5.2 Analysis Groningen descending

The interferograms labeled as *Groningen descending* (gd) and their adjacent track (gdex) are situated in the northeast of the Netherlands, covering the Dutch provinces Groningen, Friesland, and Drenthe, and a part of Germany in the east. Just off shore, the *Frisian islands* mark the boundary between the *Wadden Sea* and the *North Sea*. The Wadden Sea is a tidal area with flats and channels. Depending on the tide during the SAR acquisitions, the tidal flats are either dry or flooded. Acquisitions during ebb tide are sometimes well correlated, providing an extended area of useful interferometric phase observations.

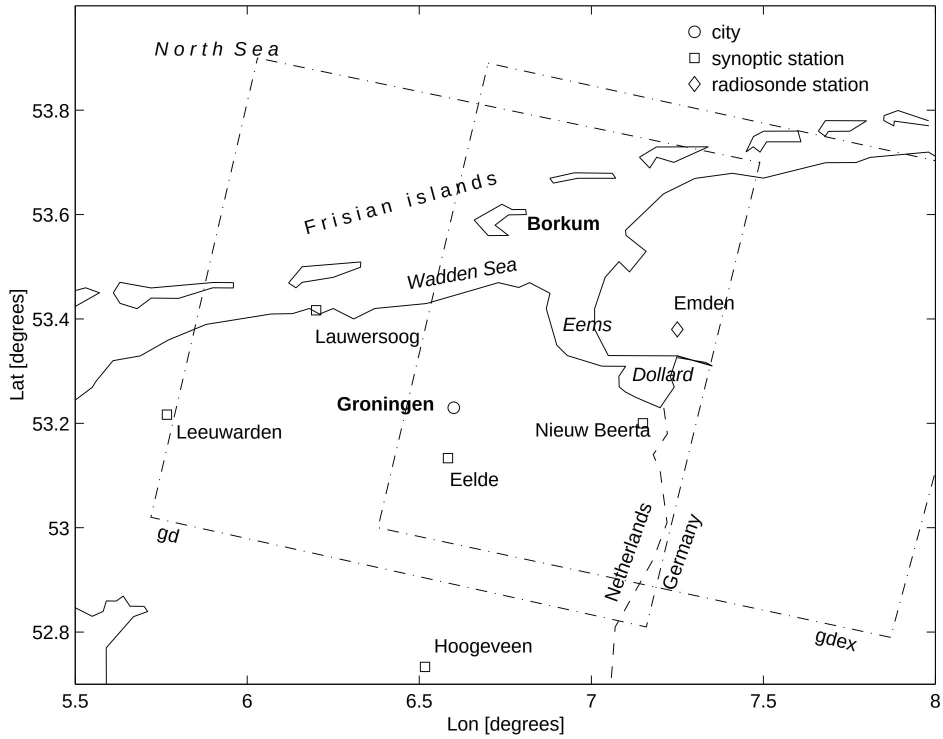

Figure 5.1 *Map of the area for the interferograms gd and gdex, showing the position of the synoptic and radiosonde stations with some relevant topographical information, referred to in the text.*

A map of the area is shown in figure 5.1. It shows the positions of the synoptic observation stations used in the analysis of the interferograms, and all other topographical information referred to in the following text. Both the stations *Eelde* and *Leeuwarden* are air fields, i.e., manned stations providing a full range of meteorological observations, including cloud types, heights, levels and coverage. The city of Groningen is shown nearly in the center of the map. Apart from the Dutch islands (Ameland and Schiermonnikoog) at the western side of the area, the first German island Borkum is labeled in the map. The Eems-Dollard estuary divides the northern parts of Germany and the Netherlands. Radiosonde observations are available from the meteorological station Emden.

The area can be considered flat for the interferometric interpretation, varying between -2 and $+3$ meters for the majority of the land surface. A small ridge covers the southern part of interferogram *gd*, with a maximal height of 20 m. Even for the longest baseline, these elevations are not significantly observable in the interferograms. Therefore, all interferograms of the area can be considered *differential* interferograms, i.e., a *flat* elevation model is subtracted.

Interferogram *gdex* is a single SAR pair from an adjacent track. Synoptic observations in this area are limited, therefore mostly satellite observations, radiosondes and larger scale weather charts are used for the analysis.

5.2.1 Analysis of interferogram gd1

Interferogram gd1 was acquired at July 15 and 16, 1995, at 10:31:58 UTC (12:31:58 LT). SAR frame number 2529. ERS-1 orbit 20909, ERS-2 orbit 1236. The parallel baseline was 3 m, the perpendicular baseline −27 m. Phase unwrapping was performed using the minimal cost flow algorithm (Costantini, 1996).

5.2.1.1 Observations

The interferogram in figure 5.2 is exceptionally disturbed, especially in the lower right corner. After unwrapping, see figure 5.3, more than 4.5 cycles difference in interferometric phase can be observed, mainly in the form of isolated anomalies with a diameter of 5–10 km. The section within the square in the unwrapped interferogram was analyzed using a histogram, see figure 5.4 and a rotational averaged spectrum, see figure 5.5. This spectrum shows a −5/3 power law in wavelengths between 1 and 25 km. The rms in this area is 3.4 rad.

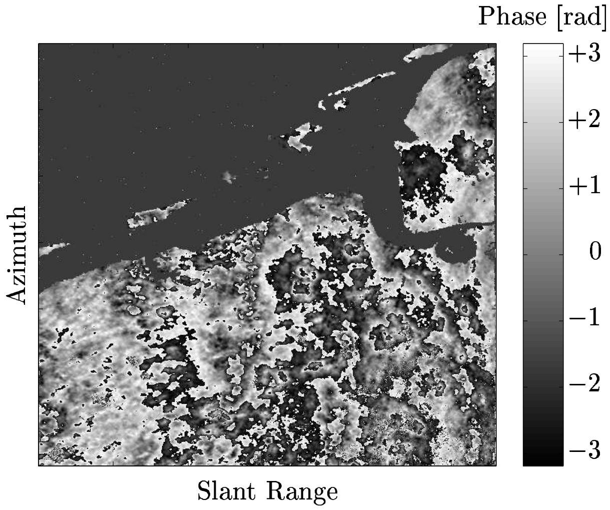

Figure 5.2 *Interferogram gd1*

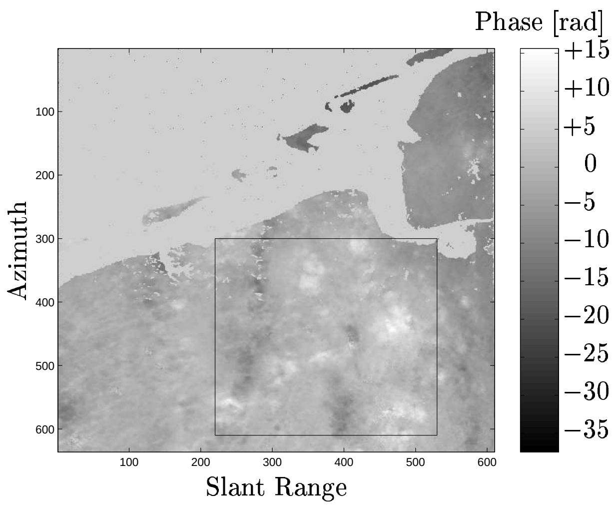

Figure 5.3 *Unwrapped interferogram gd1*

5.2.1.2 Interpretation

The main signatures of the interferogram are strong isolated cells and more or less elongated structures in azimuth direction. Due to the amount of phase delay, the hypothesis for the driving mechanism is that this is caused by a thunderstorm. This could cause local differences in humidity, pressure and temperature, which locally increases refractivity.[1]

The weather radar at day 1, figure 5.6, shows isolated showers at the locations of the negative values in absolute phase. The soundings of both days at Emden reveal instability

[1]During a thunderstorm passage, pressure changes up to 4 mbar per 10 minutes have been observed!

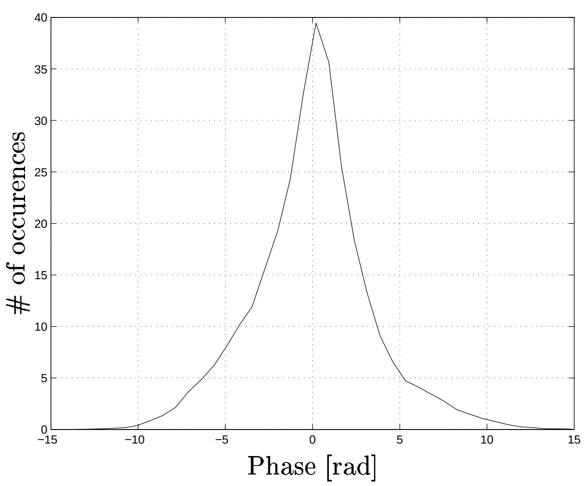

Figure 5.4 *Histogram of selected part of interferogram gd1*

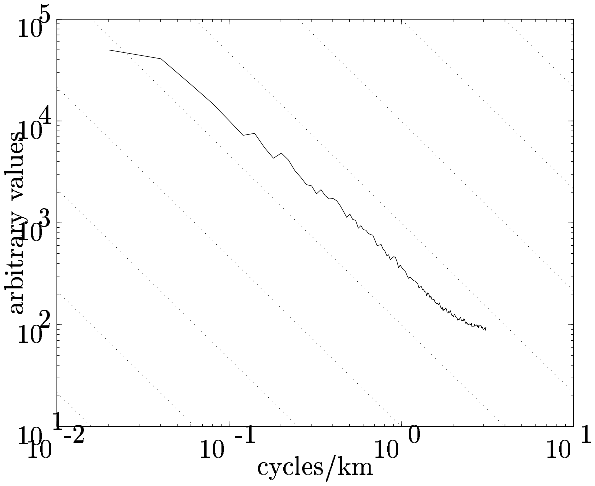

Figure 5.5 *Rotational average spectrum of interferogram gd1*

around the time of launch and ascent (launch at 11:00 UTC). They show low relative humidity at higher levels. Relative humidities at surface level at the time of SAR acquisition are 75–96%. Some isolated showers are building up around the time of the SAR acquisition. In the upper right corner of the overall weather radar image showers are reaching a height of about 6 km. These are cumulonimbus clouds. Note that at this distance from the radar, the lower part (1 km) of the rainfall is obscured due to the Earth's curvature. There is a shower over the island Borkum, in the north-eastern part of the image. Relative humidities are 75–96%. The wind direction was around 200 degrees (SSW). This corresponds with the the orientation of the negative phase values in the interferogram.

