

## MULTIBASELINE INTERFEROMETRIC SAR AT MILLIMETERWAVES TEST OF AN ALGORITHM ON REAL DATA AND A SYNTHETIC SCENE

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### ABSTRACT:

Interferometric Synthetic Aperture Radar has the capability to provide the user with the 3-D-Information of land surfaces. To gather data with high height estimation accuracy it is necessary to use a wide interferometric baseline or a high radar frequency. However the problem of resolving the phase ambiguity at smaller wavelengths is more critical than at longer wavelengths, as the unambiguous height interval is inversely proportional to the radar wavelength. To solve this shortcoming a multiple baseline approach can be used with a number of neighbouring horns and an increasing baselength going from narrow to wide. The narrowest, corresponding to adjacent horns, is then assumed to be unambiguous in phase. This initial interferogram is used as a starting point for the algorithm, which in the next step unwraps the interferogram with the next wider baseline using the coarse height information to solve the phase ambiguities. This process is repeated consecutively until the interferogram with highest precision is unwrapped. On the expense of this multi-channel-approach the algorithm is simple and robust, and even the amount of processing time is reduced considerably, compared to traditional methods. The multiple baseline approach is especially adequate for millimeterwave radars as antenna horns with relatively small aperture can be used while a sufficient 3-dB beamwidth is maintained.

The paper describes the multiple baseline algorithm and shows the results of tests on a synthetic area. The test objects are representative in size for generic buildings. Possibilities and limitations of this approach are discussed. The relevance for applications of millimeterwave InSAR as means for the extraction of characteristics of buildings is highlighted. Examples of digital elevation maps derived from measured data are shown.

### KURZFASSUNG:

Mit interferometrischem SAR können dreidimensionale Informationen über Landoberflächen gewonnen werden. Um Daten mit hoher Höhenschätzgenauigkeit gewinnen zu können, muss entweder eine große interferometrische Basis gewählt oder bei geringerer Basisbreite eine höhere Betriebsfrequenz verwendet werden. Bei höherer Radarfrequenz ist jedoch das Problem der Phasenfortsetzung schwieriger zu lösen, da das eindeutig bestimmbare Höhenintervall invers proportional zur Frequenz ist. Um diesen Nachteil auszugleichen, kann ein Multibasensansatz verwendet werden, der mehrere benachbarte Sende-/Empfangshörner mit zunehmender Basisbreite nutzt. Für die geringste Basisbreite sollte die Phasenbeziehung eindeutig sein. Das zugehörige Interferogramm wird als Ausgangsdatensatz für ein rekursives Verfahren genutzt, bei dem die Grobinformation des ungenaueren Interferogramms als Basis für das nächst feinere Interferogramm dient. Mit dem Nachteil des höheren Hardwareaufwandes ergibt sich hier ein sehr einfacher und dabei schnell arbeitender Ansatz für den Phasenfortsetzungsalgorithmus. Der Mehrbasensansatz ist besonders für den Millimeterwellenbereich geeignet, da hier Antennenhörner mit relativ geringer Apertur bereits eine ausreichende Bündelung bieten.

Der Beitrag beschreibt den Mehrbasenalgorithmus und zeigt Ergebnisse für eine generische Testszene. Die Bedeutung dieser Methode für die Bestimmung der Höhencharakteristik von Gebäuden wird besprochen. Vor- und Nachteile dieses Ansatzes werden diskutiert und Beispiele erläutert.

### 1. INTRODUCTION

Requirements for forces engaged in peacekeeping and anti-terror missions demand reconnaissance systems with all-weather capability delivering in-time information content. A solution to these requirements are lightweight SAR-Systems on-board of RPVs. For the realization of compact and robust

systems with all-weather capability, millimeterwave radars are the prime choice. In addition to the compactness of the millimetric hardware, for which even integrated subsystems on GaAs-basis are feasible, very simple and straight-forward signal-processing techniques can be used at millimeterwave frequencies. This is mainly due to three reasons (Boehmsdorff, S., 1989): The aperture length of the SAR is reduced by the

ratio of wavelengths at equal cross-range resolution, and allows lower requirements for the flight stability of the airborne platform. The amount of excessive backscattering at edges and corners of man made structures is much less due to a relatively higher geometric deviation of right angles and straightness of lines and a higher roughness of surfaces. Interferometric SAR at millimeterwave frequencies offers the additional advantage of small baselines for high height estimation accuracy. However the smaller wavelength leads also to a higher phase ambiguity, resulting in a much higher amount of sophistication for phase unwrapping at these radar bands.

