Precision estimation and geomorphological analysis based on the DEM generated by InSAR: Taking Damxung-Yangbajain area as an example*

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Abstract Digital elevation model (DEM) can be generated by interferometric synthetic aperture radar (InSAR). In this paper, the interferometric processing and analyses are carried out for Damxung-Yangbajain area in Tibet, using a pair of Europe remote-sensing satellite (ERS)-1/2 tandem SAR images acquired on 6 and 7 April 1996. A portion of the InSAR-derived DEM is selected and compared with the 1:50 000 DEM to determine the precision of the InSAR-derived DEM. The comparison indicates that the root mean squared errors (RMSE), which are used to evaluate error, are about 35, 60, 10, and 15 m in the studied area, mountainous area, basin area and near-fault area, respectively, suggesting that obvious errors are mainly in mountainous area. Besides, the limitation of InSAR technology to generate DEM is analyzed. Our investigation shows that InSAR is an effective tool in geodesy and an important complement to field surveying in some dangerous areas.

Key words: InSAR; DEM; geomorphological analysis; Damxung-Yangbajain; root mean squared error

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1 Introduction

Interferometric synthetic aperture radar (InSAR) becomes a high precise DEM-generating method and a hotspot in earth sciences, because it can provide large scale images with high spatio-temporal resolution day and night (Zebker and Goldstein, 1998; Shan and Ye, 1998). Europe remote-sensing satellite (ERS)-1/2 of European Space Agency (ESA) can provide high coherence SAR data with one day interval for producing DEM. If the InSAR-derived DEM can meet the survey requirements, the relief map can be produced based on the DEM (Liu et al, 2000).

In this paper, a pair of ERS-1/2 tandem data covering Damxung-Yangbajain, Tibet, where the terrain and physiognomy are peculiar, is processed to generate DEM. Furthermore, the relationship between the InSAR-derived DEM and the specific geological condition, and the comparison between the InSAR-derived DEM and

1:50 000 DEM are studied.

According to the principle of InSAR (Figure 1), a pair of single look complex (SLC) data can be used to produce interferometric pattern, and then to attain a relative elevation, so 3D information can be obtained. The detail of formula derivation is omitted here.

Figure 1 Geometry of SAR interferometry.

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$$h = H - \frac{B^2 - \left(\frac{\lambda \cdot \Delta\varphi}{4\pi} \right)^2}{\frac{\lambda \cdot \Delta\varphi}{2\pi} - 2B \sin(\alpha - \theta)} \cos \theta \quad (1)$$

shows the main principle of deriving elevation from the phase difference by InSAR (Wang et al, 2002), where h is the height to be determined, B is the baseline length, θ is the side looking angle, α is the baseline tilt angle, λ is

the wavelength, R_1 and R_2 are the distance between the scatter and the radar antennas (O_1 and O_2) respectively, H is the height of the radar, and $\Delta\varphi$ is the difference between the two interferometrical phases.

The main steps of InSAR data processing are shown in Figure 2. The key technology is phase unwrapping and baseline parameter acquiring (Liao and Lin, 2003).

Figure 2 Processes of InSAR.

Extending from northern Samxung in the north to Angong in the south, the Damxung-Yangbajain graben located in the southeast of Nyainqentanglha Mountain consists of six basins (i.e., Gulu, Damxung, Ningzhong, Yangbajain and Jidago) and five transverse uplifts (i.e., Yanta, Juzhila, southern Damxung, southwestern Ningzhong and southern Yangbajain) (Institute of Geology, State Seismological Bureau, 1992). It is a narrow valley of 230–240 km long, 5–25 km wide and 4 300–4500 m high with generally NE-SN trending. The graben is formed in the Himalayan movement (Wang, 1998) and becomes one of the most seismic active areas in Tibet. The 1952 Damxung earthquake and another 1411 earthquake occurred along the Nyainqentanglha southeastern piedmont fault. Figure 3 shows the tectonic environment with faults that distribute in the studied area.

2 InSAR data and processing

Compared with other kinds of remote sensing data, SAR data is more economic, reliable and effective. Deformation of faults and elevation information can be obtained by InSAR in the areas, such as Tibet, which are difficult for people to arrive (Zhang and Shao, 1998; Ning et al, 2006). In this paper, we obtain DEM using a

Figure 3 Distribution of active structures and geomorphology in the Damxung-Yangbajain graben/half-graben system. The red solid line and dashed line denote strike-slip fault and inferred fault, respectively.

pair of ERS-1/2 tandem data by InSAR technology. The studied area is about $75 \times 67 \text{ km}^2$, ranging from $89^\circ 55' \text{E}$ to $90^\circ 40' \text{E}$ and from $29^\circ 50' \text{N}$ to $30^\circ 30' \text{N}$. The parameters of SAR data are shown in Table 1.