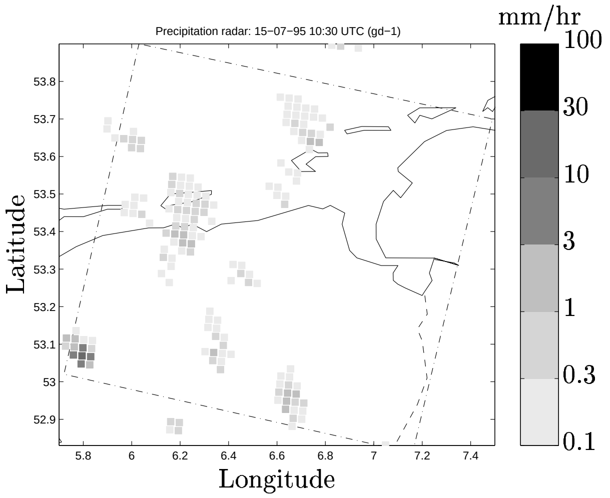

Figure 5.6 *Weather radar of day 1, 10:30 UTC*

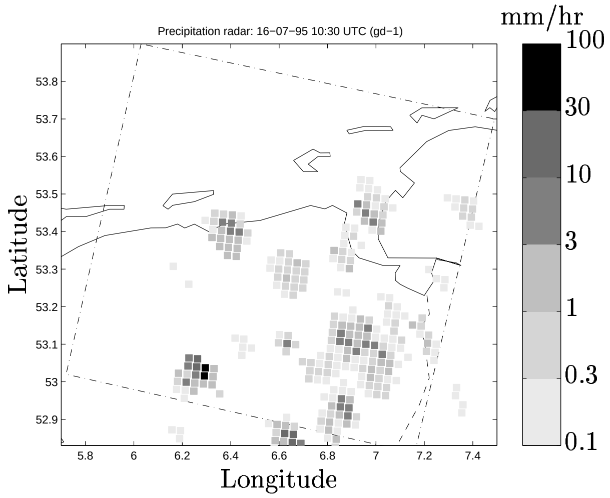

Figure 5.7 *Weather radar of day 2, 10:30 UTC*

At day 2, the high resolution VIS-channel of Meteosat shows a line of showers over the east of the Netherlands, just as the AVHRR: an organized pattern of showers, caused by a trough passage. The weather radar shows this line of showers as well, cf. figure 5.7. Here the locations of the showers are identical to the locations of the high positive absolute phase values in the interferogram. The showers reach a height of approximately 8 km.

The synoptic data show cumulonimbus with cloud base at 700 meters. Relative humidities at surface level are 72–82%, wind direction 240–250 degrees (SW).

Surface temperatures were 20°C at both days. A southwesterly flow of polar air, which became unstable due to heating up the surface, caused the thunderstorms.

The comparison of the unwrapped interferogram and the weather radar image suggests a strong correlation between the almost north-south band of showers over Groningen and the elongated structures in the interferogram.

Station	#	UTC	Day	Level 1	Level 2
Leeuwarden	270	1000	1	4/8, Cu, 700 m	4/8, Sc, 1600 m
Eelde	280	1000	1	3/8, Cu, 650 m	5/8, Ac, 3000 m
Leeuwarden	270	1100	1	7/8, Cu, 700 m	
Eelde	280	1100	1	3/8, Cu, 650 m	
Leeuwarden	270	1000	2	2/8, Cu, 650 m	
Eelde	280	1000	2	2/8, Cb, 700 m	3/8, Cu, 800 m
Leeuwarden	270	1100	2	2/8, Cu, 650 m	
Eelde	280	1100	2	2/8, Cb, 700 m	3/8, Cu, 800 m

Table 5.1 *Cloud observations gd1: 15-07/16-07-1995. The observations give the amount of cloud cover (okta), the type of cloud, and the cloud base at 2 levels.*

The cloud observations in table5.1 consist mainly of cumulus and cumulonimbus clouds. At the first day, in the morning also some higher clouds were observed.

5.2.1.3 Conclusion

Two thunderstorms, active during both SAR acquisitions, are responsible for these phase delays. The position of the rain fields detected by the weather radar coincide very well with the phase inhomogeneities. Therefore the weather radar observations can be used to predict the phase inhomogeneities in the interferogram, up to the sign difference between the two SAR acquisitions.

5.2.2 Analysis of interferogram gd2

Interferogram gd2 was acquired at August 19 and 20, 1995, at 10:31:58 UTC (12:31:58 LT). SAR frame number 2529. ERS-1 orbit 21410, ERS-2 orbit 1737. The parallel baseline was 37 m, the perpendicular baseline −81 m. Phase unwrapping was performed using the minimal cost flow algorithm (Costantini, 1996).

5.2.2.1 Observations

The interferogram figure 5.9 is relatively clean, although a "trough" can be seen at the right hand side of the image. The phase variations are spatially small, and can be characterized as "strings of pearls": lineated and frayed features which vary regularly in wideness. The directions of the strings are approximately 16 and 65 degrees. The observed structures become somewhat larger in diameter when farther from the coast. Figure 5.8 is the result of the phase unwrapping. Some of the Frisian islands still have a 2π phase shift with respect to the others, caused by the loss of coherent phase continuity over water areas. Figure 5.10 is the histogram over a representative part of the image. The rms value is 1.5 rad. Figure 5.11 shows the rotationally averaged spectrum. The $-5/3$ power law is roughly followed in the ranges between 0.3–1 km, and between 10–25 km.

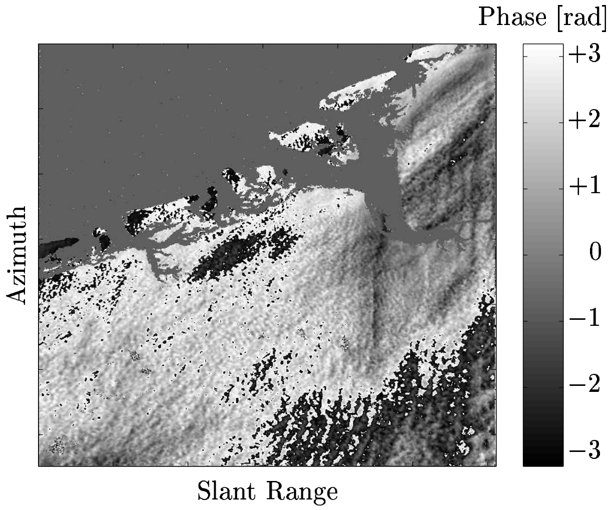

Figure 5.8 *Interferogram gd2*

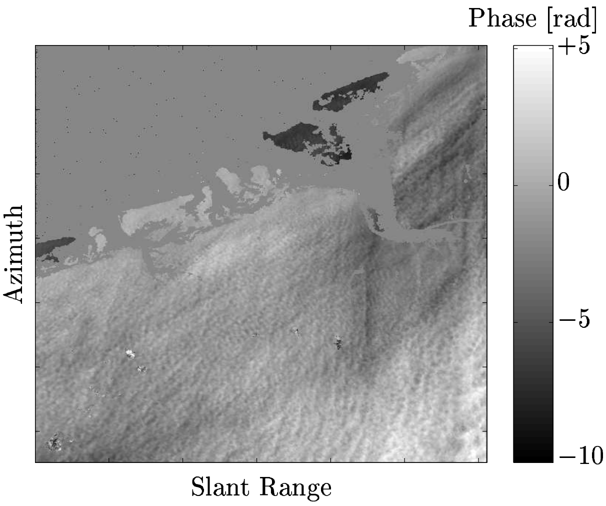

Figure 5.9 *Absolute interferogram gd2*

5.2.2.2 Interpretation

From the radiosondes, station Emden, it follows that day 1 and 2 are both very dry. However, there is some cloud cover on day 2 at low levels. The synoptic data showed that it was very warm both days (above 23°C). In Nieuw Beerta it was 29°C at 11:00 UTC. There was almost no cloud cover, at day 1 only a little cirrus (1/8) at 7 km, which can be neglected. At day 2 there may have been some low clouds in the western part of the test site (station Leeuwarden): 3/8 cumulus at 500 m. On day 1 a weak wind blew east to north-east (090-060) while on day 2 it turned to north, north-northeast (350 - 040). These directions correspond roughly with the directions observed in the interferogram.

The radiosonde data (day 1) confirms a strong subsidence inversion at 2200 m. At high levels in the troposphere it is rather dry. There is a change in wind direction of 60–70 degrees just below and above the inversion. The highest relative humidity is found at the inversion base, where it reaches 73%.

