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EVALUATION OF THE REFRACTIVITY MEASUREMENT FEASIBILITY WITH A C BAND RADAR EQUIPPED WITH A MAGNETRON TRANSMITTER

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1. INTRODUCTION

Precipitation radars are mainly dedicated to rainfall measurement, but the capability to use ground echo returns to measure the refractive index near the surface has been demonstrated (Fabry et al 1997, Fabry, 2004). This measurement is derived from phase variation between the radar and the ground echo, assumed to be a fixed target. As demonstrated during the IHOP project (Demoz et al., 2006), refractivity measurements lead to near-surface moisture estimations and, once implemented on operational radar networks, could potentially be very useful for convective storm prediction.
Radars equipped with klyston transmitters, such as the Nexrad network, have a very well defined transmitted waveform in frequency and phase, and they can be used for refractivity measurements. However, due to the cost problems, most of the operational European networks are equipped with magnetrons for which the transmitted frequency and phase are not precisely known and the refractivity measurement with a magnetron radar is still an open issue.
Meteo-France recently decided to investigate the possibilities of exploiting magnetron radars to extract near-surface humidity. After presenting the formulation of the problem, we present the first experiment we have performed with one of our operational radars. We finally briefly describe the future work.

2. FORMULATION

Formulation for a klystron transmitter
Following the formulation of Fabry (1997), : "The time τ taken by the electromagnetic waves to reach a target at range r and return to the radar is :

$$\tau = 2r\frac{n}{c} \qquad (1)$$

with c is the speed of light in vacuum and n the index of refraction, supposed to be constant all over the path. The phase of the received signal is given by" :

$$\phi = 2\pi f\,\tau = 4\pi f\, r\frac{n}{c} \qquad (2)$$

Using this equation, the index of refraction n can be deduced from an estimation of ϕ, but, because of the 2π ambiguity on the phase measurement, the index n also suffers from ambiguities and only small variations of n can be estimated, not its absolute value. Furthermore, the measurement is possible only if the range r is constant, i.e. variations of r must be small with respect to the wavelength, and, as mentioned by Fabry (2004), the ground echoes must be carefully chosen, with respect to their stability, to ensure a correct n estimation.
Doing this, refractivity maps can be used to follow low altitude moist air masses motions, and this could be very useful to improve the prediction of the convection (Demoz et al., 2006).

Specific problems generated by the magnetron transmitter
The magnetron frequency varies with time and this leads to an error in the measurement : using equation (2), a frequency variation of 5 kHz leads to a 2π phase variation at a distance of 30 km. If one consider acceptable a phase measurement accuracy of 30 degrees, this imposes an accuracy of 500 Hz for the frequency f.
For the magnetron transmitting radars, this can be a major source of error because the signal bandwidth, around 1MHz, is quite large with respect to the needed accuracy of a few hundreds of Hz.
Another error source can come from the fact that the signal is mixed with a sinus local oscillator of f_{lo} frequency. If f_{lo} is not exactly equal to f, the mean frequency at the output of the receiver is not equal to 0 and this leads to a phase variation equal to 4π (f- f_{lo}) r/c.

Formulation for a magnetron transmitter

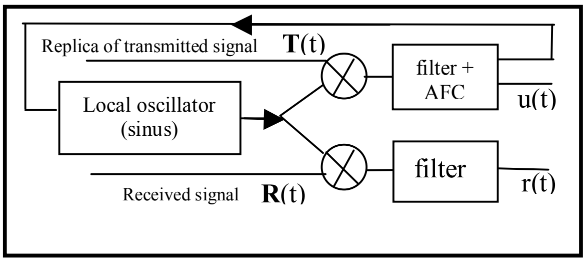

Figure 1. schematic diagram of the receiver for a magnetron radar

The receiving scheme of a magnetron radar is given in fig. 1 : the received signal R(t) is multiplied by a sinusoidal local oscillator (LO) and filtered to give the low frequency received signal r(t). A replica of the transmitted signal T(t) is also multiplied by the same LO, and filtered to give the low frequency transmitted signal. This replica is used to :

- measure the transmitted frequency to adjust the local oscillator frequency through the automatic frequency control module (AFC).
- measure the phase of the transmitted pulse, necessary to correct the received signal.