Table 1 Parameters of ERS-1/2 tandem data

No.	Satellite	Orbit	Track	Frame	Date a-mo-d	Center	
						Long /°E	Lat /°N
1	ERS-1	24713	176	2997	1996-04-06	90.331	30.261
2	ERS-2	05040	176	2997	1996-04-07	90.334	30.271
Azimuth resolution/m		28	Range resolution/m		26	Looks	5
Perpendicular baseline/m		95	Parallel baseline/m		45	Ambiguity height/m	99.04

The interferometric pattern is often affected by three factors: ① the noise of SAR data; ② the decorrelation caused by random motion of the Earth’s surface, such as vegetation growth, wind influence on vegetation and change of soil humidity; ③ the baseline decorrelation caused by different incident angles (Li et al, 2000).

Quality of the interferogram is the most intuitively estimated by coherence image. In this research, the average correlation coefficient is 0.58. The distribution of correlativities is asymmetric, and high-correlativity points are located in the uneven terrain.

Shuttle radar topography mission (SRTM) with 90 m resolution is used as the external DEM in data processing. It is subtracted from the interferometric pattern as a known terrain phase, then the residual phase is unwrapped, finally the external DEM is added back to get the elevation. Usage of external DEM can reduce difficulty of phase unwrapping, especially for the precipitous area, so as to guarantee the correctness of the phase

unwrapping result. On the other hand, external DEM can provide relative veracious elevation reference for correcting errors if the orbit parameters do not meet requirement. The iterative disk masking algorithm (Atlantis Scientific Inc., 2004) is used in the phase unwrapping.

3 Precision analysis of DEM

Scenographs produced by DEM are shown in Figure 4. The SRTM data is available as 3 arc-second (approximately 90 m resolution) DEM and the planar resolution is about 80.23 m×92.38 m. The spatial resolution of 1:50 000 DEM is about 24.95 m×25 m and that of the InSAR- derived DEM is about 20.68 m×20.31 m. The scenographs show that SRTM becomes blurry after being zoomed in; whereas the InSAR-derived DEM is better in revealing fine physiognomy compared with SRTM, which can meet the requirements of 1:50 000 map producing.

Figure 4 (a) DEM Derived by ERS-1/2 tandem radar image data; (b) InSAR-derived DEM zoomed in; (c) 1:50 000 DEM zoomed in; (d) Shuttle radar topography mission (SRTM) zoomed in.

In order to use DEM appropriately, it is important to analyze whether there is a rule of error distribution or whether the error distribution changes with terrain. Differences between the InSAR-derived DEM and the 1:50 000 DEM are obvious and some blank areas exist in the InSAR-derived DEM because of the specific terrain and radar shadow (Figure 5). Figure 5 also shows the statistical distribution of errors. Errors can be large in the areas with complex hypsography and the precision may not be good if comparing the error statistics with that of the 1:50 000 DEM.

The main reasons for errors are: ① The measurement error of the secondary planet attitude and orbit can affect the differential interferometry result. High precision

Figure 5 Distribution of the errors between the InSAR-derived DEM and 1:50 000 DEM.

DEM depends on high precision parameters of orbit and baseline. The error of elevation caused by orbit measurement can be reduced by using high precision orbital parameters or ground control points. ② The complex topography of the studied area can also cause foreshortening and layover in the SAR image. The incident angle of ERS is 23° , so the area with gradient larger than 20° can not be surveyed. The existence of shadow causes blanks in the image. And the temporal decorrelation caused by vegetation increases the noise, which make phase unwrapping more difficult. ③ The ambiguity height of the data affects the quality of DEM. In this paper, the perpendicular baseline is 95 m, which is a little small. Small perpendicular baseline is good for differential InSAR (D-InSAR), but not good for DEM generating which may be easily affected by error interferer. ④ The spatio-temporal change of atmospheric

condition can cause accessional delay of interference phase, which may reduce the precision of DEM. ⑤ The horizontal resolutions of the two DEMs are different. The InSAR-derived DEM is resampled when compared with 1:50 000 DEM, which may cause errors.

The common methods to estimate precision of DEM include point check, section plane check and contour set check (Tang et al, 1999). The former two ones are used in this paper. Firstly, the InSAR-derived DEM is resampled in order to make resolution the same as 1:50 000 DEM. Then the difference between the InSAR-derived DEM and 1:50 000 DEM is calculated point by point. The largest differences can be several kilometers, which are failing results caused by large gradient or radar shadow. Then 40 points (Table 2) are selected randomly; their longitude, latitude and elevation are acquired and the root mean squared error (RMSE), r , is calculated by

