Fig. 3. Time series of precipitable water vapor and cloud liquid for the five-day period from November 27 to 31, 1992, Porto Santo Island, Portugal.

TABLE II
POWER LAW INDEX AS A FUNCTION OF LAG INTERVAL FOR TWO TIME PERIODS DURING OBSERVATIONS AT PORTO SANTO ISLAND. THE COEFFICIENT OF VARIATION FOR PRECIPITABLE WATER VAPOR WAS 16.36% FOR MAY 27–31, DATA COMPARED TO 8.99% FOR THE JANUARY 14–18 DATA

Lag Interval (s)	Power Law Index	
	14–18 January 1993	27–31 May 1993
1800–28800	0.707	1.248
3600–28800	0.708	1.249
7200–28800	0.668	1.239

be caused by large variations in water vapor, which sometimes occur during frontal passages. The observations suggest that values of the index larger than those predicted by the model may also be caused by the presence of liquid water in clouds. Findings similar to the Porto Santo results were found for ten data sets with durations ranging from two to ten days, observed on the western coast of Sweden [6].

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An Analysis of the Interferometric Characteristics of Anthropogenic Features

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Abstract—A study of the interferometric characteristics of manmade features is presented. Tests for the assessment of their phase stability are applied for two case studies. The results indicate that small features show spatially homogeneous phase information in a single interferogram and that this information remains stable also in time even at the level of single pixels.

Index Terms—Differential SAR interferometry, manmade features.

I. INTRODUCTION

Differential SAR Interferometry (D-INSAR) has provided a valuable tool for estimating terrain deformations. This particular application of the INSAR technique, however, requires a "repeat pass" configuration (i.e., the SAR system has to be flown over the area at two different times), and this usually causes "temporal decorrelation" between the two images to occur. In general, most areas are almost completely decorrelated after a couple of months. Slow deformations such as those caused by land subsidence, therefore fall outside the range of applicability of this technique. For the same reasons, the long term monitoring of hazardous areas, which are for example, subject to frequent seismic activity, is also only partially feasible.

Despite the presence of heavy decorrelation, however, interferograms taken over several years still retain some information. This information is backscattered mainly from manmade features such as buildings, bridges, railways, and roads. These features are not likely to change their structure or composition much in the course of time and therefore, one could reasonably expect their information to be particularly "resistant" to temporal decorrelation. Indeed, an interferometric image of a highly urbanized area spanning one or more years usually shows up as a completely decorrelated image dotted with what is still strong, almost point-like information, derived mostly from these anthropogenic features. The question that then arises is whether and how this remaining information can still be used to retrieve the deformations in the otherwise decorrelated area being examined. In fact, if the phase information from these objects is revealed to be reliable, then it would be possible to determine the relative height changes between these features, obtaining information about the ongoing deformations in spite of the general temporal decorrelation [3], [4].

This paper presents a study of the information derived from highly decorrelated interferograms. In order to understand whether the non-decorrelating features over long time scales still provide valid, though pointwise information, the interferometric characteristics of these features are analyzed over the course of time using a statistical approach on a database of interferograms ranging from a day up to almost four years of ERS data. After a brief description of the database of interferograms used at our test site in Section II, the tests performed are described (Section III). In Section IV, the results of these tests are presented in detail for a selection of the studied features. Finally, conclusions and recommendations for future work are given in Section V.

Manuscript received May 14, 1999; revised October 6, 1999.

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Publisher Item Identifier S 0196-2892(00)04137-1.