The signal R(t) received from a fixed target after a time delay τ is given by :

$$R(t) = aT(t-\tau) \qquad (3)$$

where a is a constant which depends on the geometry (target, antenna, range, ..).

After multiplication by the local oscillator, we have :

$$u(t) = T(t)\, e^{-j(2\pi f_{LO} t + \varphi_{LO})} \qquad (4)$$

$$r(t) = R(t)\, e^{-j(2\pi f_{LO} t + \varphi_{LO})} \qquad (5)$$

where f_{LO} and φ_{LO} are respectively the local oscillator frequency and phase for t=0.

Using (3) and (5), r(t) becomes :

$$r(t) = a\, T(t-\tau)\, e^{-j(2\pi f_{LO} t + \varphi_{LO})} \qquad (6)$$

The desired phase $\Delta\varphi$ of the received signal, corrected for the transmitted phase, can be defined as the phase, for the delay τ , of the convolution product $v(\tau')$ between the received and the transmitted signals:

$$v(\tau') = \int_{-\infty}^{+\infty} r(t)\, u^*(t-\tau')\,dt \qquad (7)$$

Where * denotes the complex conjugate. Using (6) and (4), we obtain :

$$v(\tau') = e^{-2\pi j f_{LO} \tau'}\; a \int_{-\infty}^{+\infty} T(t-\tau)\, T^*(t-\tau')\,dt \qquad (8)$$

and for $\tau = \tau'$:

$$v(\tau) = e^{-2\pi j f_{LO} \tau}\quad a \int_{-\infty}^{+\infty} \left|T(t-\tau)\right|^2 dt \qquad (9)$$

The first term represents the phase of the convolution product whereas the second term represents its amplitude, which depends on the transmitted pulse duration and shape. The argument of the first term is the desired phase $\Delta\varphi$, given by :

$$\Delta\varphi \;=\; -2\pi\, f_{LO}\,\tau \;=\; -4\pi\, f_{LO}\,\frac{r}{c}\,n \qquad (10)$$

The conclusion is that, rather than depending on the transmitted frequency f, *the phase difference between the received and the transmitted signals actually only depends on the frequency of the local oscillator f_{LO}., the distance r and the index of refraction n.*

This result seems trivial for klystron applications since f = f_{LO} (eq. 1). But it is important for magnetron applications where f_{LO} is much easier to measure than the frequency f delivered by the magnetron.
As far as the AFC is not activated, f_{LO} remains constant and the relationship between $\Delta\varphi$ and the index of refraction n is well defined by eq. (10).

3. EXPERIMENTAL DESIGN AND FIRST RESULTS

As a first experiment, we have recorded I and Q, transmitted and received signals. The experiment was performed with the Falaise radar, in the Normandy region, 200 km West from Paris. It was focused on a particular ground echo, produced by a tower in the Caen City, 30 km away from the radar.
This radar is a C-band, with a peak power of 250 kW, a pulse length of 2 μs, an antenna beamwidth of 1°, and the antenna rotating speed is 5°/second.

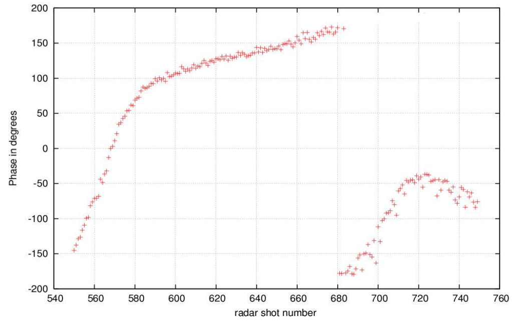

Figure 2. Phase variation with time for the signal reflected by the tower. Each point represents the phase measured with one radar pulse. The horizontal scale (of 200 radar pulses) corresponds to 600 ms, and to 3 degrees in azimuth.