Table 2 Comparison between the altitude results of DEMs

No.	Lat /°N	Long /°E	InSAR-derived DEM/m	1:50 000 DEM/m	Absolute error /m	Relative error
1	30.420 366	90.033 821	4 854.481 934	4 826.207 031	28.274 902	0.585 862%
2	30.317 602	90.183 731	5 112.557 617	5 112.266 113	0.291 504	0.005 702%
3	30.416 153	90.235 276	4 913.680 176	4 904.449 707	9.230 469	0.188 206%
4	30.405 528	90.360 701	5 220.037 109	5 225.929 199	-5.892 090	-0.112 747%
5	30.177 103	90.559 578	4 523.543 945	4 517.763 672	5.780 273	0.127 945%
6	30.225 279	90.613 700	4 657.555 176	4 655.632 324	1.922 852	0.041 302%
7	30.242 132	90.611 338	4 682.810 059	4 678.887 207	3.922 852	0.083 842%
8	30.160 433	90.606 398	4 589.191 406	4 590.230 469	-1.039 063	-0.022 640%
9	30.078 735	90.542 397	4 468.191 406	4 463.591 797	4.599 609	0.103 047%
10	30.041 000	90.520 276	4 707.437 500	4 708.329 102	-0.891 602	-0.018 937%
11	30.397 285	90.368 004	5 413.258 301	5 425.070 801	-11.812 500	-0.217 739%
12	30.208 610	90.395 065	4 972.975 098	4 972.827 637	0.147 461	0.002 965%
13	30.338 484	90.291 760	5 363.283 691	5 350.546 387	12.737 304	0.238 056%
14	30.265 212	90.377 883	5 959.395 020	5 959.956 543	-0.561 523	-0.009 422%
15	30.082 765	90.235 276	5 231.559 570	5 211.685 059	19.874 511	0.381 345%
16	30.147 794	90.141 851	5 452.041 504	5 476.702 148	-24.660 644	-0.450 283%
17	30.254 771	90.107 488	5 200.050 293	5 199.638 184	0.412 109	0.007 926%
18	30.384 646	90.471 093	5 611.527 832	5 638.745 605	-27.217 773	-0.482 692%
19	30.326 028	90.490 852	5 567.168 457	5 560.940 918	6.227 539	0.111 987%
20	30.353 139	90.616 063	5 590.375 000	5 600.552 734	-10.177 734	-0.181 727%
21	30.321 815	90.591 579	5 268.854 980	5 220.986 328	47.868 652	0.916 851%
22	30.304 962	90.552 276	5 109.443 359	5 115.711 426	-6.268 067	-0.122 526%
23	30.089 176	90.195 973	5 899.357 910	5 931.280 762	-31.922 852	-0.538 212%
24	30.399 300	90.129 609	5 075.857 910	5 083.979 980	-8.122 070	-0.159 758%
25	30.059 868	90.055 943	5 533.756 836	5 525.579 590	8.177 246	0.147 989%
26	30.273 639	90.380 245	6 128.249 023	6 164.446 777	-36.197 754	-0.587 202%
27	30.302 947	90.311 519	6 114.982 910	6 059.259 766	55.723 144	0.919 636%
28	30.395 087	90.554 639	6 071.896 973	6 077.871 582	-5.974 609	-0.098 301%
29	30.328 043	90.490 852	5 446.993 652	5 447.192 871	-0.199 219	-0.003 657%
30	30.281 882	90.372 943	6 089.278 320	5 995.455 566	93.822 754	1.564 898%
31	30.237 919	90.559 578	5 174.058 105	5 190.277 832	-16.219 727	-0.312 502%
32	30.265 212	90.210 792	5 437.871 582	5 553.077 148	-115.205 566	-2.074 626%
33	30.242 132	90.063 245	5 026.275 879	4 972.091 309	-4.184 570	1.089 774%
34	30.403 513	90.444 247	5 705.863 770	5 758.571 777	-52.708 007	-0.915 297%
35	30.372 006	90.400 004	5 285.053 711	5 323.619 629	-38.565 918	-0.724 430%
36	30.095 405	90.446 609	4 708.444 824	4 665.668 945	42.775 879	0.916 822%
37	30.112 257	90.586 639	4 917.083 984	4 968.346 191	-51.262 207	-1.031 776%
38	30.204 397	90.601 459	4 590.818 848	4 592.651 855	-1.833 007	-0.039 912%
39	30.175 088	90.616 063	4 690.658 203	4 691.560 059	-0.901 856	-0.019 223%
40	30.223 264	90.557 216	5 043.203 613	5 045.349 609	-2.145 996	-0.042 534%

the following equation:

$$r = \sqrt{\frac{\sum_{i=1}^n (y_1 - \hat{y}_1)^2}{n}}, \quad (2)$$

where y_1 and $\hat{y}_1$ are mensurated result and forecasted result respectively, and n is the number of the samples.

