock drives the signal alternatively to the vertical or the horizontal polarization feeding points of the dual-polarized microstrip squared patch antenna.

B. Receiver

An antenna similar to the one used in transmission receives the echo from the scatterer. The signals received from the horizontal and vertical polarization feeding points are processed separately. The received signal is first amplified by a low-noise amplifier. After amplification it is mixed with a portion of the transmitted signal in an active mixer. The resultant low frequency signal is filtered and amplified before being digitized and

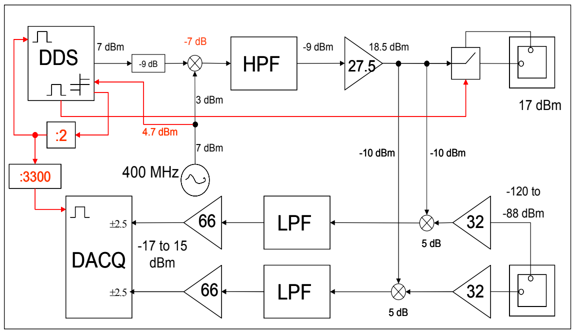

Fig. 2 Block diagram of the system

stored in a data acquisition system. The data acquisition system consists of an analog to digital converter and a set of flash memories controlled by a microcontroller to store the data. In order to increase simplicity the processing of the data is done off-line. The microcontroller has a USB interface to facilitate the transfer of the stored data to a PC.

C. Timing and control

The whole system timing is based on the 400 MHz oscillator used to upconvert the signal. The sinusoidal output of the oscillator feeds a comparator integrated in the DDS. The output of the comparator is divided by 2 in order to supply the internal clock signal for the DDS. This internal clock signal is also used to control the data acquisition system.

V. SARCAL

A Matlab-based program, SARCAL, was developed to assist in the analysis and design of synthetic aperture radars. This program considers two main architectures: FM-CW and pulse, either fully polarimetric or single-polarized.

A graphical interface has been provided to make the program user-friendly. The user can save the workspace for future sessions when quitting the program and every time that a new calculation is done the result can be saved in a text file for further study.

Since the performance of the antennas is considered one of the main constraints of the system, special attention has been paid to their design. Different antenna types (horns, apertures and microstrip antennas) and arrays of antennas can be chosen in SARCAL. Entering parameters such as the wavelength or the dimensions of the antenna the program calculates the beamwidth, the gain and the radiation pattern. If none of the antenna types given matches the requirements, the user can also introduce the antenna parameters.

The program has three main functions that are described in the following sections.

A. Design Function

This function calculates the parameters of the system from the requirements of the application. Therefore the inputs of the function are related to the platform, the antenna used, the central frequency and parameters related with the scene such as desired ground-range resolution, swath width, clutter-to-noise ratio, reflectivity and angle of incidence.

The outputs obtained are parameters related with the geometry, the synthetic aperture, ambiguities, upper bound motion compensation requirements and parameters related with the system such as the PRF, the bandwidth, the transmission power required, the sampling rate in the receiver or the dynamic range.

B. Analysis Function

This function analyzes the performance of the system in an application and checks if the radar is working properly.

The inputs of the program are therefore related with the system itself: PRF, bandwidth, transmission power, wavelength, etc.; the platform and the antennas used, the angle of incidence, the swath width and the azimuth angle used to construct the synthetic aperture.

The outputs of the function are the characteristics of the image like resolution or CNR, parameters related with the scene and the synthetic aperture radar. If the PRF or the sampling rate of the receiver is too low the program generates a warning.

C. Clutter-to-noise ratio plot

The user enters the terms of the equation of the clutter-to-noise ratio for SAR, parameters related with the antenna, and the surface among a set of different surfaces whose reflectivity as a function of the angle of incidence and the wavelength is stored in the program. The program plots then the CNR as a function of the angle of incidence. Fig. 3 shows an example of CNR plot.

Plotting the CNR is useful to have a qualitative view of the ambiguities.

VI. CONCLUSION

Although P-band SAR has been proposed for worldwide forest biomass monitoring the lack of data available has prevented the development of robust biomass estimation algorithms. The Wageningen University desires to have a small, low cost, P-band polarimetric SAR to carry out seasonal as well as long term monitoring in the Indonesian tropical forests. IRCTR has designed a suitable system.

An initial study of the requirements of the radar and its feasibility has been done. The research showed that the main constraint is the small size and the low velocity of the aircraft. Therefore an FM-CW architecture has been chosen due to its reduced power consumption. For their compactness and dual-polarization it has been decided to use dual-polarized microstrip squared patch antennas. Because of its flexibility and low cost a DDS will be used to perform the modulation.

While studying the radar, a Matlab-based program SARCAL has been developed to assist in the design and analysis of the different SAR architectures.

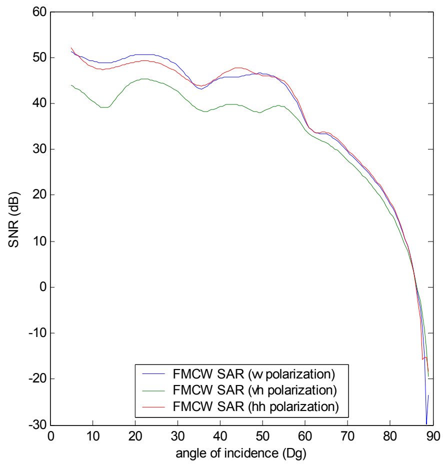

Fig. 3 CNR plot of an FM-CW SAR when observing trees

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