

Ground Subsidence Monitoring in Hong Kong with Satellite SAR Interferometry

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Abstract

Ground settlement has long been a problem in Hong Kong, as most usable land in Hong Kong was reclaimed from the sea. Ground settlement may affect building structures and underground facilities such as water supply and sewage systems built on the land. Measurements of ground settlement can provide valuable data for assessing the impacts of ground settlement and for improving designs of future land reclamation projects.

Experiments have been carried out to assess the performance of INSAR in the environment of Hong Kong especially the temporal decorrelations of SAR images and the potential atmospheric effects on INSAR measurements, and to use INSAR to study the ground settlement problem in Hong Kong. This study finds that the temporal decorrelation is an important problem in the heavily vegetated rugged areas as usually expected, and that the atmospheric effects can be very significant at times. Ground settlements measured over the airport and a residential area are presented. It can be seen from the results that both of the areas are still settling significantly many years after the reclamation.

Introduction

It is a common practice to reclaim land from the sea in Hong Kong (HK) due to the scarcity of useable land in the territory. Reclaimed land usually undergoes long periods of settlement that may affect building structures and underground facilities such as water supply and sewage systems built on the land. Monitoring of the progressive settlement of reclaimed land can provide valuable information to assess the impacts of land settlement and to improve future designs of land reclamation projects. Most existing techniques for monitoring ground settlement rely on collection of data repeatedly at selected points, and then derive the magnitudes and rates of settlement from measurements carried out at different epochs. These point-based measurement methods are generally expensive and inefficient for monitoring large areas of settlement. Besides, sparsely distributed data points are often insufficient to provide information on very localized ground settlement.

INSAR has been demonstrated to be a promising tool for measuring ground settlement related to, for example, the shrinking/swelling of irrigated fields (Gabriel, *et al.*, 1989), geothermal power production (Massonnet, *et al.*, 1997), aquifer system compaction (Galloway, *et al.*, 1998), underground quarries (Fruneau and Sarti, 2000), and ground water withdrawal (Bawden, *et al.*, 2001).

This research employs ERS-1 and ERS-2 radar images to study the ground settlement problems in HK. In particular, we will examine the sensitivity of the technique under the field and atmospheric conditions in HK.

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General Assessment of Interferometric Quality in Hong Kong

Temporal Decorrelations

Six single-look-complex (SLC) SAR images acquired with the C-band SAR sensors onboard the ERS-1/2 during 1996–1999 over this region (frame 3159, track 404) are used to assess the temporal correlations between SAR images. All the images were acquired at around 1054 local time along descending orbits of the satellites (travelling north to south and looking to west). Figure 1a shows the flight direction (azimuth 191.8°) and the ground coverage of the images. The fifteen possible interferometric combinations of the images are listed in Table 1.

As seen from the SAR amplitude image given in Figure 2, the land area of HK is generally dominated by mountains and high-rise urban centres (bright areas) located at the feet of the mountains. We choose four areas, an urban area in Kowloon with relatively low-rise buildings, an urban area on the HK Island with high-rise buildings, the Landau Island representing vegetated hilly areas, and an area in the eastern part of the New Territory with steep vegetated mountains (Figure 2) to examine the radar coherence in the areas. The areas range from 2 to 8 km².

Following the standard data processing steps, an overall coherence map is first generated for each of the interferometric pairs. The temporal decorrelation is then derived by removing the baseline decorrelation component from the coherence map (Zebker, *et al.*, 1992). The averaged temporal correlation value for each of the four typical surface areas is finally calculated. The results are shown in Figure 3 where the temporal correlation is represented as a function of the time interval between the two interferometric images. It can be seen from the results that the temporal correlation for each of the cases reduces with the increase of the time interval, and that the areas with built surfaces (low- and high-rise building areas) maintain higher correlation than the mountainous areas as temporal decorrelation is more easily caused in vegetated areas by such factors as vegetation growth, leaf fluttering, and change of water content in leaves. In addition, topographic relief also causes image shadows and layovers that can seriously affect the radar coherence.

According to Figure 3, all the surface types can maintain good temporal correlation (0.37–0.83) for short time intervals, for example, 1 and 35 days. For longer time intervals (3 months to 3 years), however, only areas with low-rise buildings can maintain sufficient correlation for interferometric processing. It is worth noting that areas with dense buildings of irregular heights cannot maintain good radar coherence due to shadows, layovers, and possible multi-path effects.