TABLE I
DATASET OF INTERFEROGRAMS USED. THE FOURTH COLUMN SHOWS THE
TIMESPAN IN TERMS OF DAYS AND THE FIFTH SHOWS THE SERIAL NUMBER
OF THE INTERFEROGRAM

master	slave	$B_{\text{perp}}(m)$	days	no
21-04-96	10-09-92	-46	1319	1
20-04-96	10-09-92	-115	1318	2
21-04-96	15-10-92	-57	1284	3
17-03-96	10-09-92	63	1284	4
20-04-96	15-10-92	-120	1283	5
16-03-96	10-09-92	52	1283	6
17-03-96	15-10-92	23	1249	7
16-03-96	15-10-92	25	1248	8
06-01-96	19-11-92	-74	1143	9
20-08-95	19-11-92	99	1004	10
19-08-95	19-11-92	37	1003	11
20-08-95	04-03-93	5	899	12
19-08-95	04-03-93	-82	898	13
04-11-93	11-02-96	-93	829	14
21-04-96	11-02-96	143	70	15
16-03-96	06-01-96	-129	70	16
20-04-96	11-02-96	76	69	17
16-03-96	21-04-96	79	36	18
17-03-96	21-04-96	77	35	19
16-03-96	20-04-96	145	35	20
16-03-96	17-03-96	24	1	21

II. DATA

The test site for this study is located in the north of the Netherlands. A database of interferograms of this site was generated following a particular procedure [2], which basically consisted of coregistering all the SLC images on an unique master before combining them with each other in interferograms. In this way, all of the database interferograms were computed on the same interpolation grid, and a given pixel came to represent in each of them exactly the same area. This is particularly important in our case, since we are interested in the information contained in anthropogenic features, which, due to the limited extension of one or just a few pixels, has to be localized with great accuracy in an interferogram. The characteristics of the set of 21 interferograms used are shown in Table I. The products used for the tests were coherence and phase images in which both the multilooking window and the coherence estimation window were of 2×10 pixels.

III. THE METHOD

In order to assess the interferometric characteristics of anthropogenic features, we considered, for our test site, both single objects and a collection of them (i.e., a complex of buildings or a city). In the following paragraphs, we will show the results of our analysis for a single feature, namely a road, and for a collection of sparse objects in a bigger area comprising an entire city.

The stability in time of the anthropogenic features was analyzed by applying the differential technique [1] on a pixel-by-pixel basis and applying different tests to the resulting differential phases. The procedure and the meaning of each test, in terms of the stability study, are illustrated in the next subsections. As for the computation of the differential phases, the following procedure was applied.

First of all, we isolated the same feature or area of interest in each interferogram, and we considered the set of all its pixels that had coherence above a certain fixed threshold $\Gamma_{\min}$. We worked with coherence thresholds from 0.5 up to 0.8. Pixels with coherence < 0.5 were not considered because the phase at that level is very noisy and also because the effects of the bias in the coherence estimation are not negligible. As

for the upper limit, coherence thresholds higher than 0.8 resulted usually in a number of selected pixels too poor for a statistical approach to be applied.

For a certain $\Gamma_{\min}$ therefore, a set of pixels S_i with their coherence and phase values was associated with each interferogram IF_i . Subsequently, one of the interferograms, IF_r , was taken as the reference interferogram for the topography extraction (i.e., its corresponding set of selected pixels S_r was taken as the reference for the comparison with the sets of pixels of the other interferograms). Each set S_i (with $i \neq r$) was in turn compared with S_r , and for each pixel belonging to both the sets, the differential phase value was computed by rescaling and subtracting from the phase value of the pixel itself in IF_i the corresponding value in IF_r [2].

Notice that all the used interferograms had baselines short enough to assume that the interferometric signal did not contain a significant topographic component (the maximum height difference in the area is less than 11 m). Only interferometric signals originating from deformations is therefore assumed to be detectable. Moreover, due to the slow rate of subsidence occurring in the area, the expected deformation on the considered time intervals would result in less than one fringe. The absence of fringes causes the interferometric phase to be already unwrapped, so in our case, phase unwrapping was not necessary. Of course, phase unwrapping must always be performed before applying the differential method whenever the topography becomes significant with respect to the baseline and/or when the expected deformation amounts to more than one interferometric fringe. In these cases, it can be a rather challenging issue if the interferogram is decorrelated. However, attempts to solve this problem are already being made [5], [6].