To overcome this shortcoming, a hardware approach has been developed using multiple baselines to deliver interferograms at different height estimation precision ranging from low to high. This approach is adequate for millimeterwaves as those different baselines can be accommodated within small geometric dimensions. For classical radar bands this can not be achieved within dimensions typical for RPVs.

## 2.A MULTIPLE BASELINE APPROACH FOR MILLIMETERWAVE INTERFEROMETRIC SAR

### 2.1 Hardware Assembly

The millimeterwave radar system for which the algorithm has been developed (Boehmsdorff, S., 2001) is equipped with a multibaseline antenna consisting of an array of six horns followed by a cylindrical lens, which achieves the azimuthal beamforming. The antenna has a 3 dB beam width of  $3^\circ$  in azimuth and  $12^\circ$  in elevation. A photo of the antenna arrangement is shown in Fig 1. E1 – E4 denote the four receiving channels, S1 and S2 the two possible transmitting ports.

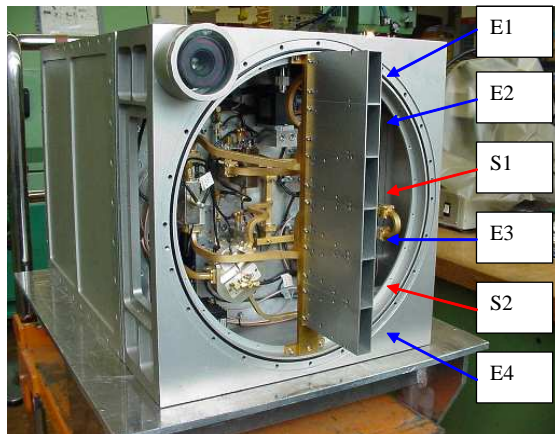


Figure 1: Radar Front - End with Multiple Baseline Antenna

From each receiver channel complex data are retrieved. Due to the geometry of the horn ensemble five independent interferograms can be extracted.

### 2.2 Basic Phase Unwrapping

The phase unwrapping method based upon this hardware approach needs at least one unambiguous interferogram, which is usually the one corresponding to the smallest baseline. In case that this one is not unambiguous, it is necessary to unwrap it with an algorithm based upon a different approach. This can

be a quite simple one like the Goldstein or Dipole algorithm [2], if the height variation of the imaged area doesn't exceed the unambiguous height dramatically. In order to start the further processing all available interferograms are stored and sorted according to their baselines. The full process is tested using a synthetic scene with a number of generic objects. This is described in the following.

## 3.DESCRPTION OF SYNTHETIC TEST AREA

The test area described here is an artificial data set, created by a program written in Matlab®. Its dimension is  $1000 \times 2000$  pixels, and it contains several sample objects of different heights and shapes. In particular there are seven generic objects to test the unwrapping algorithm and in addition two noise patches. All objects are located on a flat plane. A picture of the elevation model, which is described qualitatively in the following, is shown in Fig. 2.

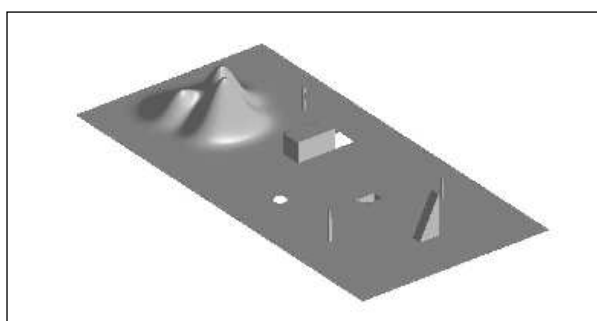


Figure 2: Elevation model of the test area. Noise patches are shown as white holes in the plane.

The first object at the upper left corner is a set of three mountains of Gaussian shape and different height and width neighbored by a round pillar. Below these there is a box, representing a man made object like a building, with a noise patch in the back simulating the shadow of the object. The next object is a round noise patch resembling a water surface where the backscattering tends to be of specular character and the phase appears noisy. Then a ramp is leading below the plane like a pit. Two rectangular pillars of different heights and an increasing ramp above a rectangular cross section complete the synthetic test area. For this test area the effectiveness of a new phase unwrapping technique, based upon an approach using more than two receiver channels at increasing interferometric basewidth will be evaluated.