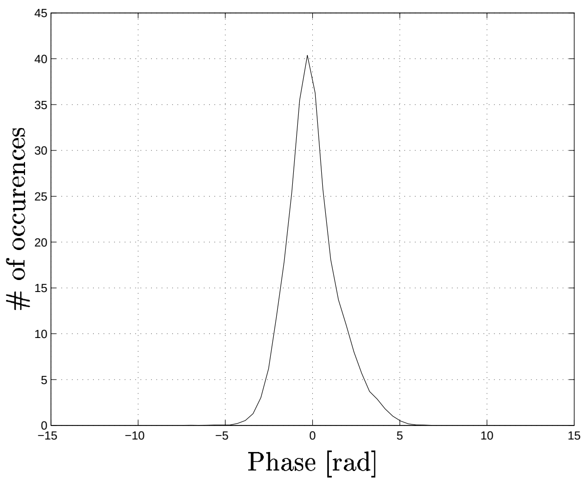

Figure 5.10 *Histogram interferometric phase interferogram gd2*

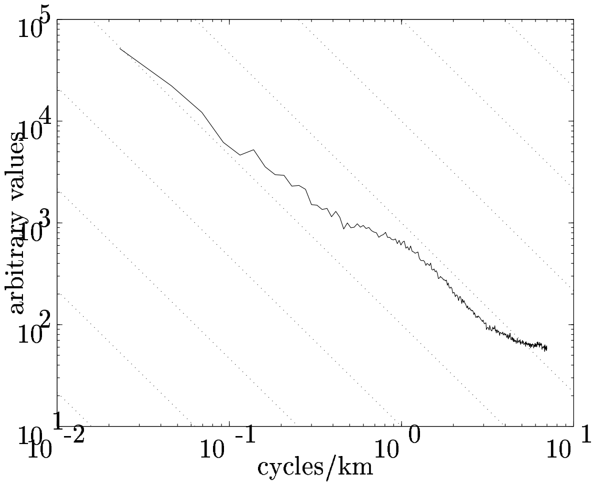

Figure 5.11 *Rotationally averaged spectrum interferogram gd2*

The weather radar did not show any rain in the test area. However, at 10:15 UTC, it still showed some signal east of the Dollard, due to a surface inversion. This is in fact an artifact of the rain detection capabilities of the precipitation radar.

AVHRR showed no clouds at day 1, and some vague cirrus at day 2. Also the Meteosat IR channel did not reveal anything in our test area.

The synoptic data revealed a north-eastern wind at day 1 and more northern winds at day 2. This seems to correlate with the directions in the interferogram. There is not much spatial variation in the relative humidity.

Looking forward in time to day 3 we see that moisture is transported into the area by the wind turning from east/ north-east to north. This probably correlates with the general appearance of the interferogram in which the coastal area seems invaded by humidity.

Station	#	UTC	Day	Level 1	Level 2
Leeuwarden	270	1000	1		
Eelde	280	1000	1		
Leeuwarden	270	1100	1		
Eelde	280	1100	1	1/8, Ci, 6600 m	
Leeuwarden	270	1000	2	1/8, Cu, 500 m	3/8, Ci, 8300 m
Eelde	280	1000	2	2/8, Ci, 8300 m	
Leeuwarden	270	1100	2	4/8, Ci, 8300 m	
Eelde	280	1100	2	2/8, Ci, 8300 m	

Table 5.2 *Cloud observations gd2: 19-08/20-08-1995. The observations give the amount of cloud cover (okta), the type of cloud, and the cloud base at 2 levels.*

5.2.2.3 Conclusions

Phase variation is small over most of the area. Since the observed directions correspond with the prevailing winds, it is expected to be caused by transport of moisture from the north. The distribution and size of the phase disturbances indicate a transition from more laminar flow in the north to more turbulent flow in the south of the area.

5.2.3 Analysis of interferogram gd3

Interferogram gd3 was acquired at December 2 and 3, 1995, at 10:31:56 UTC (11:31:56 LT). SAR frame number 2529. ERS-1 orbit 22913, ERS-2 orbit 3240. The parallel baseline was 17 m, the perpendicular baseline 44 m. Phase unwrapping was performed using the minimal cost flow algorithm (Costantini, 1996). The ERS-1 SAR had 128 missing azimuth lines.

5.2.3.1 Observations

The interferogram figure 5.13 has a striking "wave-like" feature in the lower left side of the image. The remaining parts are relatively clean. The horizontal line in the middle of the image is an artifact, possibly caused by incorrect treating of a number of missing lines in the original SAR data. Figure 5.12 results from phase unwrapping. Figure 5.14 is the histogram over a representative part of the image. The superposition of three Gaussian curves is probably caused by the sine-wave in the lower left of the image. Figure 5.15 is the rotationally averaged spectrum, following the −5/3 curve between 3 and 40 km wavelengths.

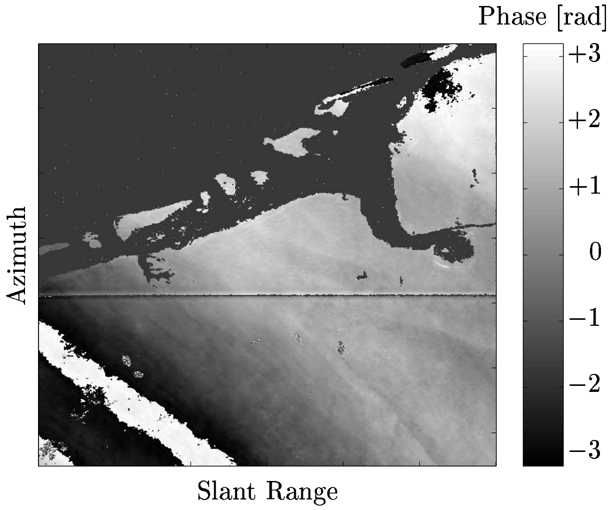

Figure 5.12 *Interferogram gd3*

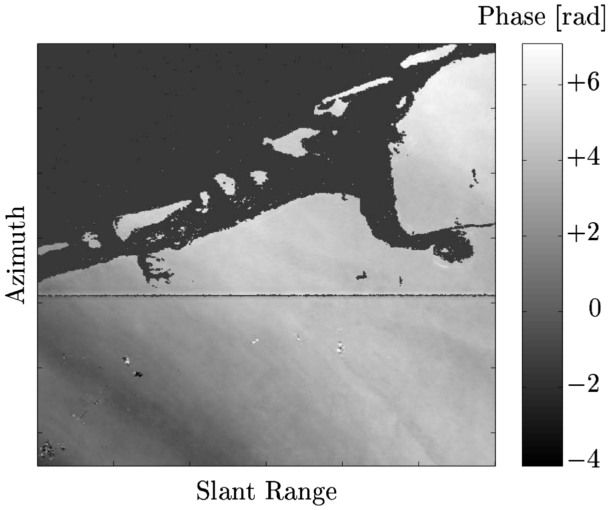

Figure 5.13 *Unwrapped interferogram gd3*

5.2.3.2 Interpretation

The most prominent feature in this interferogram is visible in the lower left corner of the scene. We have labeled this feature the "dog ear". There is a possibility that this a processor artifact, however, SAR processing with an independent SAR processor (DLR-BSAR) yielded the same error (Schättler, 1997). Different tests with other approximations of the reference phase, and using independent precise orbits (DEOS) did not eliminate the effect either. The remaining part of the interferogram seems to have few phase variations.

Since the "dog ear" has a negative sign, the cause of the effect is expected in the second SAR acquisition, at December 3. Both AVHRR and Meteosat (figure 5.16) show at this day low cloud structures in the same direction as the dog ear. According to the cloud observations 5.3 the cloud type is stratocumulus.

The weather radar shows nothing at all: no rain. From Meteosat we learn that at day 1 there was a "frontal" zone that is being pushed back at day 2. Above the Netherlands

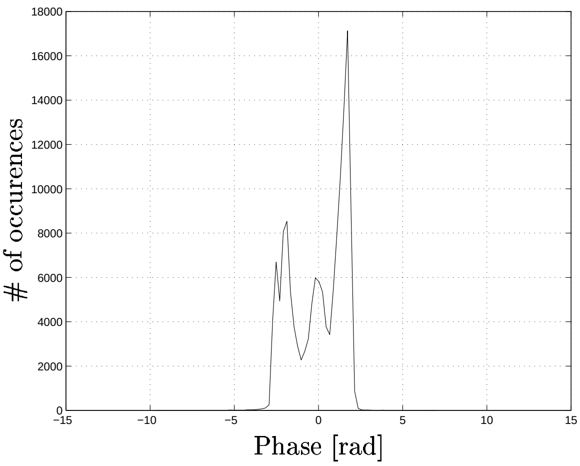

Figure 5.14 *Histogram of major part of interferogram gd3*

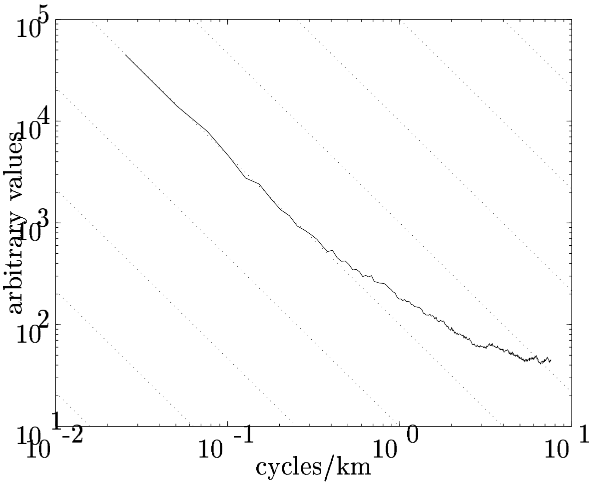

Figure 5.15 *Rotationally averaged spectrum of interferogram gd3*

there are several quasi-stationary fronts: at the boundary between warm air in SW-part and cold air in NE-part of the Netherlands.