Once the differential method had been applied, for every interferogram except for the reference one, we had a set of differential phases DF_i ($i = 1, \dots, 21, i \neq r$) determined on a pixel-by-pixel basis. To these phases, three tests were applied. The first test was aimed at evaluating the degree of "spatial homogeneity" of the set of pixels (i.e., how similar is, in a certain interferogram, the phase information coming from different pixels, under the assumption that they are subject to the same deformation). In the second test, we tried to estimate the "stability in time" of the phase of single pixels by comparing the phase values taken from the same pixel in the different interferograms of the series. Finally, the third test consists of a "correlation analysis" of the phase values of the set in different interferograms in order to identify the presence of a deformation signal within the set of pixels. This can also be seen as a check on the hypothesis, made for test number one, that all the pixels of the set are subject to the same deformations (i.e., the deformation is rigid).

It is worth observing here that the results from these tests are unlikely to be affected by atmospheric (e.g., clouds) or meteorological (e.g., rain) effects. On one side, in fact, most of such effects are expected to occur on a larger spatial scale than the considered features. In this case, the effect would be a bias of all the phase values of the feature. However, since we examine each feature separately and intrinsically, such a bias can neither be detectable, because we don't refer to a reference phase value external to the feature, nor can it have any effect on the results, which are based on measurements of standard deviations. On the other side, suppose the presence of atmospheric/meteorological effect of smaller scale than the scale of the feature does not make our results less valid. In fact, our purpose is to estimate the phase stability of a feature (e.g., the degree of phase noise present at the feature's scale). All effects, atmospheric and meteorological ones, but also incidental ones such as temporary modifications in the structure or backscattering centers of the feature acting at the feature's spatial scale, reveal themselves as noise in our analysis (since they are not likely to repeat themselves in two different interferograms, they cannot be considered signal). What we are interested in, however, is not to discriminate the sources of this

noise, but to estimate it in its totality, estimating in this way the stability of the feature itself.

A. "Homogeneity" of a Feature

The first test consisted in computing the standard deviation of the differential phases for each interferogram is

$$\sigma_i = \sqrt{\frac{\sum_{j=1}^{N_i} (d\phi_{ij} - \overline{d\phi_i})^2}{N_i - 1}} \quad \forall d\phi_{ij} \in \text{DF}_i, \quad j = 1 \dots N_i \quad (1)$$

where DF_i ($i = 1, \dots, 21, i \neq r$) is the set of differential phases $d\phi_{ij}$ of interferogram i having coherence above the chosen threshold. N_i is their number, and $\overline{d\phi_i}$ is their mean value.

This standard deviation gives a measure of the spatial homogeneity of the feature. In fact, if either the feature is not displaced in the vertical direction or, in presence of terrain deformations, is subject to a rigid movement, then all the pixels in which it is imaged will show more or less the same phase shift. The differential phases will therefore be very similar and their standard deviation will be small. Conversely, if the standard deviation of the differential phases is high, this means that pixels imaging different parts of the object are (at least partially) subject to different effects (i.e., the object carries spatially inhomogeneous information). A loss of homogeneity can be caused by incidental effects such as structural modifications of part of the feature, a partial change of the backscattering characteristics due, for example, to the presence of snow or water, or changes in the scattering centers. These effects could add noise to the differential phases of a feature, causing the standard deviation to increase. However, a high standard deviation could also be caused by a true deformation affecting different parts of the object to a different degree, which means that the feature has undergone an intrinsic deformation. As we will show, we can discriminate between the two cases by comparing the differential phases obtained in different interferograms, using the fact that, while incidental effects are unlikely to be the same in different interferograms, a true deformation signal would show up the same in interferograms ranging over the same period of time.

B. Phase Stability of a Feature in Terms of Time

Instead of computing the standard deviation of the differential phases with the spatial approach explained previously (i.e., examining all the pixels in each interferogram), one can use a temporal approach (i.e., by examining each pixel in all the interferograms). This is what was done in the second test where, by comparing the differential phase values assumed by the same pixel in different interferograms, we tried to give an estimate of the "stability in time" of the pixel itself.

