Evaluation of phase ambiguity problem due to sampling time when measuring refractivity with precipitation radar

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1. INTRODUCTION

The phase variation of ground clutter radar returns are related to changes in the atmospheric index of refraction between the radar and the ground clutter targets [Fabry et al.,1997]. This index of refraction varies with local pressure, temperature and relative humidity, so that phase changes in returns from ground targets act as an atmospheric record of these variables, and "radar reflectivity retrieval algorithms show great promise in estimating the surface layer moisture field" (Fabry2004).

Radars equipped with klystron transmitters, having a very well defined transmitted waveform in frequency and phase, can be used for refractivity measurements. However most of the operational European networks are equipped with magnetrons transmitters, for which the transmitted frequency varies with time. These variations may lead to measurement problems, and Parent-du-Chatelet and Boudjabi (2008) recently proposed a new formulation of this problem and they claim that, applying proper correction factors, measurement can be made equally well with magnetron radars or klystron radars.
Refractivity estimation by radar is based on phase differences, which can be corrupted by phase-aliasing problems due to time or space undersampling. These problems will depend on weather phenomena space or time scales.

The aim of this paper is to test the phase aliasing risks in a temperate area. Starting from a climatologically representative data-base of in-situ measurement, we compute a local refractive index time series, which we use to simulate phase variation of an hypothetical radar measurement, integrated over a given time-interval and a given space-interval. The 1-minute in-situ measurements of pressure, temperature, and relative humidity are issued from the Trappes French Meteorological Center (Météo-France, Direction des Systèmes d'Observation) data-base. This data-base, which includes a few major thunderstorms and heavy rain climatologic events, is well adapted to evaluate the radar phase-aliasing risks in this area.

2. PHASE AND REFRACTIVITY RELATIONSHIP

The propagation speed of an electromagnetic wave depends on the material through which it travels, and waves traveling through the atmosphere propagate slightly slower than in vacuum. The ratio of the speed of light in vacuum to the speed of light in medium is called the refractive index *n*, which is more easily expressed as refractivity N [Bean and Dutton, 1968] described as follows:

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

Which is related to metrological parameters:

$$N = 77.6\,\frac{P}{T} + 3.73\times 10^{5}\,\frac{e \times RH}{T^{2}} \qquad (2)$$

where T is temperature in Kelvin(K), P and e are respectively, the air pressure and saturated water vapor pressure in millibar(mb). RH is the relative humidity between 0 and 1.

The time τ taken by the electromagnetic wave to propagate through a constant refractivity medium up to a stationary target at range *r* and to come back is [Fabry et al.,1997] :

$$\tau(t) = 2\, r\, \frac{n(r,t)}{c} \qquad (3)$$

Where *c* is the speed of light in vacuum.
By including in equation (3) the variation of the refractive index *n(x,t)* along the two way path, the phase of the received signal at time *t* is given by:

$$\varphi(r,t) = 2\pi f\, \tau(t) = \frac{4\pi f}{c}\int_0^r n(x,t)\,dx \qquad (4)$$

If we consider two targets T_1 (at range r_1) and T_2 (at range r_2), at two different times t and t_{ref}, along the same azimuth. A refractivity change (between t and t_{ref}) leads to a phase difference given by [Fabry2004]:

$$\Delta\varphi(r_2,t,t_{ref}) - \Delta\varphi(r_1,t,t_{ref}) = [\varphi(r_2,t) - \varphi(r_2,t_{ref})] - [\varphi(r_1,t_1) - \varphi(r_1,t_{ref})] \qquad (5)$$
$$= \frac{4\pi f 10^{-6}}{c}\int_{r_1}^{r_2}\left[N(x,t) - N(x,t_{ref})\right]dx$$

where φ(r,t) is the phase measured by the radar at time t for a signal coming from range r.
If r_1 and r_2 are enough close together, we can assume that the refractivity is locally homogenous between T_1 and T_2 and that the phase difference can be written as :

$$\Delta\varphi(r_2,t,t_{ref}) - \Delta\varphi(r_1,t,t_{ref}) = \frac{4\pi f\, 10^{-6}(r_2-r_1)}{c}\,[N(r,t) - N(r,t_{ref})] \quad (6)$$

Ambiguity problems

Using this equation (6), and assuming that the refractivity is known at the reference time t_{ref}, the local refractivity at time t can be deduced from the phase difference $[\Delta\varphi(r_2,t,t_{ref})-\Delta\varphi(r_1,t,t_{ref})]$, accessible with the radar. But this measurement is prone to ambiguity as soon as the product $(r_2-r_1)[N(r,t)-N(r,t_{ref})]$ becomes large enough to produce phase changes greater than π.