Photogrammetric Engineering & Remote Sensing
Vol. 70, No. 10, October 2004, pp. 1151–1156.

0099-1112/04/7010-1151/\$3.00/0
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TABLE 1. INTERFEROMETRIC COMBINATIONS OF SIX ERS-1/2 SLC SAR IMAGES

Slave	E2/4767	E2/6270	E2/18759	E2/19296	E2/23805
Master	96.3.19	96.7.2	98.11.24	98.12.29	99.11.9
E1 ^a /24440 ^b	76 ^d /101 ^e	-30/-181	215/480	257/425	56/-55
96.3.18 ^c	1 ^f	106	981	1016	1331
E2/4767		-106/-282	139/379	181/324	-20/-156
96.3.19		105	980	1015	1330
E2/6270			245/661	287/606	86/126
96.7.2			875	910	1225
E2/18795				42/-55	-159/-535
98.11.24				35	350
E2/19296					-201/-480
98.12.29					315

^aE1 stands for satellite ERS-1 and E2 for satellite ERS-2; ^bOrbit number of ERS mission; ^cDate of SAR acquisition (year.month.day); ^dParallel baseline length in metres; ^ePerpendicular baseline length in metres; ^fTime interval in days between two SAR acquisitions.

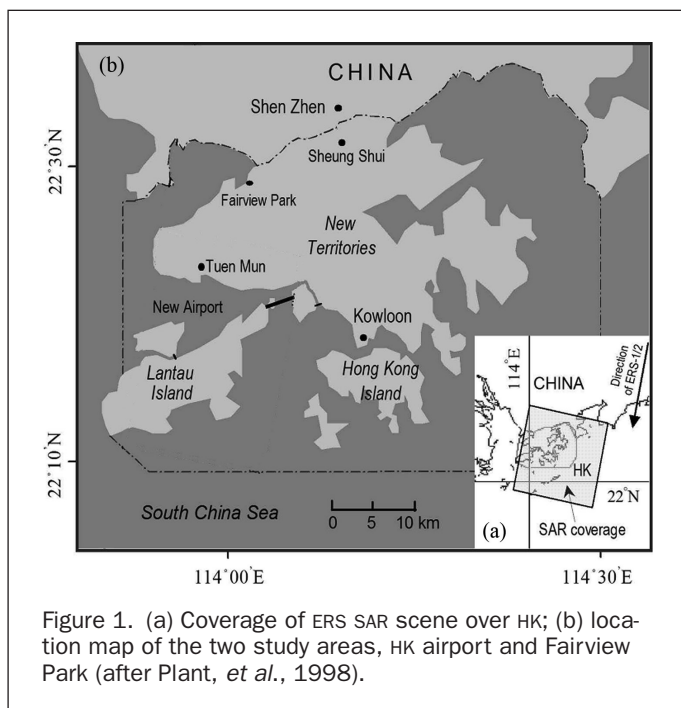


Figure 1. (a) Coverage of ERS SAR scene over HK; (b) location map of the two study areas, HK airport and Fairview Park (after Plant, *et al.*, 1998).

Atmospheric Effects

Two types of errors may potentially be introduced when microwave propagates through the atmosphere, the bending and the propagation delays. The latter dominates in case of INSAR measurements (Rosen, *et al.*, 2000). Tests have been carried out to quantify the possible atmospheric effects in this region.

A SAR interferogram generated by complex conjugate multiplication of two SAR images is a superposition of information on topography height, surface deformations, differential atmospheric delays between the acquisitions, and the noise (e.g., Massonnet, *et al.*, 1994; Tarayre and Massonnet, 1996; Hanssen, *et al.*, 1999). If there is no surface deformation between the two image acquisitions or if the deformation is known, the atmospheric signatures can be extracted from an interferogram by eliminating the contribution of the topography.

An ESA ERS Tandem pair acquired on 18 and 19 March, 1996 over HK is used for this purpose. The perpendicular and parallel baseline components for this pair of images are 100 m and 78 m, respectively. As the images have only a time interval of one day, it can be safely assumed that there is no surface deformation in the area between the SAR image acquisitions. Since satellite orbit errors generate in an interferogram

