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An FM-CW scatterometer radar: design, implementation and use on natural surfaces

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A C-band (5.3 GHz) scatterometer radar has been developed and successfully employed for backscattering measurements of natural surfaces. The instrument is based on a FM-CW scheme with a 300 MHz modulation interval. With this configuration, range resolution and independent samples within the sensor footprint area can be obtained. The aim of this work is to validate scattering models for parameter retrieval from SAR data. An example of scattering data acquisition is described in this paper: radar data have been collected in the 23° ÷ 60° incidence angle interval over bare soil areas with different surface roughness and soil moisture.

1. Introduction

OVER THE LAST FEW DECADES, the potential of radar sensors to monitor environmental parameters, such as soil moisture, surface roughness, forest biomass and ice thickness has been recognized by many experimental and theoretical works.

In fact the radar cross-section (RCS) of natural surfaces contains information about physical and morphological properties of the interfaces between air and soil. Empirical and theoretical models of microwave scattering from natural surfaces, based on statistical representation of the interface morphology, have been developed [1, 2].

Retrieval of quantitative geophysical parameters, based on inversion of both theoretical and semi-empirical models, requires a better refinement of both models and retrieval algorithms, due to the intrinsic complexity of natural targets. For example, referring to bare soils analysis, the need to improve the statistical description of real targets is normally accepted. In fact, recent anechoic chamber measurements over artificial random surfaces have confirmed a good agreement between theoretical and experimental results [3], but the hypotheses commonly assumed in the description of surfaces for which the models are valid, are seldom verified over natural surfaces.

Experimental studies of scattering from natural surfaces can be performed with both airborne Synthetic Aperture Radar (SAR) systems and *in situ* measurements with helicopter-borne or truck based scatterometer radars. The latter systems allow the possibility of measurements over smaller areas (not large enough to include a number of SAR resolution cells needed for a satisfactory RCS statistics) and a more flexible choice of operation conditions such as incidence angle and direction, transmitted and received polarization and sensor height.

To perform *in situ* RCS measurements, a C-band FM-CW scatterometer radar has been designed and developed. Object of this paper is the description of the system characteristics and of radar data acquisition over selected test areas.

2. Scatterometer project

A C-band scatterometer for *in situ* measurements of RCS has been designed, implemented and successfully tested in order to meet the requirement of ranging capability with a good range resolution for identification of different sources within distributed targets. The device can measure backscattering coefficient (RCS normalized to target area) between +10 dB and –40 dB, for target distances between 10 and 60 m and for different look angles in the 10° ÷ 60° angular interval. A dedicated software allows system control, measured data processing and displaying.

The main technical parameters are shown in table 1.

Table 1 - **Main technical parameters**

PARAMETER	SELECTED VALUE
Instrument model	Linear FM-CW radar
Frequency band	C (5.3 GHz)
Modulation band	300 MHz
Modulation signal	Triangular (60 Hz)
Antenna type	Horn antenna
Polarization modes	VV, VH, HV, HH
Incidence angle	[10°, 60°] off nadir
Measurement range	[10 m, 60 m]
Range resolution	0.65 m
IF range	1 ÷ 40 kHz
Sampling frequency	160 kHz
Calibration methods	Internal (delay line) External (corner reflector)

2.1. C-band scatterometer implementation

The device is based on the scheme FM-CW (Frequency Modulated - Continuous Wave) with independent linear polarization state for transmitted and received microwave signal in each acquisition run [1, 4].

The transmitted wave is frequency modulated, with a triangular waveform (f_{mod} = 60 Hz), in an interval of 300 MHz around the central frequency of 5.3 GHz. The received signal is down-converted, with a reference signal corresponding to a portion of the transmitted wave, and low-pass filtered in order to reject the unwanted spectral components. The output signal includes ranging information (proportional to signal frequency) and backscattering properties (proportional to signal amplitude) of the illuminated target.