If we have a set of interferograms covering approximately the same time interval, then we can expect them to carry the same deformation information. This means that in each of these interferograms the phase of a certain pixel is shifted by the same quantity with respect to a certain "reference" phase value (in the sense of the zero phase of the considered interferogram, which is not to be confused with the reference interferogram). In such a case, the phase values of the pixel in all the interferograms would be the same, and their standard deviation would be zero. Analogously to the first test, a standard deviation also gives a measure of stability here, but while in the first case, a sample of different pixels in the same interferogram was considered, here the sample consisted of the phase values from the same pixel in the different interferograms, thus giving an estimate of the intrinsic phase stability over the course of time of that particular pixel.

Since we only had to consider interferograms close enough in time to each other to assume that they contain the same information, we only

considered with this test the long term interferograms, from 1 to 14. In each of the sets DF_i ($i = 1, \dots, 14$), we subtracted from all the differential phases their mean value

$$d\phi'_{ij} = d\phi_{ij} - \overline{d\phi_i} \quad \forall j = 1 \dots N_i \quad i = 1 \dots 14. \quad (2)$$

Each pixel was then searched for in all the sets DF'_i of new values $d\phi'_{ij}$ and, when the pixel was found in at least two sets¹, the standard deviation of its phase values was computed. If M is the total number of pixels occurring at least twice in the series, then to each pixel, the following standard deviation $\hat{\sigma}_k$ can be associated:

$$\hat{\sigma}_k = \sqrt{\frac{\sum_{p=1}^{L_k} (d\phi'_{pk} - \overline{d\phi'_k})^2}{L_k - 1}} \quad p = 1 \dots L_k, \quad k = 1 \dots M \quad (3)$$

where L_k is the number of occurrences of the k -th pixel, and $\overline{d\phi'_k}$ is the mean of the L_k values taken by the pixel.

Notice that the meaning of $\hat{\sigma}$ is completely different from the meaning of the standard deviation computed in the previous test, σ , and the results of the two tests are indeed independent from each other. So a high σ can be the result of either incidental effects or a true internal vertical deformation of the feature. In this latter case, however, each a single pixel could still be very stable over the course of time and have therefore a small $\hat{\sigma}$, maintaining more or less the same shift with respect to the mean value in each interferogram. The fact that this shift is different for different pixels will cause a deformation pattern, very similar in all the considered interferograms, which can be detected by means of a correlation analysis.

C. Correlation Analysis

The standard deviation determined in the first test related to the spatial homogeneity of a feature is always different from zero. This is caused by what we can call, in the context of this research, "noise," and which comprises all effects other than real deformation such as, for example, meteorological effects and occasional changes in the feature itself. However, a high standard deviation could also indicate the presence of a signal due to a deformation that occurred intrinsically in the feature. The suspect of an intrinsic deformation can be enforced by a high stability in time of most pixels of the feature, resulting from the second test. In order to check the presence of a deformation signal, we can therefore compare the different sets with each other by computing their correlation coefficient. As in the second test, we want to consider only the sets from those interferograms that are supposed to contain the same deformation information. If N_i is the number of sets DF considered, then for each possible pair of DF 's, the correlation coefficient Cr_{ij} is computed by using their common pixels

$$Cr_{ij} = \text{corr}(\text{DF}_i \cap \text{DF}_j) \quad i, j = 1 \dots N_i \quad j \neq i \quad j, i \neq r. \quad (4)$$

It is clear that a generally high correlation coefficient between all the interferograms will indicate the presence of a common deformation signal. Conversely, all the effects other than deformation are not likely to occur in the same way in all the interferograms, so we can expect that their presence will cause a decrease in the value of the correlation coefficient.

¹We are aware of the poor significance of a standard deviation estimation based on only two measurements. However, at this stage, we were only interested in excluding pixels with only one value, which would give a fictitious zero standard deviation and would be erroneously classified as perfectly stable in time.

Fig. 1. Detail of a coherence image showing (indicated by means of an arrow) the road being examined.