## 4.DISCUSSION OF BASIC INTERFEROGRAMS

From this elevation model five interferograms were calculated for a baseline ratio of 1:2:3:4:5 relative to the first one. For the test it is assumed that the reference interferogram is unambiguous. All other interferograms are allowed to exhibit as many phase excursions as appropriate for the respective height. Due to the baseline ratios they are limited to five. In addition all simulated interferograms are corrupted with white noise of  $\pm 15^\circ$  to resemble a typical measured data set. The phase values corresponding to the ground-plane are allowed to exhibit an arbitrary offset relative to each other. The five interferograms are shown in Figs. 3-7. To localize the noise patches the pseudo correlation map is rather used. The pseudo correlation map (Ghiglia, D. C., 1998) can be used as a quality criterion when

the magnitudes of the complex values are unknown. It is defined by:

$$|z_{m,n}| = \frac{\sqrt{(\sum \cos \varphi_{i,j})^2 + (\sum \sin \varphi_{i,j})^2}}{k^2} \quad (1)$$

The two sums are evaluated in an interval of the dimension  $k \times k$  around each pixel  $(m,n)$ . The values of  $\varphi_{i,j}$  are the phase values of the interferograms. Therefore this quality map is always available, even if only the phase differences are known. Within the correlation map points of low correlation indicate areas where the phase is decorrelated. These regions are noisy patches, like shadow areas or any region which shows specular reflectance. As an example Fig. 8 depicts the pseudo correlation map for the interferogram with the widest baseline shown in Fig. 7.