To evaluate the chances to have ambiguity problems when measuring the refractivity with precipitation radars, we have plotted in table 1 the refractivity change which leads to a π phase rotation for different range integration (r_2-r_1) and for different radar wavelength.

	S band	C band	X band
(r_2-r_1)=150m	200	89	50
(r_2-r_1)=1km	30	13	7.5
(r_2-r_1)=3km	10	4.5	2.5

Table 1. *Refractivity changes (in refractivity units) leading to a π phase rotation, for different wavelength and different range integration.*

Refractivity changes can be as large as 150 between seasons, but the classical day/night change is generally close to 10 or 20 in quite conditions. Therefore we can conclude from table 1 that the chances to encounter phase aliasing problems in quite conditions are weak at S band and for range integration lower than 1km. But these chances become noticeable at C band or X band for 1km or larger range integration.

A solution for such an ambiguity problem could be to improve the sampling time δt : even if the refractivity variations are large, up to 150 units, when we compare measurements separated by months or weeks, they are probably weaker for measurements separated by days, and certainly much smaller between minutes.

3. SIMULATION STUDIES & DATA ANALYSIS

In this section, we try to evaluate the sampling time δt adapted to avoid phase ambiguity measurement problems:

- Starting from a 4 years data-base of in-situ measurements of temperature, pressure and humidity, we compute a 4 years *N(t)* time series by using equation (2). The data were obtained with an automatic weather station located in Trappes city (30km West of Paris) every minute from 2005 to 2008;
- we then compute the time variation $[N(r,t+\delta t)-N(r,t)]$ for different values of the time interval, or integration time δt (5 and 30 minutes);
- Finally, using the equation (6), we simulate the phase variation time-series which would be produced by these N variations if a radar measurement were performed above the weather station, for different range integration $[r_2-r_1]$ (1 and 3 km).

3.1. FIRST STUDY (SAMPLING TIME OF 30 MINUTES AND SPATIAL INTEGRATION OF 1Km)

The simulated phase variation time series, obtained through the method previously described, is presented in figure 1 for a "sampling time" of 30 minutes, and a "spatial resolution" of 1 km.

We observed that in the winter season we have weak phase variations, unlike the phase variation is stronger during the other seasons, particularly during summer when it exceeds ±180°.

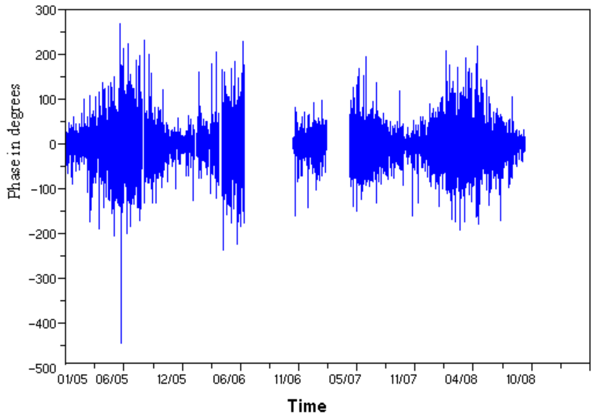

Figure1. Simulated time derivative of the phase between 2005 and 2008. Each point represents the phase-difference between two times separated by 30 minutes and integrated over a 1 km range. Several gaps correspond to missing in-situ data.

The same result is also represented as an histogram on Figure2.

