Atmospheric Phase Screen in Ground-Based Radar: Statistics and Compensation

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Abstract—In this paper we face one of the main issues in Ground-Based radar applications, i.e. the evaluation and removal of the atmospheric phase screen (APS). The time-varying delay statistics are assessed by means of both radars and meteo simulated datasets and are critically interpreted with particular reference to the entailed compensation issues. A compensation approach based on the available on-site meteo parameters (pressure, temperature, humidity) is then investigated. The technique proposes an initial calibration step on humidity which leads to significant improvements in APS removal. The results of the technique are discussed in the case of a real campaign dataset (Bolzano, Italy), that covers a temporal baseline of about one week.

Index Terms—Differential interferometry, Atmospheric artifacts compensation, Ground-Based RADAR.

I. INTRODUCTION

Ground-Based Interferometry proved itself ([1], [2]) a valuable tool for the monitoring of small scale areas, due to its short revisiting time and its millimetric accuracy on a fine resolution map of the scene. Analysis lead in previous works (see [3], [4] and [5]) on the stable targets showed that the atmospheric phase screen (APS) represents indeed the most relevant decorrelation source and has to be hence estimated and removed from the data.

In the present paper a statistical insight on APS, with reference to its time-varying characteristics, is introduced in order to provide both a quantitative idea of the disturbance and a qualitative evidence for some of the limits affecting the actual compensation techniques. The capabilities and the flaws of a compensation approach based on modeling the delay through the available on-site meteo information (pressure, temperature and humidity) are then investigated. It will be demonstrated that, under low turbulent atmospheric conditions, the proposed technique, based on the model refinement through a humidity calibration step, leads to significant improvements in the compensation performance. The analysis has been carried out on both meteo station information and GB-RADAR datasets collected during different acquisition campaigns by means of instruments operating in both Ku and X bands.

In section II a brief mathematical overview of the target model, with particular reference to the atmospheric delay, is provided, while in section III the APS statistics and their relation to the compensation issues are discussed. Section IV is then dedicated to the proposed compensation approach and in the end the compensation results on a real campaign dataset are illustrated and commented in section V.

II. DELAY MODEL

The model associated to the generic $i^{th}$ stable target in the $i^{th}$ image can be written as (see [6]):

$$y_p(i) = a(i) \cdot (b_p \exp(j\varphi_p(i))) + \omega(p, i)$$

(1)

where $a$ is the overall gain of the $i^{th}$ image, $b$ is the specific amplitude of the target, $\omega(p, i)$ accounts for both the clutter noise and the thermal noise: it can be assumed a zero-mean independent circular gaussian (ccG) process. In the end, $\varphi_p(i)$ is the target phase:

$$\varphi_p(i) = \varphi_{0,p} + \frac{4\pi}{\lambda} \left( \rho_p + d_{atm,p}(i) \right)$$

(2)

where $\varphi_{0,p}$ is the backscatter phase, $\rho_p$ is the LOS distance of the scatterer and $d_{atm,p}(i)$ is the additional APS one-way delay, with $\lambda$ referring to the central wavelength of the transmitted band. The approximated formulation of the equivalent atmospheric delay expressed in meters for almost straight paths is [7]:

$$d_{atm,p}(i) = 10^{-6} \int_{L_p} N(\vec{r}(l), i) dl$$

(3)

where $N$ is the refractivity index of the atmosphere. It’s related to the index of refraction $n$ through the equation $N = 10^6 \cdot (n - 1)$ and it’s a function of the space $\vec{r}$ and the time of $i^{th}$ image acquisition. Expression (3) states that the delay for the $p^{th}$ target results from the integration of the refractivity function along the ray path $L_p$ from the radar to the target. The refractivity model proposed in [8] is taken as reference in our analysis. Its expression is:

$$N = N(P, T, H) = N_{dry} + N_{wet} =$$

$$77.6 \frac{P_d}{T} + \left( 71.7 + \frac{3.744 \times 10^5}{T} \right) \frac{e}{T}$$