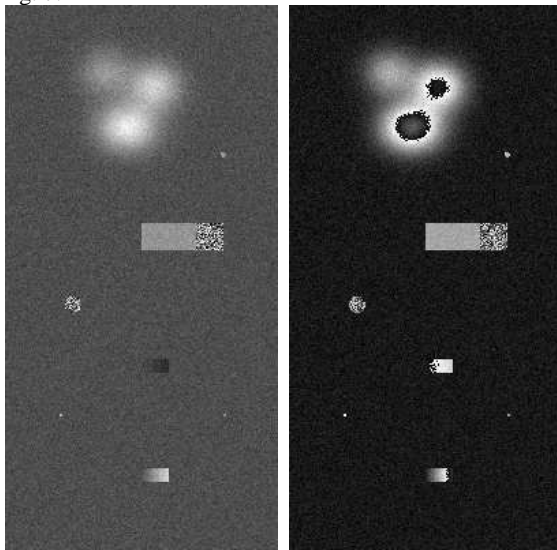


Figure 3: Interferogram, Baseline 1

Figure 4: as Fig. 3, Baseline 2

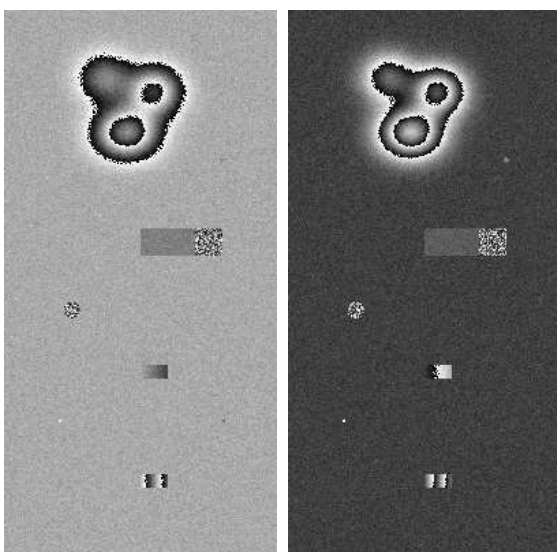


Figure 5: as Fig. 3, Baseline 3

Figure 6: as Fig. 3, Baseline 4

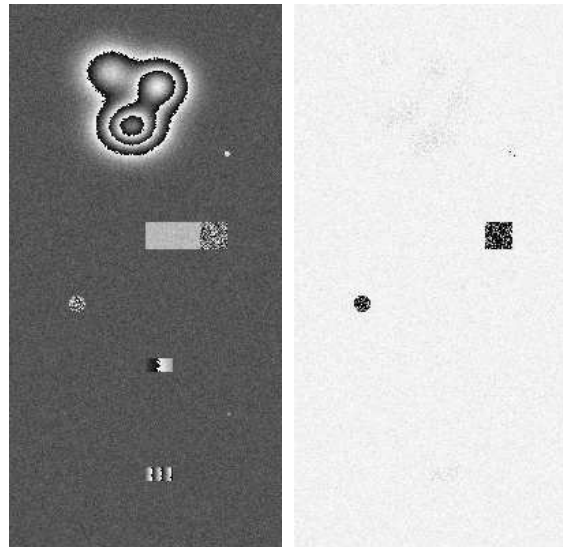


Figure 7: as Fig. 3, Baseline 5

Figure 8: Pseudo correlation map related to Fig. 7

The chart of Fig. 8 shows clearly the areas of low correlation within the noisy patches. In addition the limits of the box, the two pillars and the descending ramp are marked as areas of low correlation because of the considerable phase variation, although the phase within that limits is well defined. The border of the ascending ramp is marked with dashed lines which is due to the periodic correlation of the phase values (modulo  $2\pi$ ) while the phase values are increasing in comparison to that of the ground plane. Although the pseudo correlation map has the disadvantage of indicating steep terrain as low correlated it can be used as a tool to guide the phase unwrapping algorithm. In the example it serves to define areas where phase unwrapping is possible. After creating the interferograms at increasing baseline width it is possible to establish the unwrapping algorithm.

## 5. PHASE UNWRAPPING ALGORITHM FOR MULTIPLE BASELINE INSAR DATA

### 5.1 Description of the Process

As mentioned under 2.2 the algorithm needs at least one unambiguous interferogram as an initial starting point. It is postulated for the evaluation process, that the first interferogram, related to the narrowest baseline, is unambiguous. For further processing all interferograms are sorted according to their baselines. The unwrapping algorithm works iteratively using one interferogram after the other. From the preceding interferogram a look-up table is generated and used for unwrapping the next interferogram with higher interferometric base width where the phase is ambiguous but exhibits a higher precision. This is repeated until all interferograms are processed successively. It has to be pointed out, that unlike in the usual residues approach, no paths around ambiguous areas have to be searched to unwrap the phase. All undefined pixels within the resulting interferogram are strongly restricted to their location, and there is no error spread in the image plane. Errors that occur are mainly due to excessive phase noise. Due to the scaling of the successive interferograms which has to be done during the unwrapping process, the noise contributions are also scaled by the same ratio and therefore

erroneous pixels may occur. To solve this problem, the algorithm searches for suspicious isolated pixels within the resultant interferogram. For those pixels a test procedure determines if adding  $\pm 2\pi$  gives a better result matching them to the surrounding pixels. The flow chart of the unwrapping algorithm is given in Fig. 9.