IV. RESULTS FOR SELECTED FEATURES

A. Case I: A "Road"

The first object to be examined shows up in coherence images as a highly coherent linear feature the size of 1 pixel in the range direction and extending in the azimuth direction. Its coherence image for one of the long term interferograms is shown in Fig. 1. It is localized in correspondence of a road, and we will refer to it as "road," although it cannot be stated where exactly the signal is reflected from. We actually suspect that the backscattering comes not from the road itself, but from its edge or from a structure located at its edge such as a guard rail. We would like to stress, however, that it is not relevant in this context, as this kind of feature, which is significant as such, gives a highly coherent signal. The only relevant factor is whether or not such a high coherence corresponds to phase stability in time. First of all, the spatial homogeneity of the road was checked by computing the standard deviations σ in each interferogram. The values obtained for different values of $\Gamma_{\min}$ are shown in Fig. 2, together with the corresponding number of pixels considered for the computation. It can be observed that, with the exception of IF's 3 and 13, where passing from a $\Gamma_{\min}$ of 0.7 to 0.8 causes an increment in the standard deviation, in all interferograms, σ becomes smaller as $\Gamma_{\min}$ increases. This is to be expected if one assumes that having a higher coherence implies having less noisy, and therefore more reliable, information. However, the improvement in the standard deviation with increasing coherence thresholds varies greatly from one interferogram to another. A difference in standard deviation values between long and short term interferograms is also visible in Fig. 2. Interferograms ranging from one day (number 21) to 70 days (number 15) have a σ at the level of 0.4 radians even for $\Gamma_{\min}$ 0.5, while in long term interferograms (from 1 over 1319 days, up to 14 over 829 days), the standard deviation is in most cases higher and varies more strongly with different thresholds. As we shall see later on, there is a possible explanation for this difference between short and long term interferograms. There are still long term interferograms showing σ 's at the level of 0.4 to 0.6 radians for $\Gamma_{\min}$ of 0.7 and 0.8. See for example, 1, 2, 4, and 6. Notice also that these same interferograms show smaller standard deviations than other (long term) interferograms spanning shorter time intervals, such as those from 9 to 14. This suggests that σ does not depend on the considered time interval.

Fig. 2 shows the number of pixels used for the computation of the standard deviations. The long term interferograms show about the same number of pixels for each considered $\Gamma_{\min}$, while the number

Fig. 2. Standard deviation σ for the road and number of pixels used (coherence threshold $\Gamma_{\min}$: circles = 0.5, triangles = 0.6, squares = 0.7, diamonds = 0.8).

of highly coherent pixels changes clearly as one progresses from long to short term interferograms. The only exception is 17, which has a lower number of highly coherent pixels. An analysis of the coherence image showed that this interferogram indeed suffers from a heavier decorrelation than the other short term ones, and we strongly suspect that this was because of the presence of snow at the time when one image was taken.

Let us now take a closer look at the differential phases from which the σ 's have been computed. Fig. 3 shows the differential phases along the road in two of the considered interferograms, namely, a tandem interferogram (above) and a long term one (below). The x -axis represents the line coordinate of the pixels (in the multilooked products, the road is a vertical line of constant range coordinates), and the y -axis is the differential phase value in radians. Note that, since we do not have a reference phase, the differential phase values in themselves do not have a real significance. Our purpose is only to visualize the spread of the values along the road.

In the first case, the phase along the road is rather constant, as already indicated by the low values of σ in Fig. 2, while in the case of the long term interferogram, the phase values are more dispersed, which corresponds again with the higher standard deviations observed in Fig. 2. However, what is remarkable is that this pattern is very much the same in the first ten interferograms of the series. This might suggest that a deterministic signal is present in the differential phase. In other words, the road *has changed* in the course of time, and the pattern actually represents the deformation that has occurred. Note that this deformation is of about 0.5 cm, which is plausible for a road in the space of a few years' time. The similarities can easily be seen if the differential phases of two interferograms are placed in the same plot, as is done in Fig. 4. They are confirmed also by the results of the computation of the correlation coefficient for all the possible pairs of the 14 long term interferograms, which showed a particularly strong agreement among the first eight differential interferograms. The correlation value for the case shown in Fig. 4 was 0.98. Since the road has undergone an intrinsic deformation, the standard deviation σ cannot be considered as a measure of its phase stability in space with respect to all the possible incidental effects. However, by looking at the differential phases, the road appears to be divided into three sections, as indicated in Fig. 4, and while the third section consists of few pixels and varies rather greatly from one

Fig. 3. Differential phases along the road in two cases.