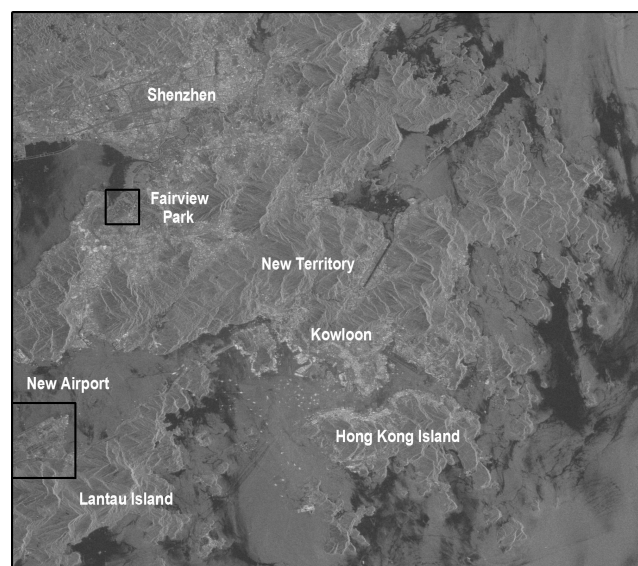


Figure 2. SAR amplitude image of HK.

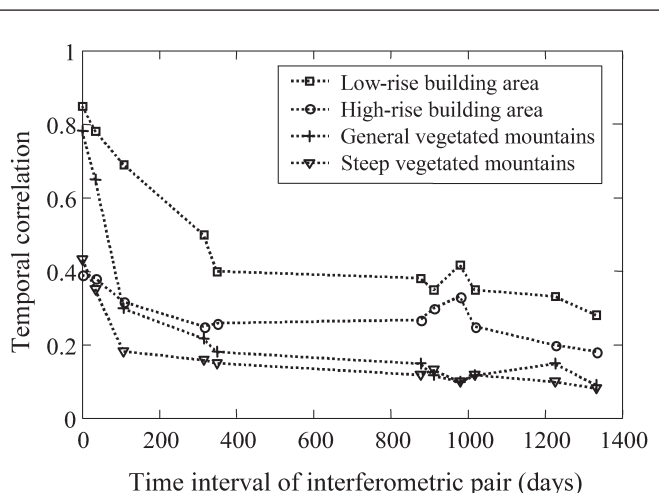


Figure 3. Variations of radar coherence with time interval between images.

long wavelength phase shifts similar to the long wavelength atmospheric disturbances (Tarayre and Massonnet, 1996; Hanssen, 1999), careful baseline refinement is necessary in the interferometric processing. Besides, the phase trend that caused by residual flat earth phase and residual orbit errors is removed with a linear model. Figure 4 shows one of the amplitude images, where rectangles A and B are a flat and a hilly area, respectively, that maintain good coherence. The two areas are about 6 km × 11 km and 5 km × 10 km, respectively, in size. Since the ionospheric disturbances have wavelengths of tens of kilometers or longer, the ionospheric effects in these two areas are considered unobservable (Hanssen, 2001).

For area A, since the perpendicular baseline is short (100 m as mentioned earlier) and the majority of the surface varies within 5–10 m except for a small ridge with a height of less than 40 m in the northwest part, the variations of the interferometric phase can be considered due largely to radar signal path delays caused by the atmosphere. For area B, a DEM created from the digital map provided by the Lands Department

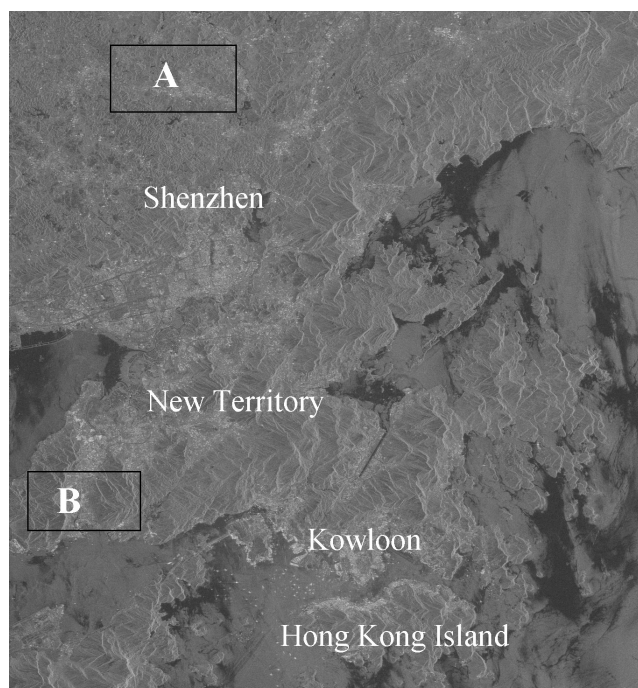


Figure 4. Amplitude SAR image of HK and its neighboring region. A and B are flat and hilly areas, respectively, chosen for the study.