(4)

where two components are identified: a dry (or hydrostatic) component $N_{dry}$, related to the partial pressure of dry gases $P_d$, and a wet component $N_{wet}$, dependent on the partial pressure of water vapour $e$. The pressures $P$, $P_d$, and $e$, linked by the relationship $P_d = P - e$, are expressed in mbar, the temperature $T$ is expressed in $K$ and the relative humidity in percentual points ($\%$). The water vapour pressure $e$ can be computed using the Magnus-Teten formula in [9]. Though the dry component is the larger of the two, the wet refractivity is the most problematic one, as it presents the strongest fluctuations.
The delay statistics were extrapolated from ground-based devices operating in both Ku and X band and from meteo data collected by accessible weather stations. With concern to the GB-RADAR data, it must be specified that the analysis was carried out on strong and stable targets and that the phase instabilities (due e.g. to thermal drifts [3],[4]) on the longer-term acquisitions were compensated by means of internal calibration schemes. Thus the assumption: 

\[ \angle y_p(i_2) - \angle y_p(i_1) \approx \frac{4\pi}{\lambda} (d_{atm,p}(i_2) - d_{atm,p}(i_1)) \]  

should hold.

The variograms in Fig. 1a refer to very short-time statistics (milliseconds to seconds) extracted from the measured displacement of near-range targets during different real-aperture radar campaigns (the short distances are due to the rapid worsening of the radar cross-range resolution). Acquisitions were carried out in both the Ku and X bands showing no dependency on the frequency. Most importantly, notice that even on very short intervals the APS fluctuations, which conform to a fractal behaviour according to the Kolmogorov theory [7], represent the major phase disturbance. The latter statement can be evinced from the fact that the curve nugget, supposedly related to the thermal noise, is very low compared to the their scale, hence being in agreement with (5).

The long term statistics in the Fig. 1b are derived from both simulated displacements from meteo data and real displacements measured by the synthetic aperture GB-RADAR in the test campaign illustrated in section V. The very first part of the curves (up to a few hours) agrees to a fractal behaviour as expected, while in the remaining part the statistics become conditioned by the daily oscillating patterns of the meteo parameters. According to the six-months meteo database (black curve), the sill of the variogram is reached in 1-5 days period on average; notice however that particular realizations could require more than a week, and that as a consequence delays within a few days baseline cannot be safely assumed independent. Furthermore, the meteo data referring to the experiment week (red and green curves) show that, without exhaustive information of the meteo conditions along the path (in order to correctly evaluate the integral in (3)) only a partial agreement with the radar data (blue curve) can be reached.

From a quantitative standpoint the variograms show that a 570 m range target yields on average a 50 mm² APS variance, although larger values such as 5 cm² can occur in unfortunate conditions. The necessity of a proper compensation step is then straightforward, though the choice on the technique more suited to the scenario is not always banal. The compensation problem can be approached by means of three different techniques: the most robust one is represented by the DInSAR technique based on the presence of motionless targets, a.k.a. Ground Control Points (GCP) ([4],[2],[5]) in the scene. Differently, the PS technique discussed in [6] discriminates the APS from target displacement by assuming their statistical independence. However from Fig. 1b it becomes evident that such method would be ineffective on the short revisiting intervals of our experiment. The last approach consists in the exploitation of the available weather data collected nearby the experiment scene. As pointed out by our previous analysis and by other authors’ works (see [3] and [5]), this technique can be limited by both inaccuracies in the collected measures, due e.g. to unorthodox positioning of the weather stations, and by spatial heterogeneities caused by the nature of the terrain and by the action of the wind [10].

An attempt was then made to assess the wind impact on the measured phases through a brief analysis upon three representative stable targets at 232 m, 570 m and 815 m in the Bolzano experiment. The delay histories of the targets were detrended by applying to the data a lowpass filter with window length of 40 minutes. The phase residuals of such processing were divided into two datasets according to the mean wind speed in each time window. A threshold of 0.5 km/h on the wind speed leads to the variograms in Fig. 2a. Although the wind conditions were on the whole rather mild an average 1.5 increase factor can be read in the plotted trends due to the wind action. Also, in Fig. 2b the relationship between the APS fluctuation, measured on a stable GCP, and the wind speed is represented, yielding a 0.57 correlation coefficient: notice that not always high wind speed implies fluctuations in the delay. According to such results a proper handling of the wind information could help in further improving the compensation procedure, e.g. by removing from the dataset the windy images.
Fig. 3. Diagram for the determination of the calibration parameters. The humidity tuning is performed by means of a linear transformation; the new humidity is substituted to measured humidity in the refractivity model described by eq. (4). The two best candidates $\hat{\alpha}$ and $\hat{\beta}$ are elected by maximizing the overall coherence for the group $\Omega$ of stable targets (Ground Control Points). It has to be noticed that a single steady target is sufficient for carrying out the procedure.