Fig. 4. Comparison of the differential phase values of two interferograms. In order to compare the values, the mean was subtracted in each interferogram. The vertical lines in the plot delimit the three sections in which the road can be divided.

interferogram to the other, the first two parts remain quite similar in the ten longest term interferograms. In particular, along the first section, the phase values seem to be rather uniform, suggesting that within this part of the road no intrinsic deformation occurred. We decided therefore to repeat the test on the spatial homogeneity by considering only this section. In Fig. 5, the standard deviations σ of the first section are plotted together with the number of considered pixels. As one can see, for this section, the values are lower than when we consider the whole road in most cases. Except for those cases where too few pixels were selected (i.e., 14 and 17 for $\Gamma_{\min} = 0.8$ and 14 also for $\Gamma_{\min} = 0.7$), and which therefore should not be considered, the other interferogram σ drops well below 0.4 radians already at $\Gamma_{\min} = 0.6$, and in some cases, this happens even with $\Gamma_{\min} = 0.5$.

Finally, we tried to estimate the phase stability in terms of time of single pixels, as described in Section III-B. For this purpose, we considered the long term interferograms from 1 to 8, which, as also indicated from the correlation values, showed the most similarities and thus, can be assumed to contain the same deformation information. The coherence threshold for the pixels selection was set at $\Gamma_{\min} = 0.5$, and in each interferogram, we took the mean value as a reference (zero) value for the phases. For every pixel occurring at least twice with coherence > 0.5 in the eight interferograms, the standard deviations $\hat{\sigma}$ were computed. These are shown in Fig. 6, together with the corresponding number of occurrences for each considered pixel. As one can see, there are several pixels occurring in all the eight long term interferograms

Fig. 5. Standard deviations σ for the first section of the road and number of used pixels ($\Gamma_{\min}$: circles = 0.5, triangles = 0.6, squares = 0.7, diamonds = 0.8). Fig. 6. Standard deviations per pixel $\hat{\sigma}$ computed on the set of the first eight interferograms and number of times that each pixel occurs in the set. $\Gamma_{\min}$ is here 0.5.

and showing a remarkable temporal stability, with $\hat{\sigma}$ ranging from 0.2 to 0.4 radians.

B. Case II: A City

Unlike the first case, where a single feature was considered, we took as a second case study a city (i.e., a collection of anthropogenic targets). These are mostly buildings, covering only one or a few pixels in the images; moreover, they are spread over a large area, of about 4.8×6.8 km. The standard deviations per interferogram σ are shown in Fig. 7. The values are definitely larger than in the previous case, ranging from approximately 0.55 up to 1.25 radians in the first 17 interferograms of the series. Only in the shortest time intervals, from 35 days, do their values become smaller. Since interferograms 15 to 17 relate to short intervals, this seems also to indicate that in this case, short term interferograms do not necessarily lead to lower σ 's than long term

Fig. 7. Standard deviation per interferogram σ for the city and number of pixels used ($\Gamma_{\min}$: circles = 0.5, triangles = 0.6, squares = 0.7, diamonds = 0.8).

Fig. 8. Standard deviation per each pixel $\hat{\sigma}$ for the city in the first 14 interferograms for $\Gamma_{\min} = 0.5$.

ones. Moreover, the value of the standard deviations does not seem to be related to the value of $\Gamma_{\min}$, as in the other case. For example, for interferograms 15 and 17, a threshold $\Gamma_{\min} = 0.8$ gives worse results than $\Gamma_{\min} = 0.5$. Notice finally that the number of selected pixels is much larger than in the other case and drops more heavily (to about half of the pixels) when $\Gamma_{\min}$ is increased by 0.1.