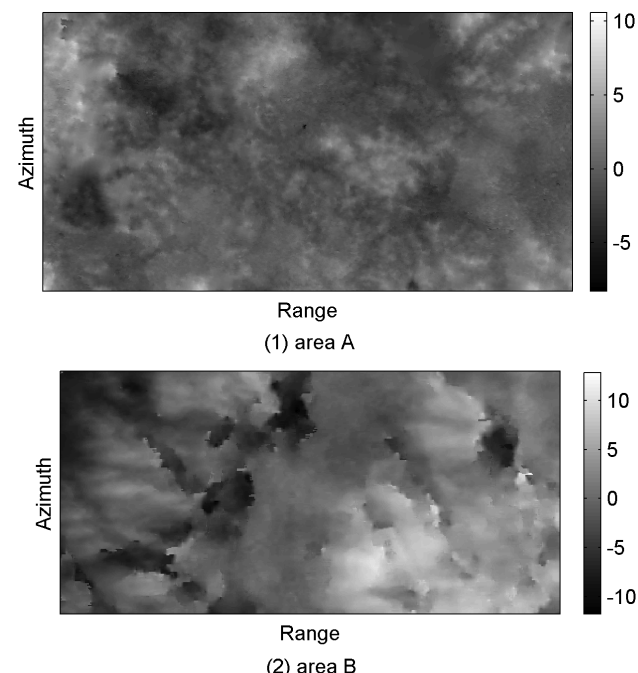


Figure 5. Unwrapped interferometric phases for areas A and B (with topographic phase removed) (units: radians).

of the HK Government was used to remove the topographic component from the interferogram. Figure 5 shows the unwrapped interferometric phases in the two areas. The mean differential atmospheric delays in each of the areas are then calculated and removed from the unwrapped interferograms.

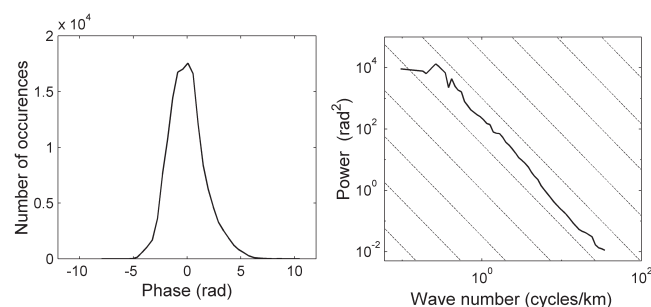


Figure 6. Histogram (left) and power spectrum (right) of differential atmospheric delays for area A.

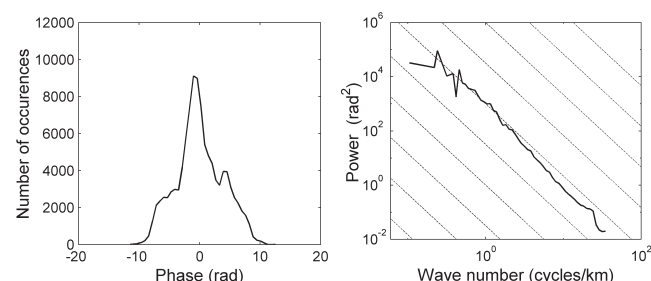


Figure 7. Histogram (left) and power spectrum (right) of differential atmospheric delays for area B.

A 2D Fast Fourier Transform (FFT) is performed next for each of the areas and the results are squared to obtain the power spectrums. The histograms and the 1D rotationally averaged power spectrums thus obtained are given in Figures 6 and 7, respectively.

The power spectra of the differential atmospheric delays in both of the areas on the whole follow the power law of the Kolmogorov turbulence (Tatarski, 1961). The results are in good agreement with those presented by Hanssen (1999, 2001). The dashed lines in the figures are the $-8/3$ power law values. The power law index varies with the scales slightly, which is consistent with the turbulence behavior of such phenomena as integrated water vapor and the wet delays in radio ranging.

It can be seen from the results that the absolute power of the differential atmospheric delays in area B is larger than that of area A. This is considered due to, as mentioned earlier, the fact that in flat areas, only the turbulent mixing processes of the troposphere affect INSAR measurements whilst in mountainous areas both the turbulent mixing and vertical stratifications come into effect.