The synoptic data show that it was cold, around the freezing level. There is a high relative humidity, therefore the air is very moist, especially in the SW-part in low levels (0–1000m) almost 100% RH. All stations in the test area report misty weather: reduced visibility between 2.5–3.7 km. At day 1 it was totally clouded. There was stratocumulus with base at 400 m. The radiosonde of De Bilt (day 1) shows very dense cloud layer between 50–1000 m. In the SW-part of the observed area part of this low cloudiness can be present at day 1. Note that NOAAs AVHRR does not see this, since it is hidden under cirrus clouds, with tops above 8 km. Also, the amount of solar flux is low, indicating thick cloud cover. At day 2 the solar flux is higher, which indicates less thick cloud cover. The solar flux is, however, more variable over the area, which indicates inhomogeneities in the cloud thickness.Synops-station Eelde, reports 2/8 cumulus at about 400 m with holes in the cover. The wind at both days was ESE (90-100 degrees).

Station	#	UTC	Day	Level 1	Level 2	Level 3
Leeuwarden	270	1000	1	2/8, St, 200 m	8/8, St, 300 m	
Eelde	280	1000	1	3/8, St, 150 m	5/8, St, 200 m	8/8, St, 300 m
Leeuwarden	270	1100	1	1/8, St, 200 m	8/8, St, 300 m	
Eelde	280	1100	1	3/8, St, 100 m	5/8, St, 200 m	8/8, St, 250 m
Leeuwarden	270	1000	2	3/8, Sc, 500 m	8/8, Sc, 600 m	
Eelde	280	1000	2	5/8, Sc, 350 m		
Leeuwarden	270	1100	2	2/8, Sc, 650 m	8/8, Sc, 800 m	
Eelde	280	1100	2	3/8, Cu, 400 m		

Table 5.3 *Cloud observations gd3: 02-12/03-12-1995. The observations give the amount of cloud cover (okta), the type of cloud, and the cloud base at 3 levels.*

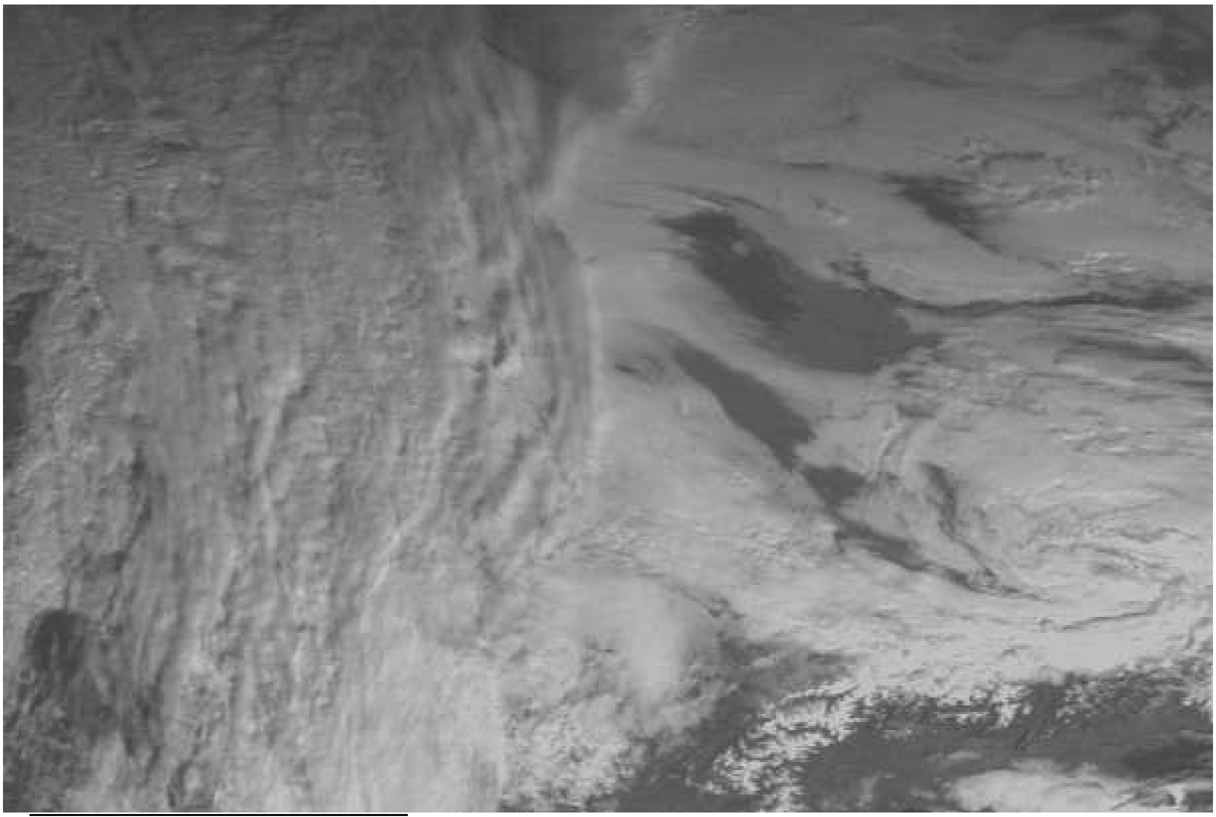

Figure 5.16 *Visual image Meteosat, 03-12-95, 10:30 UTC, gd3. The Netherlands are located in the center of the image. Refer to figure 5.139 at page 113 for orientation.*

5.2.3.3 Conclusions

Since the "dog ear" has a negative sign, localized delay changes at the second acquisition cause this effect. The combination of the satellite observations from Meteosat and NOAA with the manual cloud observations and radiation flux measurements show a non-uniform cloud cover. The effect is therefore probably caused by a localized cloud band in northwest–southeast direction.

5.2.4 Analysis of interferogram gd4

Interferogram gd4 was acquired at March 16 and 17, 1996, at 10:31:46 UTC (11:31:46 LT). SAR frame number 2529. ERS-1 orbit 24416, ERS-2 orbit 4743. The parallel baseline was 16 m, the perpendicular baseline −18 m. Phase unwrapping was performed using the minimal cost flow algorithm (Costantini, 1996).

5.2.4.1 Observations

The interferogram (figure 5.17) exhibits many small waves in varying directions. The unwrapped interferogram, the absolute phase, is shown in figure 5.18. Two parts of the absolute phase are extracted from this image, and analyzed using the Radon transform (figures 5.19 and 5.20). Part A is the large square, part B the smaller one. From these transforms, the dominant directions of 41 and 45 degrees, counterclockwise from the positive azimuth axis, can be found for part A and B respectively. Wavelengths are 2.4 and 3.5 km respectively. The waves in part A have an amplitude of less than 0.7 rad, in part B less than 1 rad. A 3D visualization of part B is given in figure 5.21.

Figure 5.22 is the histogram over a representative part of the image. It shows that phase variation is very little, with an rms of 0.6 rad. Figure 5.23 is the rotationally averaged spectrum. The −5/3 line is only followed in the longer wavelengths: 12–45 km. Clearly, the wave patterns in the interferogram cannot be considered isotropic, which is one of the assumptions in Kolmogorov turbulence theory (Tatarskii, 1971).

An extensive GPS campaign was performed during the period in which the SAR images were acquired, see Hanssen (1996); Stolk et al. (1997).

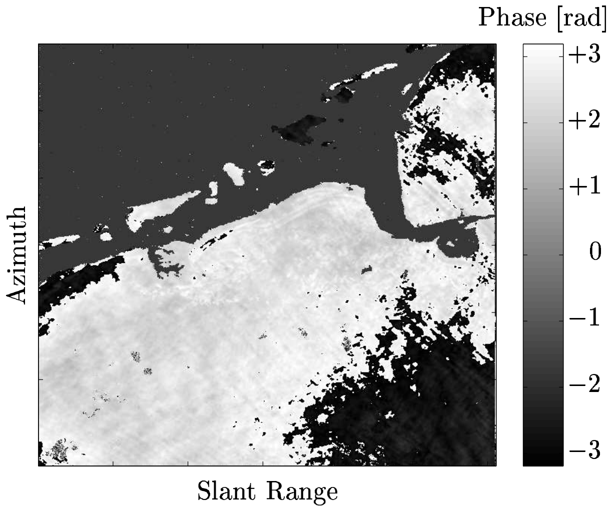

Figure 5.17 *Interferogram gd4*

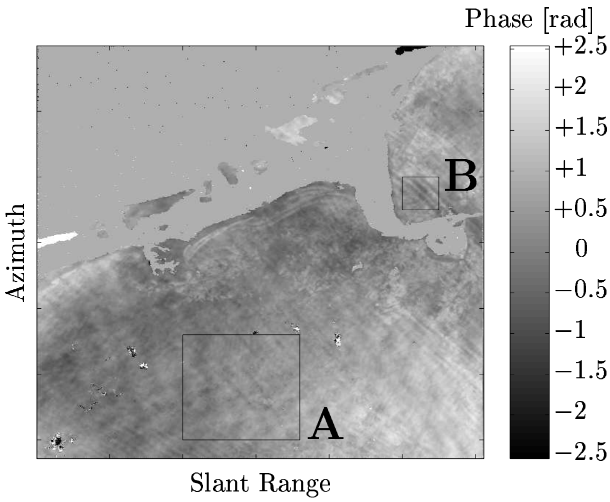

Figure 5.18 *Unwrapped interferogram gd4*

5.2.4.2 Interpretation

The main signal consists of waves with relatively short wavelengths, 3 km, in different directions. Hypotheses for these effects are: (1) cloud streets or gravity waves, (2) wave effects on top side of fog, or (3) a subsidence inversion.