The fact that the σ 's are generally higher than in the previous case is probably due to the fact that we do not have here one large, unique feature, but a collection of smaller ones. Of course, these features are all different and each one can be subject in a different way to all the possible effects that could cause a bias in its phase value without affecting

Fig. 9. Standard deviation per interferogram σ for the city and number of pixels used only for pixels with $\hat{\sigma} < 0.4$ ($\Gamma_{\min}$: circles = 0.5, triangles = 0.6, squares = 0.7, diamonds = 0.8).

the coherence. After all, the selected pixels do not belong physically to the same feature, so they are expected to behave less homogeneously.

Fig. 8 shows the standard deviations per pixels $\hat{\sigma}$ in the series of the first 14 interferograms for $\Gamma_{\min} = 0.5$. Unlike in the case of the road, most of these pixels only occur in a limited number of interferograms (up to six) with coherence above $\Gamma_{\min}$. The information thus originates in general from different scatterers in different interferograms or, in an equivalent way, the coherence of most scatterers oscillates around the value 0.5. This is also confirmed by the fact that, using a coherence threshold $\Gamma_{\min} = 0.6$, the number of pixels occurring at least twice in the long term interferograms, of which we could image the $\hat{\sigma}$ as in Fig. 8, was reduced to less than half (the image is not reproduced here for reasons of space). Since most pixels have a $\hat{\sigma}$ of less than 1 radian, it seems that a reasonable portion of them could still be considered stable at that level, and perhaps give lower standard deviations per interferograms. We therefore tried to improve the homogeneity in space by redetermining the σ 's for only the pixels with $\hat{\sigma} < 0.4$ rad. The resulting σ 's are shown in Fig. 9. The improvement with respect to the values computed by using all the pixels in Fig. 7 is clearly visible and ranges from 0.1 up to even 0.8 radians depending on the interferogram. The selection has considerably reduced the number of pixels which, however, apart from a couple of cases for $\Gamma_{\min} = 0.8$, is always large enough to justify the statistical approach. Finally, the correlation coefficient has been computed for all the possible combinations of the first 14 interferograms and for $\Gamma_{\min} = 0.5$. No particularly high correlation values were noticeable, which confirms the random character of the differential phases and thus the absence of a signal.

V. CONCLUSION

Manmade features were tested for their phase stability in space and in time on a pixel-by-pixel basis. For this purpose, the differential phases of the pixels, which constitute the image of a given feature, were considered. The standard deviation per interferogram of these values, called σ , was taken as a measure of the stability in space (i.e., the homogeneity) of the feature itself, according to the hypothesis of absence of internal deformation. For the two case studies presented here, namely a road and a city, values of σ ranging mostly from 0.6 to

1 radians were obtained. In the case of the road, however, the increase in σ was caused by the presence of a deformation signal within the road itself, a presence confirmed also by the high correlation between the phases in different interferograms. In this sense, the differential technique has demonstrated its aptness for the study of deformations even of single features. As for the city, it is reasonable to expect a more reduced homogeneity, since it is not a single object but a collection of objects and therefore, the chance is higher that some of them will be affected by different effects, causing a disturbance in their phase information. Finally, the stability over the course of time of each pixel of the feature has been tested, this time computing the standard deviation $\hat{\sigma}$ of the differential phase values taken by each pixel in the different interferograms. Again, in the case of the single feature, results were better than for the city, and most pixels turned out to be stable at the level (in terms of $\hat{\sigma}$) of up to 0.4 radians. The latter was finally taken as a limit for the selection of the most stable pixels, and with these, the σ of the city was computed again. The result was a remarkable improvement in the spatial homogeneity with respect to the case when all pixels were being used.

ACKNOWLEDGMENT

The author would like to thank R. Scharroo and P. Visser of DEOS, Delft, The Netherlands, for providing the ERS precise orbits.

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