The RMSE of the differential atmospheric delays for the two areas are 2.04 and 3.66 radians, respectively. Under the assumption of Gaussian distribution, the differential atmospheric delays can vary from -4.08 to 4.08 radians in area A, and from -7.32 to $+7.32$ radians in area B at the 95 percent confidence level. This translates into peak-to-peak variability of 8.16 and 14.64 radians, respectively for the two areas. The potential peak-to-peak errors in DEM and deformation measurements thus introduced, when assuming a 100 m perpendicular baseline, are estimated and given in Table 2.

Settlement Measurement for Selected Areas in Hong Kong

In this section we will concentrate on two reclaimed land areas in HK, the newly constructed Chek Lap Kok Airport (approximately 12 km²) and a low-rise residential area, Fairview

TABLE 2. POTENTIAL ERRORS IN INSAR MEASUREMENTS
(ESTIMATED FROM INSAR DATA)

Area	Area A	Area B
Peak-to-peak deformation errors (cm)	3.64	6.52
Peak-to-peak DEM errors (m)	130	230

Park (approximately 2 km²) (see Figure 1b and Figure 2). For the airport, among the six ERS-1/2 images, none of those obtained in 1996 can be used as the airport was in an intensive construction stage at the time (Plant, *et al.*, 1998) and the construction activity cause all the images to have very low radar coherence. Therefore, among all the 15 possible interferometric combinations listed in Table 1, only three (18, 19 March, 1996, a Tandem pair; 24–29 November, 1998; and 29 December, 1998–09 November, 1999) are useable. In contrary, for the Fairview Park area, relatively high correlation remained for all the interferometric combinations.

The Chek Lap Kok Airport started operation on 06 July 1998, to replace the old Kai Tak Airport. The new airport was built over a large man-made island of 12.48 km², north of the Lantau island (see Figure 1b and Figure 2). Three-quarters (9.38 km²) of the land used for the airport was reclaimed from the sea, whereas the remaining quarter was formed by excavating two existing granitic islands, the Chek Lap Kok Island (3.02 km²) and the Lam Chau Island (0.08 km²) (Plant, *et al.*, 1998), as highlighted in the enlarged SAR amplitude image of the airport (see Figure 8). Fairview Park is a residential area of about 2 km². The area was reclaimed over 10 years ago. It is covered mostly by one or two story buildings.

Settlement Measurement over the New Airport

Interferograms

To obtain a differential interferogram across the airport, our interferometric data processing chain includes: (1) accurately

co-registering two SAR images, (2) forming and filtering an interferogram, (3) removing flat-earth phase trend using precise orbit data, (4) phase unwrapping, and (5) removing topographic phase using an independent DEM. The DEM used is created from a digital map provided by the Lands Department of the HK Government. The RMSE of the DEM is smaller than 1.0 m. The phase unwrapping is carried out with the branch-cut method (Goldstein, *et al.*, 1988), starting at the pixel corresponding to benchmark No. 14 (see Figure 8) and assuming its phase value equal zero.

The differential interferograms thus generated for the airport are shown in Figure 9. Since the flat-earth trend and the topographic phase have been removed, the residual phase can be considered to be the radar range changes caused by uneven ground settlement, atmospheric effects and random noise.

The phase variations over the 35-day interferogram are little (Figure 9b) while those over the one-day period are very significant (Figure 9a). The most likely reason for the clear fringes in the one-day interferogram is the atmospheric delays since it is unlikely to have such significant settlement over such a short time period. The results echo those presented in the section on atmospheric effects. Figure 9c shows significant differential phase variations that are most likely resulted from ground settlement accumulated over the 315 days as to be verified with levelling results below. It is very interesting to note that the measured phase values appear to be very smooth across the two excavated islands, Chek Lap Kok and Lam Chau, indicating no or little ground settlement in the areas since they consist of original stable granite (Plant, 1998). Over the reclaimed areas however, the phase values vary significantly.

The random noise in an interferogram resulted from radar decorrelation is a nonlinear function of the time interval of the interferometric pair. The random noise may cause a maximum error of about 4 mm in the measured settlement when using the 315-day interferogram. The corresponding error for the 35-day pair is about 3 mm and this is possibly higher than the possible ground settlement within the period. Therefore, only the 315-day interferogram will be studied further.

INSAR-Leveling Comparison

We will compare the settlement results computed from the 315-day interferogram with leveling measurements at the 28 benchmarks shown in Figure 8.