The weather radar does not show anything at both days. The synoptic data indicate that it was cold, just above freezing level. There was no rain, it was misty with a visibility between 2.1 and 4 km. Both Leeuwarden and Eelde reported 8/8 cloud cover, with especially much

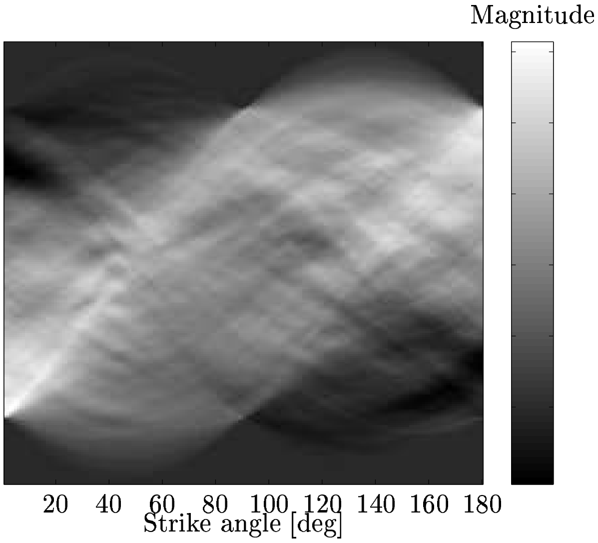

Figure 5.19 *The Radon transform of part A of the absolute interferogram*

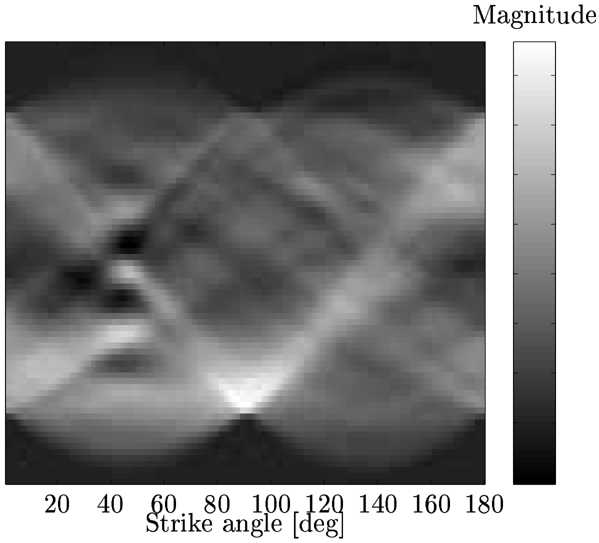

Figure 5.20 *The Radon transform of part B of the absolute interferogram*

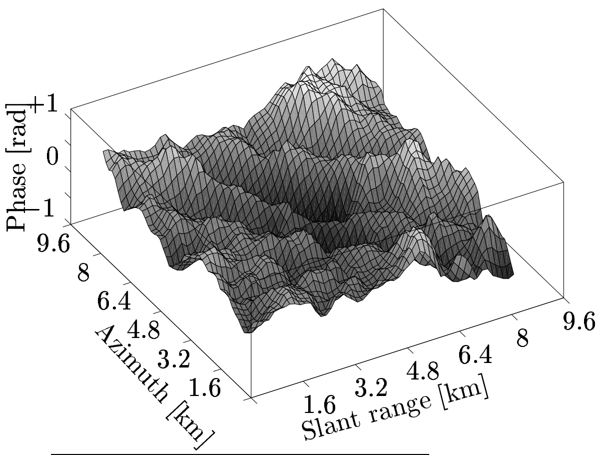

Figure 5.21 *A 3D view of the waves in part B of the absolute interferogram*

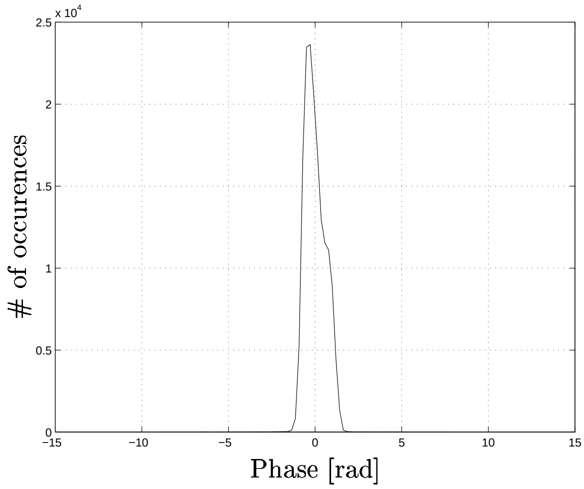

Figure 5.22 *Histogram of major part of interferogram gd4*

low-level clouds: 5/8 stratocumulus at 400 m in Leeuwarden and 6/8 stratus at 350 m in Eelde, see table 5.4. On both days the wind direction was east, with a wind force 4 at the first day. At day 2, Eelde reports 5/8 stratocumulus at 400–500 m, and Leeuwarden 5/8 stratocumulus at 3800 m. More layers are observed at day 2 than at day 1. Meteosat VIS reveals a closed cloud cover, with several layers. The IR image shows that the clouds at day 1 are not that high, while at day 2 there is also higher (colder) cloud cover. NOAA AVHRR observations of day 1 reveal very many cloud wave features in the area, in different directions. The directions observed in the interferogram are also just visible in the AVHRR imagery, although the resolution level needs to be tweaked.

At the surface the wind direction is east. Low stratocumulus cloud streets are oriented east-west. However, at higher altitudes the wind becomes more southern oriented. From the radiosonde data it is found that there can be cloud levels at different altitudes.

The atmosphere is unstable in the layer below 800 m on the first day and 1500 m on

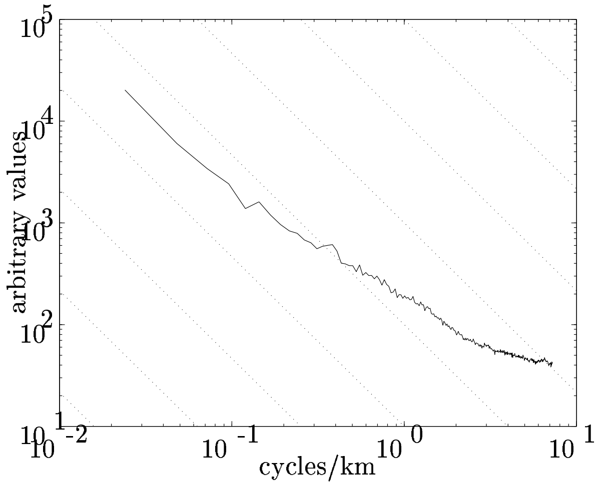

Figure 5.23 *Rotationally averaged spectrum of interferogram gd4*

day 2. Due to an inversion, it is stable above this height.

Station	#	UTC	Day	Level 1	Level 2
Leeuwarden	270	1000	1	8/8, Sc, 400 m	
Eelde	280	1000	1	8/8, St, 300 m	
Leeuwarden	270	1100	1	8/8, Sc, 400 m	
Eelde	280	1100	1	8/8, Sc, 400 m	
Leeuwarden	270	1000	2	7/8, Sc, 450 m	8/8, Sc, 1200 m
Eelde	280	1000	2	8/8, Sc, 400 m	
Leeuwarden	270	1100	2	7/8, Sc, 500 m	8/8, Sc, 1200 m
Eelde	280	1100	2	8/8, Sc, 400 m	

Table 5.4 *Cloud observations gd4: 16-03/17-03-1996. The observations give the amount of cloud cover (okta), the type of cloud, and the cloud base at 2 levels.*

5.2.4.3 Conclusions

The hypothesis of wave effects on the top side of the fog seems to be very unlikely, since there is not much wind at that altitude. Also there are no signs of a subsidence inversion from the radiosonde. Based on the observations of cloud bands in the AVHRR imagery, the phase fluctuations in the interferogram are very likely to be caused by anisotropic cloud distributions at several layers. Gravity waves at the inversion level is probably the driving mechanism for the observed waves in the interferogram.

5.2.5 Analysis of interferogram gd5

Interferogram gd5 was acquired at April 20 and 21, 1996, at 10:31:59 UTC (12:31:59 LT). SAR frame number 2529. ERS-1 orbit 24917, ERS-2 orbit 5244. The parallel baseline was 34 m, the perpendicular baseline −76 m. Phase unwrapping was performed using the minimal cost flow algorithm (Costantini, 1996).

5.2.5.1 Observations

The interferogram (figure 5.24) shows small undulations, within half a cycle, and a longer wavelength feature, causing just one fringe in the middle of the interferogram. Waves with a small wavelength (2–3 km) can be observed in the lower left and the upper right corner of the interferogram. Longer wavelength striated effects are visible just right of the middle of the interferogram (wavelengths 10–13 km). It seems that the waves become more turbulent towards the lower right part of the interferogram, where a honeycomb pattern can be observed The unwrapped interferogram, the absolute phase, is shown in figure 5.25. Figure 5.26 is the histogram over the main part of the image, showing two superposed Gaussians, due to the large curvature in the interferogram. Overall rms is 1.4 rad, although the two separate Gaussians have rms values of approximately 1 and 0.45 rad respectively. Figure 5.27 is the rotationally averaged spectrum. Wavelengths following the −5/3 power law include the 0.5–2 km range and the 10–45 km range.