IV. MODEL-BASED APPROACH

The meteo-based approach here proposed aims to account for slow-varying atmospheric heterogeneities, while still relying on the meteo model described in section II. A bias in the refractivity measured by the meteo station from the average refractivity of the scene represents indeed a common situation, mostly attributable to the water vapour fluctuations [7]. A calibration step on humidity was therefore conceived to tune the refractivity to its presumed average values, by exploiting the known GCPs at farther ranges. We wish to emphasize the fact that the method operates exclusively on the meteo data, not on the delay formulas, thus being able to preserve a physical consistency; hence the name of the technique 'Model-Based' compensation. The procedure consists of a rather harsh but yet effective first order tuning on humidity:

$$H_{\text{cal}}(\alpha, \beta, i) = \alpha H(i) + \beta$$  (6)

where $H$ is the measured humidity. The space of the parameters $\alpha$ and $\beta$ is explored through an exhaustive search: calibrated humidity $H_{\text{cal}}$ is computed for all the $(\alpha, \beta)$ pairs and the associated delay is evaluated through (4) and (3), the latter being substituted by the approximated expression convenient to the data at disposal, e.g the linear delay in (8) for the Bolzano campaign. The best candidates $\hat{\alpha}$ and $\hat{\beta}$ are then chosen by the algorithm by maximizing the average coherence of the group of targets $\Omega$ [11]. The coherence of the p-th target $C_p$ computed on $N_i$ images is defined as:

$$C(p) = \frac{1}{N_i} \sum_{n=1}^{N_i} \exp(j\epsilon_p(n))$$  (7)

where the phase $\epsilon_p$ represents, with reference to ((1)), the residual $\epsilon_p = \ell y_p - \hat{\phi}_{\text{atm},p}$, with $\hat{\phi}_{\text{atm}}$ being the estimated atmospheric phase delay, function of $\alpha$ and $\beta$. The targets pointed by $\Omega$ are the known steady targets (GCPs); to this end, it must be evidenced that, in the case of the simplest but common scenario represented by a single meteo station under the hypothesis of uniform atmosphere, the procedure needs only one GCP. A scheme of the procedure is reported in Fig. 3: the number of images $N_i$ determines the computational cost of the procedure and the robustness of the $\alpha$ and $\beta$ estimates. Acceptable interval lengths should be in the order of a few days at least, since we want to correct systematic humidity variations, usually showing on a daily basis; though, we have yet to assess how often the calibration procedure should be reiterated with reference to long time campaigns. We stress then the fact that, whereas other techniques ([4],[5]) require to estimate one or more model parameters for every image, our technique needs only two parameters for each meteo station dataset, updated on a long-time basis: e.g. in our test campaign (see next section) a single estimate of $\alpha$ and $\beta$ was enough for the whole week sequence. Furthermore, the procedure safely operates on the wrapped phases: this represents an advantage when compared to techniques based on the radar data alone, implicitly demanding a correct unwrapping procedure. This latter can indeed be troublesome if the PS distribution is inadequate (e.g. with holes along range) and the frequency is very high (such as the Ku-band used in our tests).

V. BOLZANO TEST CAMPAIGN

A. Test Site Description

As mentioned throughout the paper the analysis has been carried out on the experimental data collected in Bolzano (Italy), where a GB-SAR device (the IBIS-L) constantly monitored the scene during the time from 15 to 22 June 2008.
The device works in Ku band with a central wavelength of about 1.8 cm and is able to achieve a range resolution of 0.5 m and a maximum cross-range resolution of about 4.5 mrad. The scene is illuminated with a revisiting interval of about 8 minutes; as a result a dataset of about 1500 synthetic images was produced during this test campaign. Since the scene was not fully accessible, which is indeed a common case, only this single weather station close to the radar could be exploited. The measures collected by the station, and reported in Fig. 4, picture a scenario with strong fluctuations in temperature and humidity, characterized by rather mild wind conditions; it must then be specified that no precipitations occurred during the acquisitions. The geographic settings consist of an almost flat inhabited terrain in the foreground (first 600 m circa) just underneath a mountainside which extends up to a range of about 1200 m. In Fig. 5 the picture of the instrument view together with the amplitude map of the targets in the scene is shown. Since the scene had to rely on a single meteo dataset, we decided to depend on a very coarse yet reasonable (particularly for short distances) approximation: i.e. refractivity has been assumed uniform with respect to space, as hypothesized also in [5]. The generic delay in (3) becomes:

$$d_{atm,p}(i) = 10^{-6} \times N(0, i) \cdot \rho_p.$$ (8)

More complicated atmospheric models, such as the ones based on vertical profiles for pressure, temperature and humidity, were also considered, but their implementation didn’t bring any significant improvement.