The interferometric phase values are converted into height changes on a pixel-by-pixel basis. Figure 10 shows the resulting settlement map in the HK80 Grid System with a resolution of 20 m × 20 m. The subsidence ranges from –50 to 0 mm across the area over the nearly one-year period, while nearly no subsidence is visible throughout the two excavated islands (Figures 8 and 10).

When comparing the INSAR to leveling measurements at the 28 benchmarks (Figure 8), the mean difference is –3.5 mm and the RMSE difference is 6.9 mm. Excellent agreement (within 2–3 mm) exists for points in and near the stable areas while divergence (about 10 mm) (points 4, 9, 15, 17 and 20) appears in the reclaimed area.

Settlement Over the Area of Fairview Park

We conducted similar tests for the Fairview Park area as those for the airport as introduced above. Good coherence (up to 0.65 on average) was maintained in the area for all the interferometric combinations even for the pair with an interval of nearly three years. This is primarily due to the special shapes and finishing of the roofs of the low-rise buildings in the area. Figure 11 shows a 3D-settlement map derived from the SAR image pair acquired on 19 March, 1996 and 29 December, 1998. The results obtained show that the area was clearly settling between 1996 and 1999. Although no independent information is available to confirm the interferometric results, the

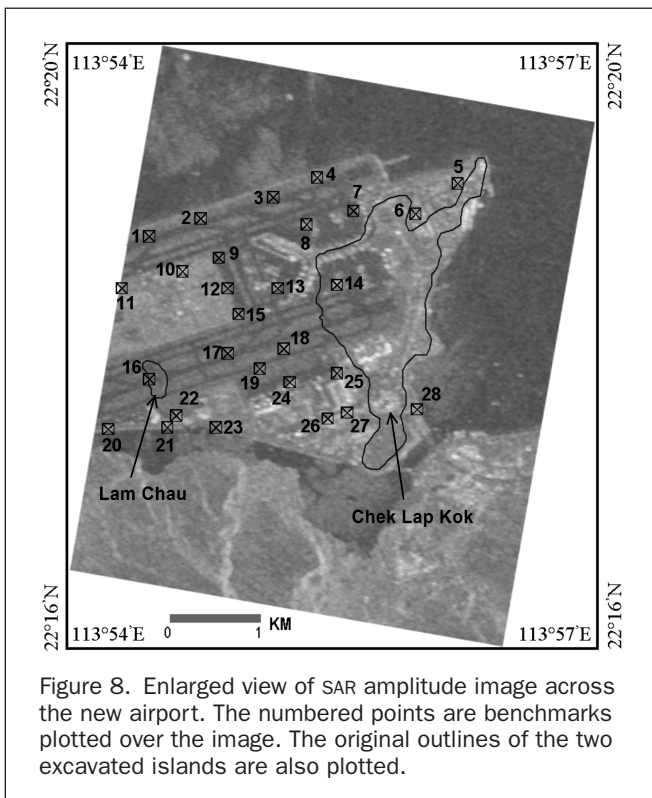
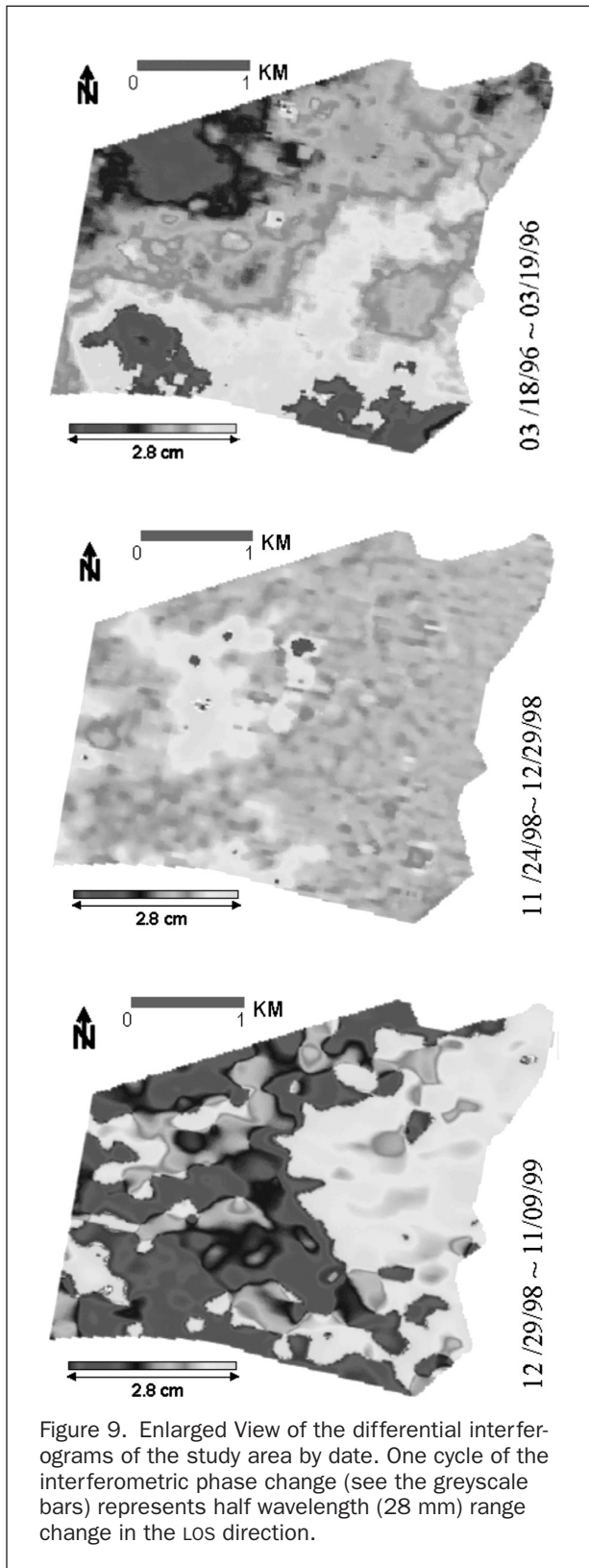
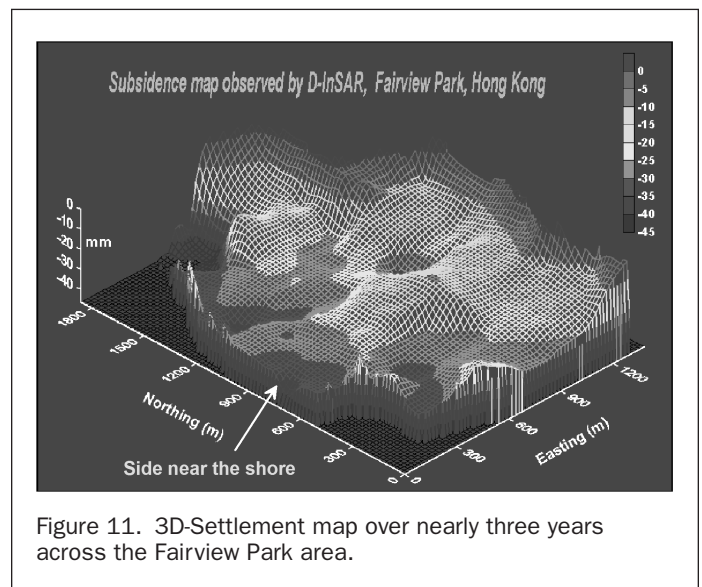
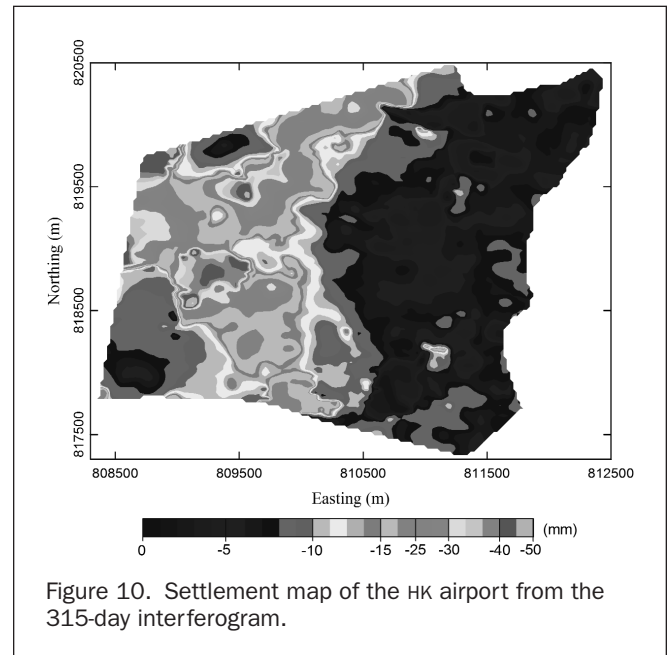


Figure 8. Enlarged view of SAR amplitude image across the new airport. The numbered points are benchmarks plotted over the image. The original outlines of the two excavated islands are also plotted.



series of settlement maps from other pairs (not shown here) are quite consistent with each other. It is very interesting to note that the subsidence (about 40 mm) on the side near the sea is much larger than that (about 0 mm) on the side farther from the sea, and that the gradual variations across the area are clear.