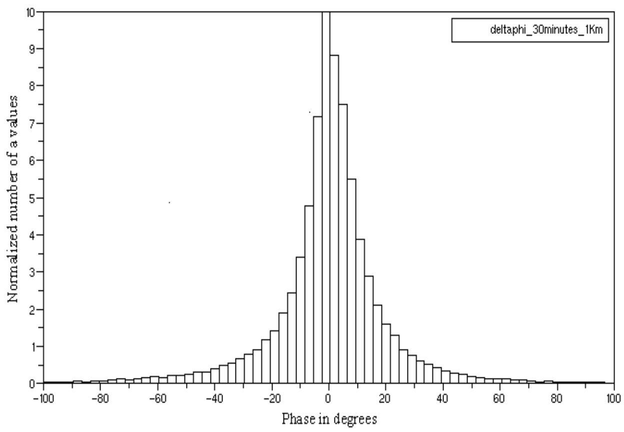

Figure2. Histogram of Simulated time derivative of the phase between 2005 and 2008. Each point represents the phase-difference between two times separated by 30 minutes, and integrated over a 1 km range (1 Jan 2005 to 31 Dec 2008).

Figure 2 shows that the phase variations spectrum is very large. The main population is centered around 0°, in between ±20°. From time to time, phase difference values reach, and even exceed the 180° limit.

We can conclude from these first results that, using a 1 km spatial integration and a 30 minutes temporal integration, we do have ambiguity measurements problems, particularly during summer time.

3.2. SECOND STUDY (SAMPLING TIME OF 5 MINUTES AND SPATIAL INTEGRATION OF 1Km)

The same study was performed in the same conditions, except that we have decrease the sampling time from 30 minutes to 20, 15, 5 minutes in order to define the limit condition to avoid phase ambiguities.

The obtained results (not shown here) demonstrate that for 10, 15 and 20 minutes integration times, we still have strong phase variations, greater than 180°, which will lead to ambiguity problems. Using a lower sampling time of 5 minutes, we still observe (figure 3) large phase differences, but generally lower than 180°.

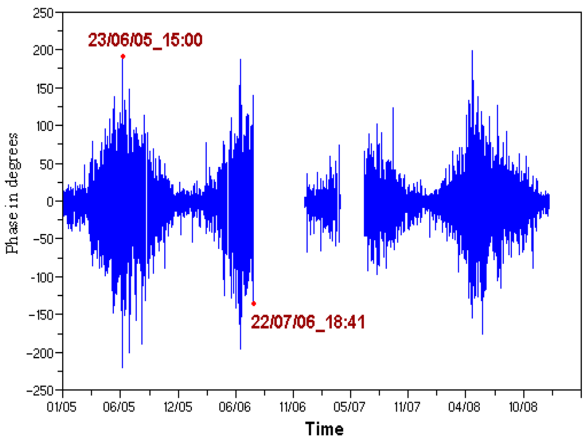

Figure3. Simulated time derivative of the phase between 2005 and 2008. Each point represents the phase-difference between two times separated by 5 minutes and integrated over a 1 km range. Several gaps correspond to missing in-situ data.

The same simulation data are also represented as an histogram on Figure4. The distribution is narrow, and values are mostly centered around (0° and ±10°).

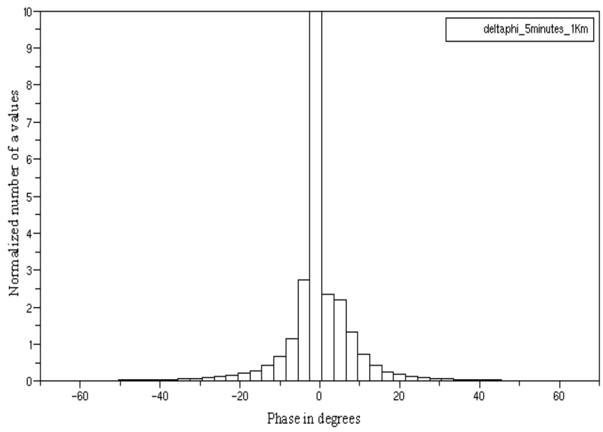

Figure4. Histogram of Simulated time derivative of the phase between 2005 and 2008. Each point represents the phase-difference between two times separated by 5 minutes, and integrated over a 1 km range (1 Jan 2005 to 31 Dec 2008).

From this second study, we can conclude that, with a 5 minutes integration time and a 1km spatial-integration, the phase ambiguity occurrence is quite small, but not completely negligible.

In the same condition if we use a sampling time of 5 minutes, and increase the spatial integration from 1 km up to 3 km, we obtained the same graph (not shown here) except that the vertical scale is three times larger than the values obtained with 1 km of spatial resolution.