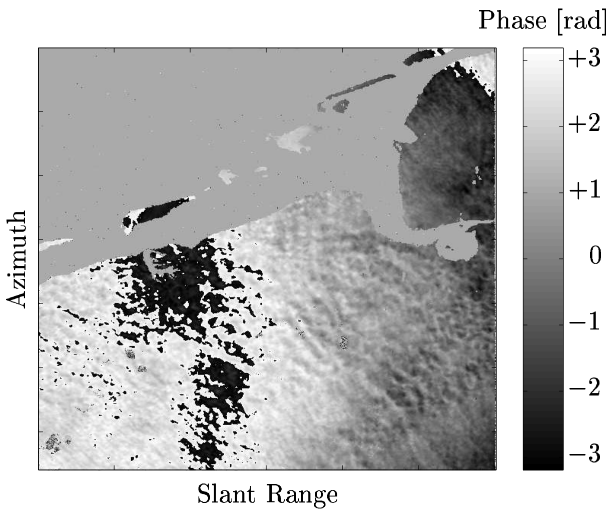

Figure 5.24 *Interferogram gd5*

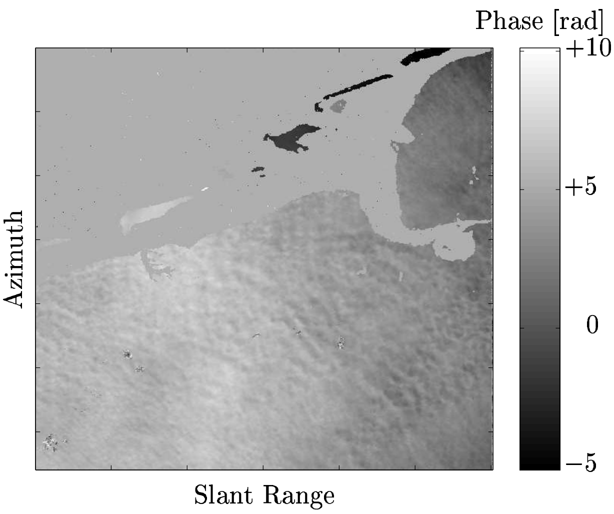

Figure 5.25 *Unwrapped interferogram gd5*

5.2.5.2 Interpretation

The weather radar indicates no rain at both days. AVHRR observations shows cirrus clouds at day 1. The Meteosat IR image shows some flaky structures at day 1, but almost no structure at day 2.

The synoptic data give a weather category 5 at day 1, which indicates haze. This is possibly due to solid particles. The relative humidity is 50–60%, which indicates very dry air! In the area 6/8 cirrus is reported at about 7–8 km. Eelde also reports some medium level clouds for day 1: 3/8 altocumulus at about 3.5 km. At day 2 there is also only a little cirrus cloud cover. Table 5.5 lists the cloud observations. The solar flux of 220 is very high (which indicates sunny weather), and the temperatures vary around 20°C.

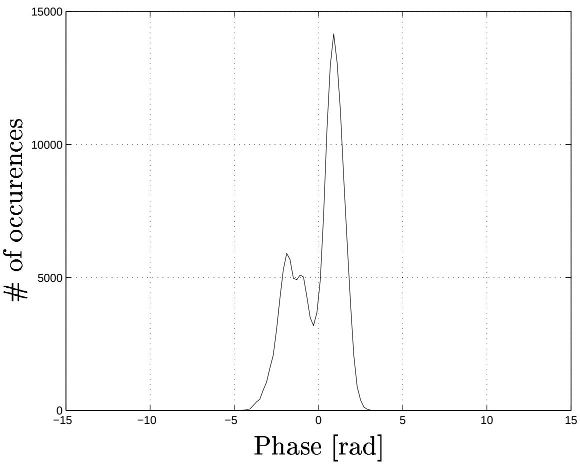

Figure 5.26 *Histogram of major part of interferogram gd5*

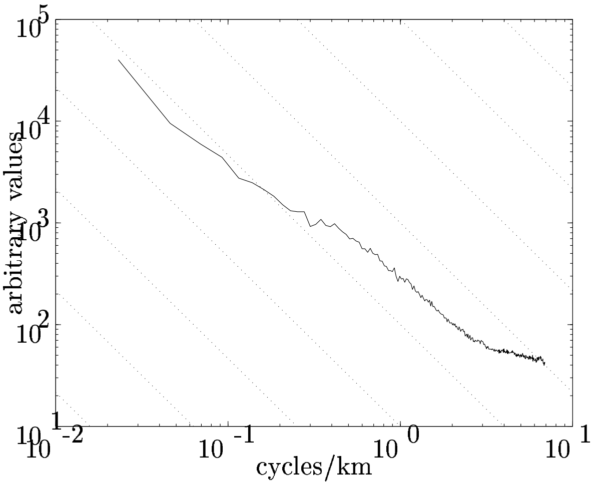

Figure 5.27 *Rotational averaged spectrum of interferogram gd5*

For the interferogram we would therefore also expect that there are not much variations in water vapor. The radiosonde data reveal no signs of an inversion at both days.

Surface wind directions were south-southeast at day 1, and more south to south-southwest at day 2. The structures in the interferogram are tending more towards the south-eastern direction. From the radiosondes, however, we find that wind is veering with height. At the height of the cirrus clouds, 8–9 km, the wind direction was both days more south-west, which is nearly perpendicular to the wave effects in the interferogram.

Station	#	UTC	Day	Level 1	Level 2
Leeuwarden	270	1000	1	6/8, Ci, 8300 m	
Eelde	280	1000	1	6/8, Ci, 8300 m	
Leeuwarden	270	1100	1	6/8, Ci, 8300 m	
Eelde	280	1100	1	1/8, Ac, 3300 m	7/8, Ci, 8300 m
Leeuwarden	270	1000	2	5/8, Ci, 8300 m	
Eelde	280	1000	2	3/8, Ci, 8300 m	
Leeuwarden	270	1100	2	5/8, Ci, 8300 m	
Eelde	280	1100	2	3/8, Ci, 8300 m	

Table 5.5 *Cloud observations gd5: 20-04/21-04-1996. The observations give the amount of cloud cover (okta), the type of cloud, and the cloud base at 2 levels.*

5.2.5.3 Conclusions

Evidence for the observed effects is poor for this situation. Based on the discrepancy between the surface winds and the direction of the waves in the interferogram, it is expected that the driving mechanism for these effects is at a higher altitude. Only the influence of cirrus clouds at day 1 could have a significant effect in the interferogram, since relative humidities were fairly constant with height. The perpendicular direction of the wind at the height of the cirrus clouds agrees with this hypothesis.

5.2.6 Analysis of interferogram gd6

Interferogram gd6 was acquired at May 25 and 26, 1996, at 10:31:50 UTC (12:31:50 LT). SAR frame number 2529. ERS-1 orbit 25418, ERS-2 orbit 5745. The parallel baseline was 52 m, the perpendicular baseline 99 m. Used phase unwrapping algorithm: minimal cost flow (Costantini, 1996). The SAR processing is subject to an error in the Sampling Window Start Time (SWST) shift. This causes the loss of coherence in the band in the upper right corner of the interferogram.

5.2.6.1 Observations

Interferogram gd6, shown in figure 5.28, exhibits atmospheric phase variation of up to 1 cycle. A clear direction is visible in the artifacts, from lower left to middle right. It seems that the striation is becoming more turbulent in the right part of the image, where they dissolve in more isolated cells. In the left part of the interferogram, more laminar flows are observed. The unwrapped interferogram, the absolute phase, is shown in figure 5.29. Figure 5.30 is the histogram over the main part of the image, with an rms value of 1.8 rad. Figure 5.31 is the rotationally averaged spectrum, showing a small band of −5/3 behavior between 0.4–1 km and 15–50 km wavelengths.

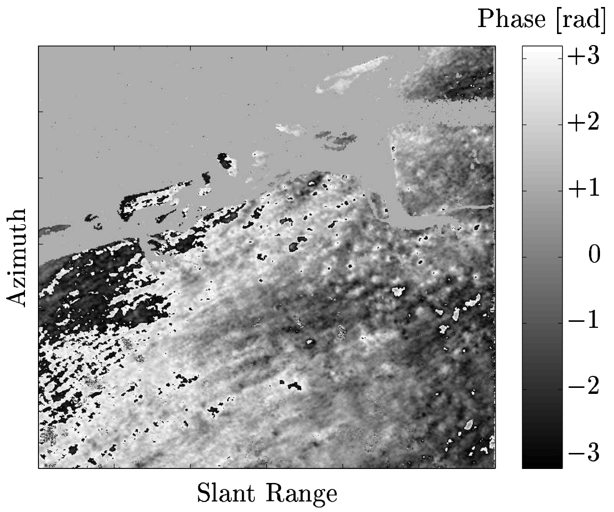

Figure 5.28 *Interferogram gd6*

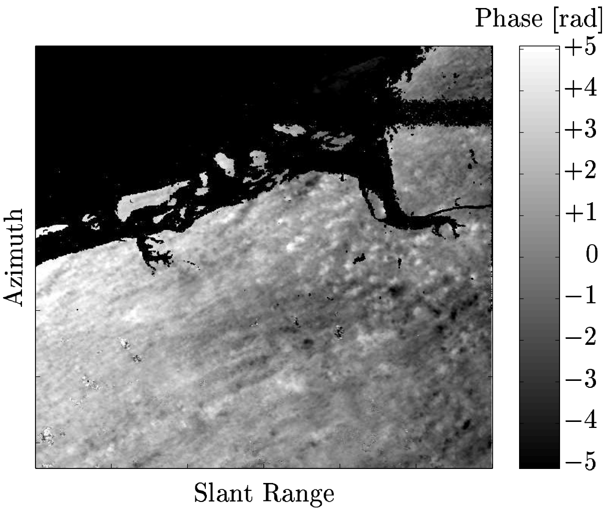

Figure 5.29 *Unwrapped interferogram gd6*

5.2.6.2 Interpretation

This interferogram is composed of the still rather humid air of day 1, after the passage of a front and rainfall, and the rather dry, but unstable air of the second day. The instabilities at the second day could be the cause of the phase disturbance in the interferogram.