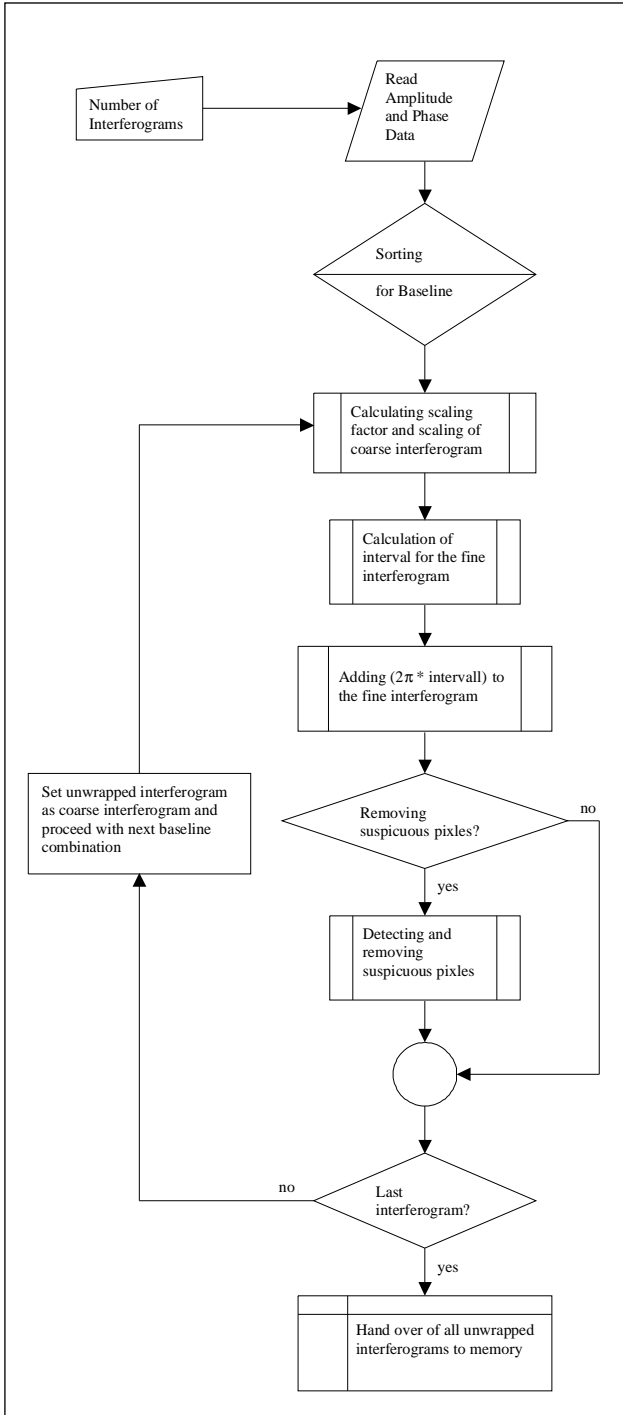


Figure 9: Flow chart of the unwrapping algorithm

Within all figures the gray scale is the same, where black represents  $-\pi$  and white  $\pi$ . The algorithm starts with the first channel combination and unwraps all following ones. To visualize the success of the coarse to fine unwrapping process Fig. 10 shows the raw phase as vertical profile related to the synthetic area and Fig. 11 the corresponding unwrapped phase. It can be seen that the algorithm leaves most values untouched except at those positions where the phase is wrapped around. It has to be pointed out, that the algorithm presented here works fully automatically after choosing the input parameters and provides the user with five interferograms of different quality that have no or only a few residues left outside the noisy patches of shadow areas.

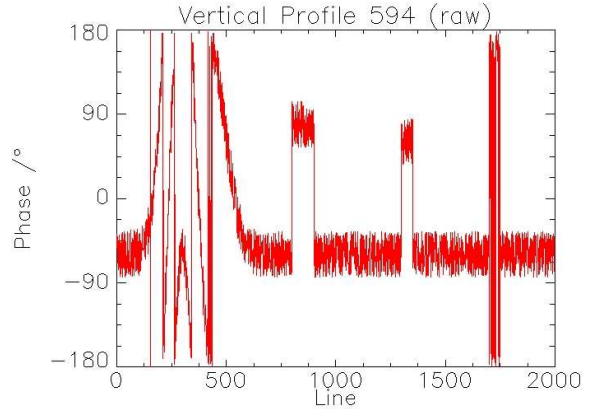


Figure 10: Vertical Profile of raw Phases

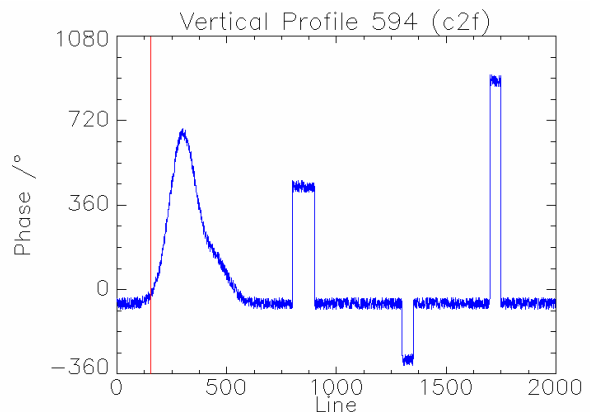


Figure 11: Vertical Profile gained by Coarse to Fine Process

### 5.2 Comparison with a Conventional Unwrapping Method

To demonstrate the advantage of the new coarse to fine unwrapping process (C2F) a conventional unwrapping method using residues has been applied to the model scene. Fig. 12 shows the comparison. It is obvious, that at those parts of the interferogram, where noise patches or even singular noise pixels appear the conventional method runs into problems and errors are spreading into the interferogram. To eliminate them a special treatment has to be done. The C2F-method does not suffer from such difficulties. As demonstrated under chapter 5.1 a vertical profile through the interferogram plane has been calculated and is shown in Fig. 13. It shows the difficulties for the Dipole method to cope with certain features of the

interferogram, namely holes in the plane and increasing ramps with multiple phase periods. Comparing the calculation time requirements it turns out, that the C2F Algorithm is about ten times faster than the conventional process.