Conclusions

- INSAR can be used effectively to monitor ground settlement in flat and less built-up areas in HK even over long time spans. The steep mountainous and high-rise building areas in HK however present some difficulties for employing the technology.
- The atmospheric effects on INSAR measurements in HK can vary significantly both with time and location. The estimated effects from a tandem SAR pair over two test areas have indicated that centimeter errors in deformation measurements and up to 200 m DEM errors for typical baseline lengths. Therefore, care must be taken when interpreting INSAR results obtained in the region. On the other hand, the atmospheric effects on some of the settlement measurement results obtained in this study are apparently negligible. Further research is necessary to better understand and to develop methods to mitigate the atmospheric effects.
- The 315-day interferogram for the airport area has revealed varying magnitudes of settlement (up to 50 mm) between December 1998 and November 1999 due mainly to the

compression of soils beneath the seabed and the creep of the fill materials. The original outlines of the excavated islands can clearly be identified on the interferogram. The results agree well with levelling measurements. The interferometric measurements over the area of Fairview Park indicate up to 40 mm of settlement over a nearly three-year period.

Acknowledgments

The research was partly supported by the Faculty of Construction and Land Use of the Hong Kong Polytechnic University and by a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No. PolyU5064/02E).

References

- Bawden, W.G., W. Thatcher, R.S. Stein, K.W. Hudnut, and G. Peltzer, 2001. Tectonic contraction across Los Angeles after removal of groundwater pumping effects, *Nature*, Vol. 412:812–815.
- Fruneau, B., and F. Sarti, 2000. Detection of ground subsidence in the city of Paris using radar interferometry: Isolation of deformation from atmospheric artifacts using correlation, *Geophysical Research Letters*, Vol. 27:3981–3984.
- Gabriel, A.K., R.M. Goldstein, and H.A. Zebker, 1989. Mapping small elevation changes over large areas: Differential radar interferometry, *Journal of Geophysical Research*, Vol. 94:9183–9191.
- Galloway, D.L., K.W. Hudnut, and S.E. Ingebritsen, 1998. Detection of aquifer system compaction and land subsidence using interferometric synthetic aperture radar, Antelope Valley, Mojave Desert, California, *Water Resources Research*, Vol. 34:2573–2585.
- Goldstein, R.M., H.A. Zebker, and C.L. Werner, 1988. Satellite radar interferometry: Two-dimensional phase unwrapping, *Radio Science*, Vol. 23:713–720.
- Hanssen, R.F., T.M. Wechwerth, H.A. Zebker, and R. Klees, 1999. High-resolution water vapor mapping from interferometric radar measurements, *Science*, 283:1297–1299.
- Hanssen, R.F., 2001. *Radar Interferometry: Data interpretation and Error Analysis*. (Kluwer Academic Publishers, Dordrecht), 308 pp.
- Massonnet, D., K.L. Feigl, M. Rossi, and F. Adragna, 1994. Radar interferometric mapping of deformation in the year after the Landers earthquake, *Nature*, 369:227–230.
- Massonnet, D., T. Holzer, and H. Vadon, 1997. Land Subsidence caused by the East Mesa geothermal field, California, observed using SAR interferometry, *Geophysical Research Letters*, Vol. 24: 901–904.
- Plant, G.W., C.S. Covil, and R.A. Hughes, 1998. *Site Preparation for the New Hong Kong International Airport, 50-80*, Thomas Telford Publishing Ltd, London.
- Rosen, P.A., S. Hensley, I.R. Joughin, F.K. Li, S.N. Madsen, E. Rodriguez, and R.M. Goldstein, 2000. Synthetic Aperture Radar Interferometry, *Proceedings of The IEEE*, 88(3):333–382.
- Tarayre, H., and D. Massonnet, 1996. Atmospheric propagation heterogeneities revealed by ERS-1, *Geophysical Research Letters*, 23(9):989–992.
- Tatarski, V.I., 1961. *Wave propagation in a turbulent medium*, McGraw-Hill, New York.
- Zebker, H.A., and J. Villasenor, 1992. Decorrelation in interferometric radar echoes, *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 30:950–959.