3.3. TWO CASE STUDIES

To try to understand the origin of the largest observed phase variations, we have selected two particular events during the 4 years period: (23 June 2005 and 22 July 2006).

For verification, we have plotted the temporal variations of humidity and temperature for the two events on figure 7 and figure 8.

During the 23 June 2005 event (fig. 7), we observe a strong humidity variation of about 37% (figure 7(a)), and a strong temperature variation of about 7° (figure 7(b)), during a short 20 minutes time-lag (from 1449 UTC to 1510 UTC). These variations lead to a refractivity change of about 14 N-units, which corresponds to the development of a convective cell followed by heavy rain after 15h10, as observed by a rain gage (not shown here).

During the second event of 22 July 2006 we observe a 33% humidity variation (figure 8(c)), associated to a 5° temperature variation (figure 8(d)), from 1833 UTC to 1845 UTC leading to a refractivity change of about 9 N-units.

During these 10 minutes a thunderstorm was probably formed above Trappes City but we did not experienced rain at this moment. The dramatic temperature decrease is probably related to the birth of a storm cell which was formed above Trappes city and then moved elsewhere. This hypothesis is confirmed by the presence of a big cell on radar image after 1900 UTC.

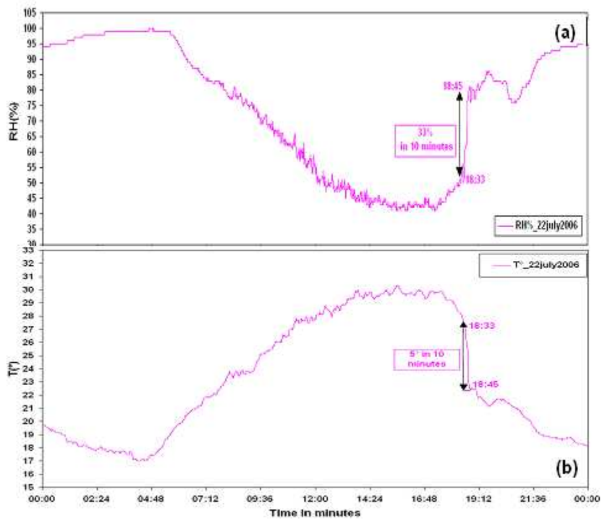

Figure7. (a): Temporal variation of the humidity in (%). (b): Temporal variation of the temperature in degrees during 23 June 2005 event.

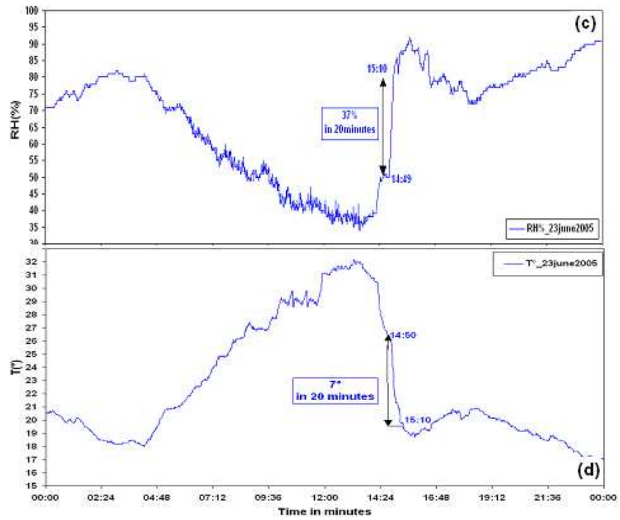

Figure8. (c): Temporal variation of the humidity in (%). (d): Temporal variation of the temperature in degrees during the event of 22 July 2006.

4. CONCLUSION

We have show in this paper that the refractivity estimation, based on phase differentiation with time and space can be degraded by phase aliasing problems. These problems increase with frequency (sensible at S-band, important at C-band and more important at X-band).

To avoid these ambiguity problems, and in order to identifies major thunderstorms and climatologic extreme events. We must choose an adequate condition of sampling time as well as an adequate spatial integration.

The result obtained in this paper, based on the simulation studies with In-Situ refractivity measurements during 4 years, show that for C-band radar there would be no phase ambiguity if we compared the refractivity measurement between a few minutes and for a range integration lower than 1km.

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