The chosen modulation resolves backscattering signals from different scatterers within the antenna footprint. In fact, the frequency of the scattered wave is subtracted from the frequency at the transmitting antenna, and the difference between these two frequencies is proportional to the distance R of the scatterer according to the relationship:

$$\Delta f = a\Delta t = \frac{2B}{T_{mod}}\frac{2R}{c} = \frac{4B}{cT_{mod}}R \qquad (1)$$

where a is the slope of the triangular wave, B the modulation bandwidth and T_{mod} the modulation period.

In order to measure the backscattering properties of the target as a function of range, the Fast Fourier Transform (FFT) is applied to the analog signal. The sampling is synchronized with the modulating waveform in order to acquire only useful signal during a single upward or downward modulation sweep.

The range resolution ΔR_{min} of the radar system can be calculated as:

$$\Delta R_{min} = \frac{c}{2}\Delta t_{min} = \frac{cT_{mod}}{4B}\frac{f_c}{N} \Rightarrow \Delta R_{min} = \frac{cT_{mod}}{4B}\frac{1}{T_{useful}} \qquad (2)$$

where f_c is the sampling frequency, N the number of acquired samples and T_{useful} is the useful period for acquiring the analog signal (Figure 1).

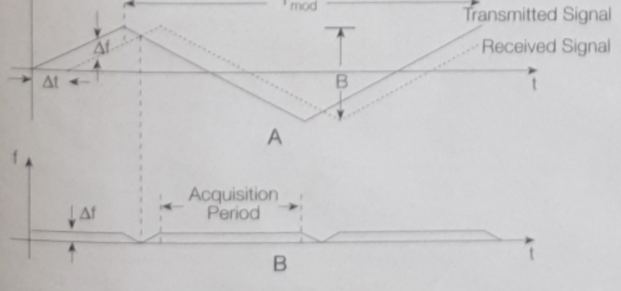

Figure 1 **A: transmitted and received signals for a point target located at a distance *R* (the delay is proportional to the distance); B: result of the frequency subtraction.**

2.2. System description

The diagram shown in figure 2 illustrate the main RF components of the C-band scatterometer.

The radio frequency (RF) signal is generated by an *Yttrium Iron Garnet* (YIG) tunable oscillator operating in the 2 ÷ 6.16 frequency range with a peak power level of 100 mW. The output signal is frequency modulated with a triangular voltage synthesized and controlled by a microcomputer (PC). An isolator with a high isolation (>20 dB) and low VSWR is installed at the oscillator output port to improve the frequency stability of the oscillator. The signal at the oscillator output is divided, through a 10 dB directional coupler, between the transmitting antenna and the local oscillator (LO) port of a low-level double-balanced mixer. Further isolators are installed in order to decrease impedance mismatch. The backscattered signal is fed to the mixer RF port through a band-pass filter followed by a low-noise GaAs FET pre-amplifier of medium gain (~33 dB) in order to improve *SNR*. The resulting of mixing operation is an intermediate frequency (IF) spectrum. Mechanical coaxial switches allow three different operative functions: acquisition of backscattered signal, internal calibration and radiometry.

The scatterometer employs *horn* antennas (15 dB gain): their polarization states (VV, VH, HH, HV) are selected before each acquisition run. The antennas are mounted on a pivoting support and placed at a mutual distance of one meter. This dual-antenna configuration provides an excellent co-polarized and cross-polarized isolation.

Data collection, operative configuration and triangular modulation synthesis are controlled by a PC trough a *user friendly* graphic interface. The radar return signals from the measurement channel and the processed data (calibration parameters, received power spectra, RCS and backscattering coefficients) can be dispayed in real time.

Signal processing is accomplished by a general purpose data acquisition card (NI-DAQ AT-MIO-16E2). This allows the generation of all necessary control signals, increasing the signal dynamic range through a gain controlled amplifier, and performing a real-time sampling of the IF time-domain signal.