Fig. 2 shows phase measurement versus azimuth when the antenna crosses the tower. The measurements are well coherent together, with a scatter less than 10°. The observed variation is characteristic of the phase response of the antenna beam.

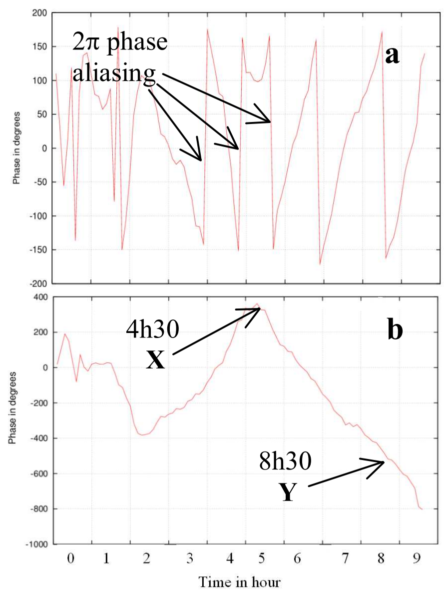

Figure 3. Phase variation with time for the signal reflected by the tower. Each point represents a 5' measurement and horizontal scale) corresponds to the 9 hours duration of the experiment. The raw phase (a) and the de-aliased phase (b) are both represented.

The phase of the signal received from the tower versus time during the 9 hours of the experiment is plotted on fig. 3. One independent measurement was made each 5'. The raw phase (a) experiences sharp variations obviously due the to 2π aliasing. On the de-aliased phase (b), we observe a variation of 1000° from point X (4h30) to point Y(8h30). It is attributed to the variations of the refractivity N which is related to the index of refraction n by (Fabry 1997) :

$$N \;=\; (n-1)\,10^{-6} \qquad (11)$$

This refractivity can be computed with the following equation :

$$N = 77.6\frac{P}{T} + 3.73\times10^5\,\frac{e}{T^2} \qquad (12)$$

Where P is the pressure in mb, T the temperature in °K and e the water vapour pressure in mb, which can be computed with the relative humidity U.

Time	U%	P(mb)	T (°K)	N
4h30 (**X**)	93	1021.2	280.7°	330
8h30 (**Y**)	95	1022.3	281.6	333

Table 1. Meteorological parameters measured in the Caen City at 4h30 (X in fig. 3), and 8h30 (Y in fig. 3), and refractivity parameters N computed from them.

The meteorological in-situ measurements corresponding to the X and Y points of fig. 3 are presented in table 1, with the reflectivity parameter N deduced from these measurements. Between 4h30 and 8h30, we observe an N variation of 3. Using (2) and (11), we can compute the corresponding phase variation for a distance of 30 km and a frequency of 5.6 GHz. This computation gives a phase variation of 1210°, comparable to the phase difference of 1000° observed between X and Y on fig. 3b.

4. FUTURE WORK

The next step will be to implement real time accumulation of I and Q data to produce maps of the phase. We will then develop methods to de-aliase the phase with respect to range and time, in order to convert the phase maps into reflectivity maps. As a first validation of the method for our radars, the refractivity will be compared to in-situ measurement of pressure, temperature and humidity.

After that, we plan to install (in autumn 2008) the method in real time on 4 S-band radars located in South-East of France (Bollène, Nîmes, Opoul and Collobrières) during the HYMEX campaign. In situ measurements, GPS water-vapour measurements as well as the model output will be used to validate the refractivity estimations.

Finally an assimilation method will be developed for the French numerical model AROME and the impact of the assimilation of the refractivity on the convection prediction will be evaluated.

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