From the weather charts we learn that at day 1 a cold front has just passed: there is polar air in the area. Some clouds are moving in the tail of this cold front, as we observe from the AVHRR data. From the precipitation radar we see that a vast field of rain is located in the south-east part of the Netherlands. It does not rain in the test area at the moment of the day 1 SAR acquisition.

The synoptic data show at day 1 for station Eelde: 5/8 cumulus at 500 m and 6/8 altocumulus at 4 km, see table 5.6. In total, 7/8 cloud cover is reported. For station Leeuwarden: 2/8 cumulus at 300 m, and 4/8 cumulus at 400 m. Station Hoogeveen

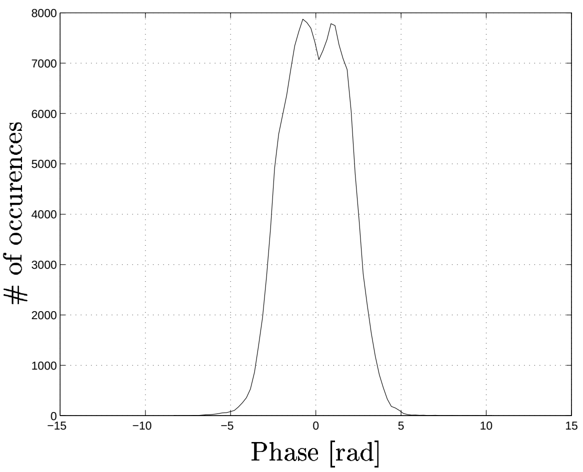

Figure 5.30 *Histogram of major part of interferogram gd6*

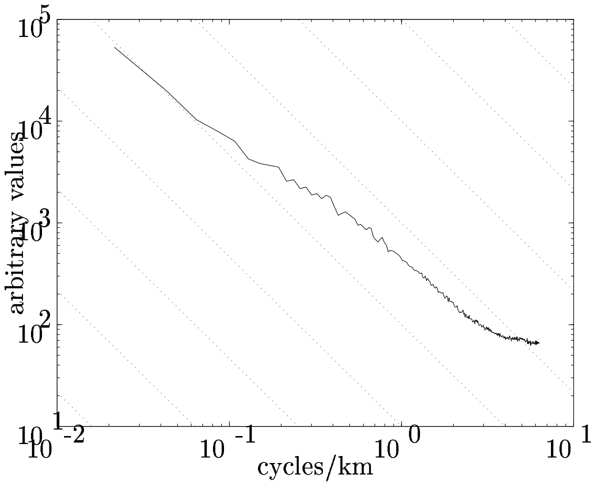

Figure 5.31 *Radial averaged spectrum of interferogram gd6*

(279) reported some precipitation (4 mm). The wind direction turns from west to west-southwest in the interferogram, see figure 5.32.

At day 2, the area is still in polar air. Station Eelde observes 2/8 cumulus at low altitude and 5/8 altocumulus at 3300 m. Leeuwarden denoted 2/8 cumulus at 800 m, and 4/8 altocumulus at 3 km. There is more sunshine on day 2 and a fair amount of wind from west-southwest,see figure 5.33.

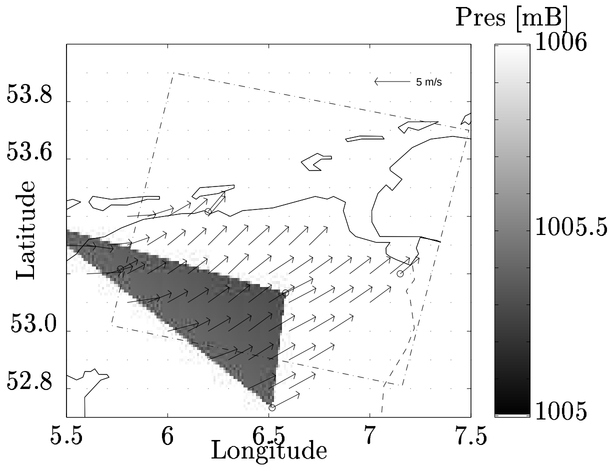

Figure 5.32 *Pressure and surface wind field gd6, day 1, 10:00 UTC*

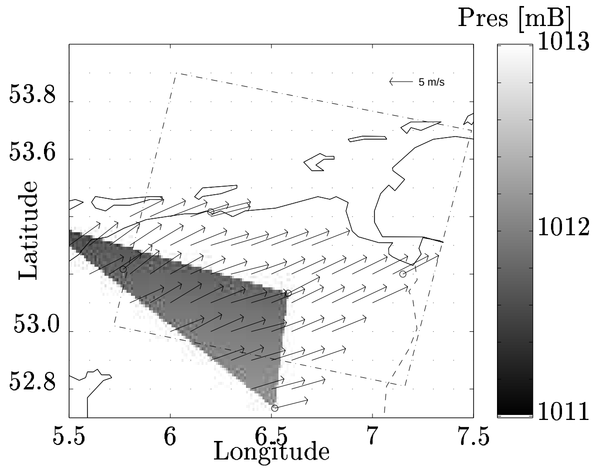

Figure 5.33 *Pressure and surface wind field gd6, day 2, 10:00 UTC*

At day 2, we see in the AVHRR image that cloud streets seem to be forming directly over our test area. The direction and significance of these cloud streets corresponds closely with the direction in the interferogram, where we find striation in the direction of the surface winds. The amplitude and diameter of the phase effects increases towards the east, as corresponds with the AVHRR imagery. It is possible that this wind "carries" moisture over the IJsselmeer to our test area which condensates due to convective heating over land, and thus forms the cloud streets. A plot of the wind vectors in the area confirms this hypothesis.

Station	#	UTC	Day	Level 1	Level 2
Leeuwarden	270	1000	1	2/8, Cu, 400 m	4/8, Cu, 500 m
Eelde	280	1000	1	5/8, Cu, 500 m	6/8, Ac, 3300 m
Leeuwarden	270	1100	1	1/8, Cu, 400 m	5/8, Cu, 500 m
Eelde	280	1100	1	3/8, Cu, 650 m	6/8, Ac, 3300 m
Leeuwarden	270	1000	2	2/8, Cu, 800 m	4/8, Ac, 3000 m
Eelde	280	1000	2	3/8, Cu, 1100 m	
Leeuwarden	270	1100	2	3/8, Cu, 800 m	
Eelde	280	1100	2	2/8, Cu, 1000 m	5/8, Ac, 3300 m

Table 5.6 *Cloud observations gd6: 25-05/26-05-1996. The observations give the amount of cloud cover (okta), the type of cloud, and the cloud base at 2 levels.*

5.2.6.3 Conclusions

Cloud streets in the wind direction are the most likely cause for the artifacts in the interferogram. Transport of moisture from the IJsselmeer changes from laminar flow to turbulent flow in the area. Main indicators for the effects are the AVHRR imagery and the synoptic observations.

5.2.7 Analysis of interferogram gd7

Interferogram gd7 was acquired at August 3 and 4, 1996, at 10:31:48 UTC (12:31:48 LT). SAR frame number 2529. ERS-1 orbit 26420, ERS-2 orbit 6747. The parallel baseline is 46 m, the perpendicular baseline 103 m. Phase unwrapping was performed using the minimal cost flow algorithm (Costantini, 1996). There were no precise state vectors available for the ERS-1 orbit, which resulted in a relative baseline error of 6.3 m. A manual correction for the orbit errors was therefore necessary. Furthermore, the SAR processing caused an error in the handling of the Sampling Window Start Time Shift. This caused the loss of coherence in the upper right corner of the interferogram.

5.2.7.1 Observations

Atmospheric artifacts, growing in scale from the upper to the lower side of the image (figure 5.34), are characteristic in this interferogram. The amplitude of the artifacts is growing towards a bit more than a cycle. No specific direction is visible in the disturbances. In the northern part of the area, the patterns have a small honeycomb pattern. The unwrapped interferogram, or the absolute phase, is shown in figure 5.35. Figure 5.36 is the histogram over the main part of the image, showing a smooth Gaussian curve with an rms of 1.8 rad. Figure 5.37 is the rotationally averaged spectrum. Between 0.5 and 2.5 km wavelengths, the $-5/3$ Kolmogorov power law is followed.