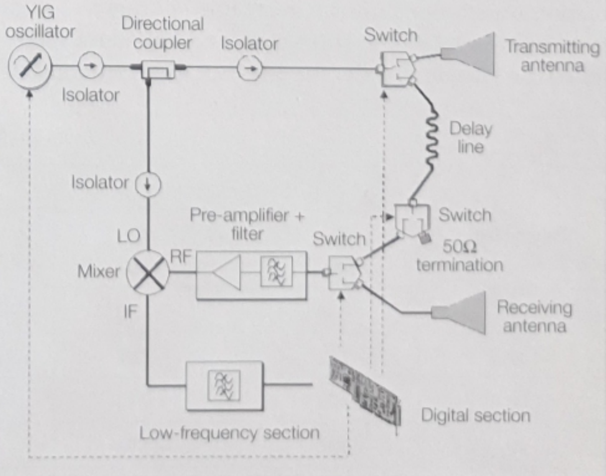

Figure 2 **C-band scatterometer diagram: microwave unit, low-frequency and digital sections.**

Before digital acquisition, analog signal filtering is accomplished by a second-order Butterworth high-pass filter in order to cut signals below 1 kHz due to the antenna cross-talk. A subsequent sixth-order Butterworth low-pass anti-aliasing filter removes frequencies above 40 kHz.

The A/D-conversion is synchronized to the modulation signal: starting at each turn-around of the triangular wave, 1024 samples are acquired with a sampling frequency of 160 kHz after a delay of 1 ms. For each acquisition run, 100 time-domain sequences (during subsequent upward or downward modulation sweeps) are acquired in order to reduce environmental and internal noise by averaging the corresponding frequency spectra. For each transmitted and received polarization state, different acquisition runs, over non-overlapping footprints, are performed. This allows the inclusion of many independent samples in the antenna footprint, resolving the signal from point targets, and improving the statistics for extended targets [5].

The acquired radar backscattering signals together with ancillary data, including time and date of measure, polarization mode, height and look angle are recorded in a mass storage device for a post-processing data analysis. This is performed according to the following steps:

- windowing and applying FFT to each time-domain signal, stored in the backscattering data archive;
- averaging the resultant frequency spectra, each one corresponding to an acquisition run;
- selection of useful spectra in which are located the independent samples, based on height, look angle and antenna beamwidth;
- computation of internal and external calibration parameters to estimate RCS;
- backscattering coefficient retrieval by averaging the independent samples collected during the acquisition runs over non-overlapping footprints and normalized to the illumination integral evaluated through the antenna pattern and the geometrical parameters.

The device also includes two different calibration processes: external and internal calibration. External calibration is performed using trihedral corner reflectors located at different distances from the receiver in order to check the antenna parameters variations. Internal calibration is performed using a delay line of known characteristics in order to test short-term and long-term stability of the system. Finally, the noise of the scatterometer is determined by pointing the antennas to the sky and measuring the reciprocal matching (in this phase the high-pass filter is excluded).

3. Experimental results and conclusions

The instrument has been employed in two experiments. The first one was carried out on 20-21 February, 1998 over a 100*250 m^2 area of an experimental Test Site, of Bari University, Faculty of Agricultural Science. The site was ploughed in order to obtain two separate areas with different degrees of roughness. The first area (Field 1), with dimensions 45*130 m^2, showed a low degree of roughness, with row directional structures, due to ploughing residual. The second area (Field 2, with dimensions 45*80 m^2) showed a more evident roughness.

The second experiment was performed on 10-11 November, 1998 over a 150*300 m^2 area near Matera. This test area showed a degree of roughness comparable with the Field 1 of the first experiment. In both occasion roughness measurements were carried out. In particular, in the first experiment surface profiles were acquired with a 3 m long needle-like profile meter, with a horizontal resolution of 1.5 cm. Profiles in the directions parallel to the radar beam incidence direction (range), perpendicular (azimuth) and diagonal were collected.