The analysis was carried out on a limited group of 1025 scatterers chosen as the most stable targets according to the PS dispersion index [6]. By means of other monitoring techniques, all the relevant geographic features in the scene are known to be motionless; consequently the deviation of the estimated target displacement from a flat trend will serve as figure of merit to assess the approach performance. The latter information would certainly be considered a fundamental asset for a GCP compensation such as [5] (representing the reference option), since lots of targets could be exploited. Though, if we had to approach the case without a-priori information, except for a few fixed scatterers, and thus we could not exclude the possibility of large-scale deformations, the application of the aforementioned technique could be troublesome. The APS ramps estimated from only a few spaced GCPs could in fact be affected by phase ambiguities, in particular with reference to noisy images, due to the very high frequency. Differently, a compensation approach based on the meteo data, presumably yielding less accurate results, can be considered more robust with respect of this latter issue.

Initially, APS compensation was attempted without resorting to the calibration technique: the resulting interferometric phases (with respect to the first image chosen as master) are shown in center panels in Fig. 6. The panels convey that a regular component characterized by periodic fluctuations can be identified in the residual’s behaviour. By simply taking a look at both the residual and humidity curves, a close relationship between these two data appears evident. Therefore, as the statistics in Fig. 1 already predicted, it’s safe to state that the proposed delay model fails to completely remove from the data the dependence from humidity.

### B. Calibration Results

The calibration procedure discussed in section IV was then applied to the data by choosing a single GCP: a known fixed target at 570 m range. It can be noticed from Fig. 7 that the calibration effects on humidity were indeed a magnification of its fluctuations. Such a model refinement brought visible improvements (see the residuals in Fig. 6 right panels) on middle-range targets, as expected, but was nonetheless capable of improving near and far-range targets as well, suggesting that the atmosphere spatial correlation during the whole experiment
duration was good. However, critical time intervals still exist, especially around mid-day, when temperature is very high (as a consequence the tolerance on meteo errors is lower) and wind typically blows stronger (see analysis in section III).

An image pre-selection step was therefore introduced before the calibration in order to exclude from the dataset the potentially turbulent images basing on the aforementioned criteria. Two conditions were demanded: 1) an average wind speed (evaluated on a 40 minutes window) lower than the 0.5 km/h fixed threshold; 2) night-time acquisition (00:00 to 06:00). The results of such pre-filtering are shown in Fig. 8 by means of the residual of the GCP used as reference for the calibration. A comparison with the previously computed residuals reveals that a further improvement is achieved. The latter qualitative impression conform to the analysis in Fig. 9, where coherence is proposed as an effective figure of merit to quantitatively evaluate the compensation performance. It must be noticed that, whereas the refinement steps are able to yield a sensible coherence increase on middle-range targets up to 600 m, the results on the most distant targets still can’t be considered acceptable for a robust displacement estimation: the reasons have to be attributed to both to inhomogeneities in the troposphere and a lower SNR.

VI. CONCLUSIONS

The statistical analysis on the APS phenomenon confirmed the importance of a proper compensation process in order to reduce the heavy fluctuations affecting the data. An approach based on the refinement of the meteo delay model by means of a humidity calibration was then proposed. The approach requires the estimate of only a couple of parameters for an interval of days, thus it is quite robust. Moreover, it is not affected by wrapping, a sensible problem in ku-band. On the other side, it is not as accurate as a compensation made by a set of GCP distributed all over the scene. Its application to the Bolzano 8-days dataset could reduce the APS fluctuations to less than 2 mm for targets up to approximatively 500-600 m. A wiser selection of the image dataset (supposedly the least turbulent) based on wind and acquisition time criteria, allowed then a further 0.1 point coherence improvement.

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REFERENCES


Fig. 7. Results of the calibration procedure performed on a GCP at 570 m range. (Left) Figure of merit (target coherence) in the (α,β) domain and (right) difference between the measured humidity and the one calibrated according to the α,β best candidates.

Fig. 8. Residual example for a GCP used as reference for calibration after the compensation: the improvements achieved with calibration are evident, though critical zones still exist. The further dataset reduction (blue curve) through image pre-filtering is able to cut out most of the more turbulent areas.

Fig. 9. Coherence evaluated over the whole sequence (8 days) before compensation (blue), after APS removal without humidity calibration (magenta) and with calibration either without (green) or with (blue) image pre-selection.