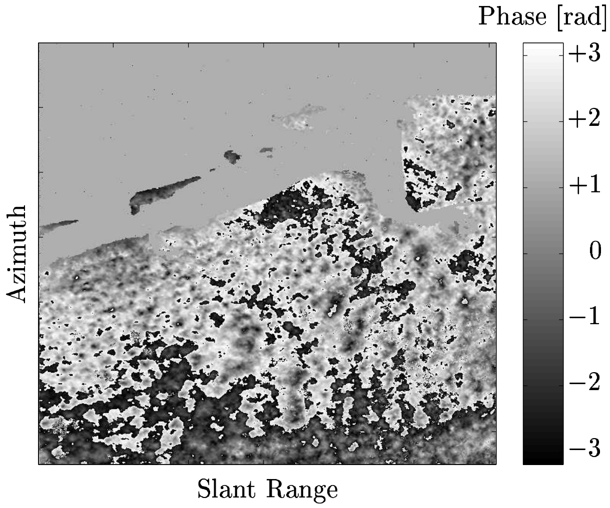

Figure 5.34 *Interferogram gd7*

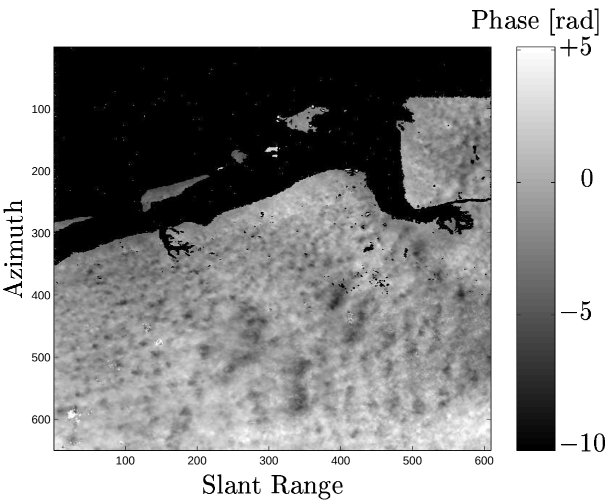

Figure 5.35 *Unwrapped interferogram gd7*

5.2.7.2 Interpretation

The weather radar does not show any rain on both days. The synoptic data indicate that there was a north-western wind at day 1 (4 m/s), with very good visibility. At day 2, the visibility is again splendid, while the wind was weaker (1–2 m/s) and from the east. At day 1, about 4/8 cumulus is observed at approximately 900–1100 m. At day 2, there is about 2/8 cumulus at about 1000 m. Based on the cloud observations, local disturbances in the interferogram are expected. At both days, the temperature was around 19°C.

The first day, there was an in-flow of humidity from the sea, the second day this in-flow was cut-off by eastern winds.

AVHRR-images from 11:50 UTC show at day 1 cumulus clouds, growing from the northern coast line to the lower side of the interferogram. Their influence should be a positive

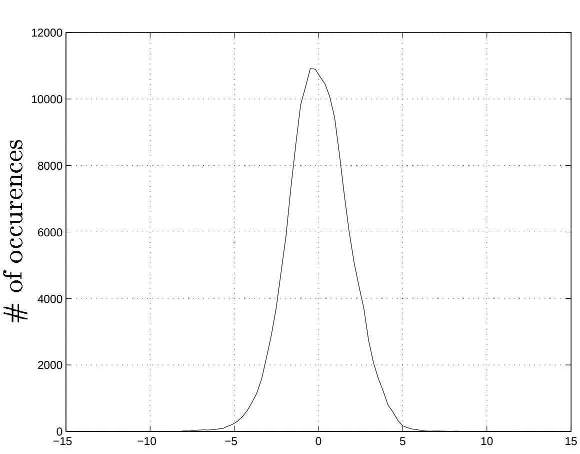

Figure 5.36 *Histogram of major part of interferogram gd7*

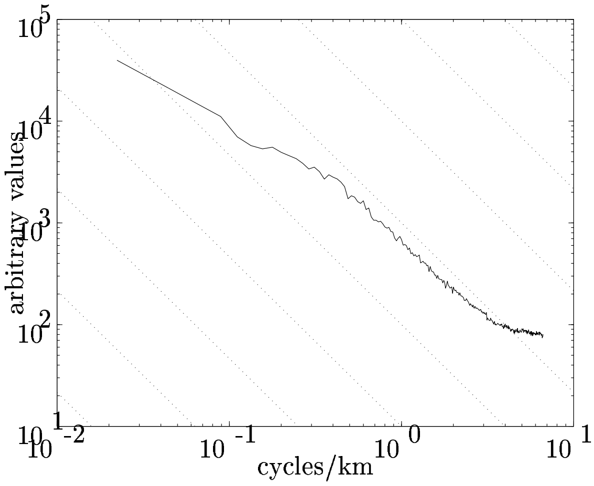

Figure 5.37 *Rotational averaged spectrum of interferogram gd7*

interferometric phase. This pattern can be recognized in the interferogram. At the same time at day 2, only some very small cumulus clouds are visible, having a more ore less east–west orientation. Their influence should, however, be small. These clouds, both at day 1 and 2, are too small to be distinguished in the Meteosat data.

Station	#	UTC	Day	Level 1	Level 2
Leeuwarden	270	1000	1	4/8, Cu, 900 m	
Eelde	280	1000	1	4/8, Cu, 1100 m	
Leeuwarden	270	1100	1	4/8, Cu, 900 m	
Eelde	280	1100	1	3/8, Cu, 1100 m	3/8, Sc, 3000 m
Leeuwarden	270	1000	2	2/8, Cu, 800 m	
Eelde	280	1000	2	1/8, Cu, 1000 m	
Leeuwarden	270	1100	2	2/8, Cu, 1100 m	
Eelde	280	1100	2	1/8, Cu, 1100 m	

Table 5.7 *Cloud observations gd7: 03-08/04-08-1996. The observations give the amount of cloud cover (okta), the type of cloud, and the cloud base at 2 levels.*

5.2.7.3 Conclusions

The observed effects in the interferogram are due to cloud cover heterogeneities: cumulus clouds in varying sizes. The direction on which the artifacts grow in amplitude and size corresponds closely with the wind direction at day 1.

5.2.8 Analysis of interferogram gdex2

Interferogram gdex2 was acquired at February 26 and 27, 1996, at 10:29:05 UTC, or 11:29:05 LT. SAR frame number 2529. ERS-1 orbit 24144, ERS-2 orbit 4471. The parallel baseline is −15 m, the perpendicular baseline −31 m. Phase unwrapping is performed using the minimal cost flow algorithm (Costantini, 1996). This interferogram, covering the Dutch-German border area around the Eems estuary, was originally not planned for this study. Considering its availability, however, it has been included as well. The amount of synoptic observations for the area is limited.

5.2.8.1 Observations

The interferogram gdex2, (figure 5.38), is characterized by mainly a long wavelength trend, of almost 1 cycle from the upper left side to the lower right side of the image. Due to its nature, it is not expected that orbit errors are causing it, although a small trend could still be caused by orbit inaccuracies. In two parts of the unwrapped interferogram, outlined by the square boxes A and B shown in figure 5.39, small waves can be observed. A 3D view of these parts is shown in figure 5.40 and 5.41, and profiles perpendicular to the waves in figure 5.42 and 5.43. Profile A has a wavelength of about 1 km and an amplitude of less than 0.4 rad. The direction of the waves is −60 degrees with respect to the azimuth direction, which corresponds to −44 degrees with respect to the north. Profile B has a shorter wavelength, around 600 m, and an amplitude of 0.4 rad. The direction is the same as for extraction A.

The histogram, figure 5.44 indicates a superposition of three Gaussian curves, centered around −3, −1, and 3 radians respectively. The superposition is caused by the long wavelength curve over the interferogram. The overall rms is 1.9 rad. Figure 5.45 is the rotationally averaged spectrum, showing a perfect −5/3 power law behavior over the range from 0.012 to 1.2 cycles per km, corresponding with wavelengths between 800 m and 80 km.

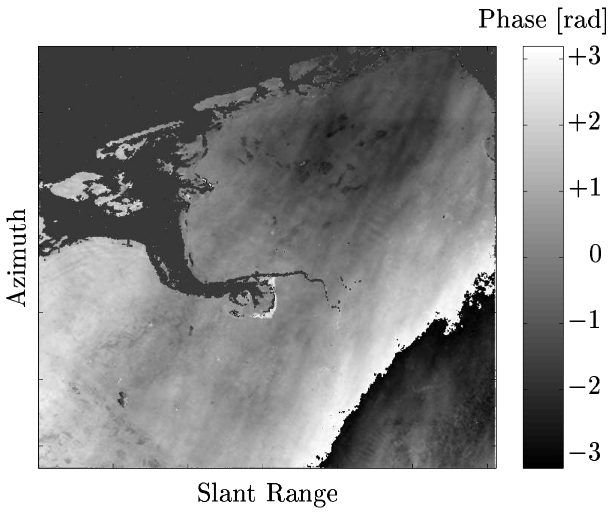

Figure 5.38 *Interferogram gdex2*

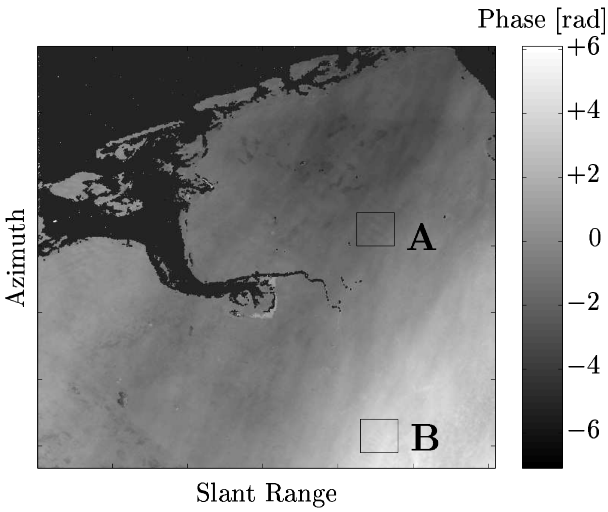

Figure 5.39 *Unwrapped interferogram gdex2*

5.2.8.2 Interpretation

In the interferogram smooth variations and waves of small wavelength and amplitude are observed. Based on the weather charts, the smooth variations might be due to a