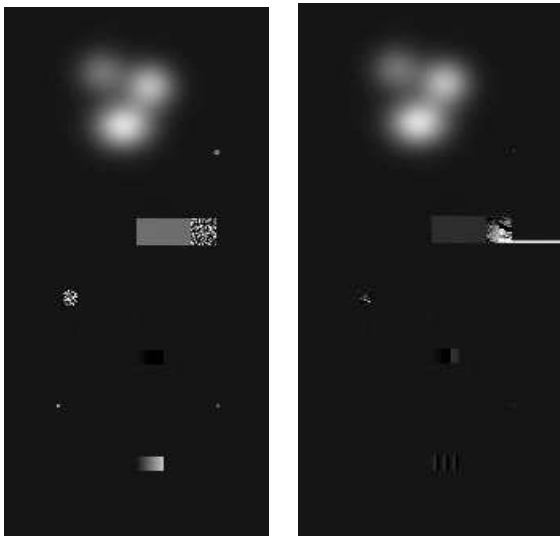


Figure 12: Comparison of Results of C2F-process and conventional Dipole Method

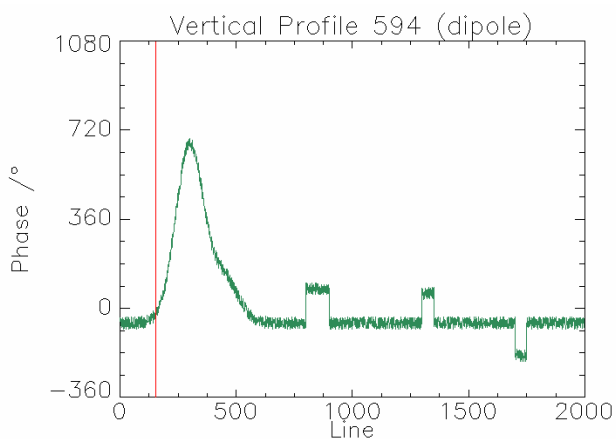


Figure 13: Vertical Profile gained by Dipole Method

Fig. 14 shows a section of the residue chart for the circular region incorporating phase noise contributions in comparison with the corresponding section of the way chart. The latter describes the path which may not be exceeded by the phase unwrapping process.

The example shows, that even with multiple folding of the interval  $[-\pi, \pi]$  the algorithm delivers correct values, as long as the interferogram is unambiguous. The method avoids a time consuming calculation of the adequate integration path with the expense of a higher amount of hardware. It has further to be pointed out, that there is no error continuation within the image plane as with residue based methods, and all erroneous values stay strictly limited to its vicinity.

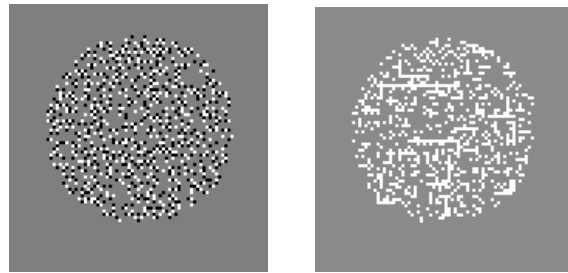


Figure 14: (left) Residue Chart, negative Values = white, positive Values = black, (right) Representation of the Way Chart, allowed Ways = grey, Not allowed Ways = white

## 6.SUMMARY

At mm-wave frequencies even with moderate baselines, i.e. in the order of 30 cm, a good height estimation is possible, which is appropriate to resolve the shape of man-made objects. On the other hand a severe disadvantage is the high height ambiguity due to the short phase repetition frequency at mm-wavelengths. So much emphasis has to be put into the phase-unwrapping algorithm. Appropriate for the possibility of small geometrical dimensions and ease of processing is the hardware approach of a multiple baseline antenna which makes the employment of the described coarse-to-fine algorithm possible. Because scaling is important for this process an appropriate ratio of consecutive baselines is essential. Good results can be achieved with a ratio of 5. Nevertheless the limitation of this algorithm is, that one initial unambiguous interferogram is necessary to start with. As the absolute phase variation in each unwrapped interferogram is constant, the relative phase variation becomes smaller within each of the consecutively unwrapped interferograms. The system and the algorithm presented here, is a suitable approach for mm-wave frequencies where the dimension of the multibaseline antenna itself does not exceed that of the sensor front-end.

## 7.REFERENCES

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