In the second experiment a 25 m long laser profile meter with a horizontal resolution of 0.5 cm was employed. Digital surface profiles were analyzed to test the validity of natural surfaces representation based on self-similarity properties of fractional Brownian motion processes [6].

On each field, 20 soil moisture measurements were carried out with a Time Domain Reflectometer (TDR). In order to characterize electromagnetic properties of the surfaces, values of dielectric constant were calculated from the values of volumetric moisture by means of a semiempirical relation [7].

In the first experiment three series of co-polarized backscattering radar data were acquired, respectively on Field 1 and 2 with a sensor height of 15 m and on the only Field 1 with a sensor height of 25 m. The incidence angles were between 23° and 60°. In the second experiment a complete acquisition series, for a sensor height of 15 m, was performed.

Table 2 – **Measured values**

Angle (deg)	EXP.1-FIELD 1		EXP.1-FIELD 2		EXPERIMENT 2	
	σ°_{VV} (dB)	σ°_{HH} (dB)	σ°_{VV} (dB)	σ°_{HH} (dB)	σ°_{VV} (dB)	σ°_{HH} (dB)
23	–4.40	–4.45	–3.08	–0.67	–7.99	–7.77
30	–7.03	–7.07	–5.85	–2.92	–8.98	–9.40
40	–9.71	–9.14	–5.25	–6.43	–10.54	–8.57
50	–12.16	–12.73	–6.91	–7.43	–10.65	–11.81
60	–13.28	–15.31	–10.53	–8.04	–11.21	–12.87

Since backscattering coefficient (σ°) is an exponentially distributed random variable, 36 independent samples were needed in order to obtain an rms error of ± 0.9 dB on the average value. Because the angular width of a single resolution cell, at incidence angle of 23° and sensor height of 15 m, is 6.4°, this width has been assumed as the interval, centered on the nominal incidence angle, that defines the significant resolution cells. As the incidence angle and sensor height were increased, more independent samples were included in the fixed angular interval; as consequence, less acquisition were then required.
In table 2 the measured σ° values are summarized.
These data showed sensitivities to surface roughness, soil moisture, incidence angle and wave polarization in good agreement with an electromagnetic simulation based on a self-similar surface model and a physical optics Kirchhoff approach [6].

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REFERENCES

[1] Ulaby FT, Moore RK, Fung AK: *Microwave Remote Sensing: Active and Passive*. Vols II-III, Addison-Wesley, 1982.

[2] Fung AK, Li Z, Chen KS: Backscattering from a randomly rough dielectric surface. *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 30, n. 2, 1992.

[3] Nesti G, Pampaloni P, Coppo P, Hallikainen M, Mancini M, Troch P, von Shonermark M: *Experimental Research at the EMSL on Scattering Properties of Non Vegetated Terrains*. Proceedings of IGARSS'95, Florence 10-14 July 1995.

[4] Skolnik MI: *Introduction to Radar System*. McGraw-Hill, 1981.

[5] Monakov AA, Vivekanandan J, Stjernman AS, Nyström AK: Spatial and Frequency Averaging Techniques for a Polarimetric Scatterometer System. *IEEE Transactions on Geoscience and Remote Sensing*, Vol. Ge-32, n. 1, 1994.

[6] Casarano D, Buono G, Paparella F, Posa F, Sabatelli V: *Scattering from bare soils: C-band multi-polarization scatterometer measurements*. Proceedings of EUROPTO - VIII European Conference on Remote Sensing, 1998, Barcelona, Spain, SPIE , Vol. 3497

[7] Hallikainen MT, Ulaby FT, Dobson MC, El-Rayes MA, Wu L: Microwave Dielectric Behavior Of Wet Soil - Part I: Empirical Models and Experimental Observations. *IEEE Transactions on Geoscience and Remote Sensing*, Vol. Ge-23, n. 1, 1985.

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