RMSEs of the whole image and 40 points are separately 53.21 m and 33.59 m with largest error of 115.21 m. There are 10 points with errors above 35 m. The difference in RMSE between 40 points and that of the whole image is less than 1 pixel.

Section planes are made randomly on DEM in order to validate the result. Eight section plane curves are made in x -, y -, and arbitrary direction respectively (Figure 6). As listed in Table 3, RMSE of each section plane shows the difference between the RMSEs is less than 1 pixel. Besides, the InSAR-derived DEM exhibits the same trend of terrain and main hypsographic features as that of 1:50 000 DEM with average correlation coefficient of 0.99.

RMSE of section planes in different directions is basically consistent to that of 40 points and the whole image with the difference of less than 1 pixel. So it can

Figure 6 Comparative relief profiles between the identical points of InSAR-derived DEM and 1:50 000 DEM in x - (a), y - (b) and arbitrary directions (c).

Table 3 RMSE of different profiles in x -, y -, and arbitrary directions

(unit in m)

Direction	r_1	r_2	r_3	r_4	r_5	r_6	r_7	r_8	Average
x direction	33.49	23.25	38.11	24.72	44.82	22.30	21.11	38.10	30.74
y direction	32.18	49.77	22.44	28.87	31.39	24.73	38.19	35.59	32.89
Arbitrary direction	45.35	42.75	20.90	29.56	33.56	33.35	38.84	26.61	33.86

Note: $r_1, r_2, \dots, r_8$ denote the root mean squared error of the eight sections.

be considered that the precision of InSAR-derived DEM of the Damxung-Yangbajain area is about 35 m. By the same estimating method, we get the precision is about 60, 10 and 15 m in mountainous area, basin area and the near fault area, respectively.

4 Geomorphological analysis

The Nyainqentanglha southeastern piedmont fault, i.e., western boundary fault of Damxung-Yangbajain graben/half-graben system, strikes northeast and dips southeast, with total length of 240 km. The fault exhibits complex geometric pattern and active characteristic. The fault is divided into three sections, i.e., northern section with NNE-trend, central section and southern section. Among them, the central section striking $N40^{\circ}\text{--}50^{\circ}\text{E}$ and with length of 130 km, consists of several strands characterized by left-lateral strike-slip normal fault, forming three subzones with left-step en echelon pattern. The stepovers generate pull-apart structures in northwest of Damxung and north of Yangbajain, where develop two subparallel $N30^{\circ}\text{--}40^{\circ}\text{E}$ -trending faults and shear-extensional fracture, respectively (Institute of Geology, State Seismological Bureau, 1992).

The NE-trending Damxung-Yangbajain graben and half-graben system consists of six sub-basins and five horsts in turn. The western boundary of the system is controlled by the active Nyainqentanglha southeastern piedmont fault, and the eastern boundary is controlled partly by active faults (Figure 7). The system is asymmetric in the cross-section due to different activities

Figure 7 Slope map produced by InSAR-derived DEM.

along both eastern and western boundaries of the system.

The central and southern section of the Nyainqentanglha southeastern piedmont fault starts at north of Damxung, extends toward southwest to west of Yangbajain, then turns southward to west of Yangyinxiang with a total length of 136 km. The surface rupture of the central-southern section is divided into two sections by strike and active characteristics. One is left-lateral strike-slip normal fault, extending from Damxung in the north to Yangbajain in the west along the strike of $N45^{\circ}\text{E}$, with length of 108 km. The maximum vertical offset is 8–9 m near the west of Ningzhong and the maximum horizontal offset 11–13 m near the north of Yangbajain. The other extends from the Yangbajain to Yangyinxiang along north-south direction, with a length of 28 km. It consists of a series of tensile and shear-tensile ruptures with right-lateral offset 2–4 m and vertical offset 1–4 m. The maximum vertical offset is 5 m (Institute of Geology, State Seismological Bureau, 1992). The central and southern section of the fault is associated with the south of Damxung $M8$ earthquake in the year 1411. Field investigation in the studied area also demonstrates that the surface rupture is still obvious (Figure 8).

Figure 8 Surface rupture caused by Damxung earthquakes in history.

5 Conclusions

Based on a pair of ERS-1/2 data on 6 and 7 April 1996, this paper generates the elementary DEM of Damxung-Yangbajain area, from which we can get abundant hypsographic information, by InSAR technology. Comparing with SRTM (90 m resolution) and 1:50 000 DEM (25 m resolution), the resolution of InSAR-derived DEM is about 20 m, which suggests that DEM generated by InSAR can meet the 1:50 000 mapping requirement in terms of resolution. Then we esti-

mate the precision by comparing it with 1:50 000 DEM, by taking RMSE as the error index. The result indicates that errors exist to different extents, while obvious errors are mainly in mountainous area. And the error in the whole studied area, mountainous area, basin area and the near-fault area are about 35, 60, 10 and 15 m, respectively.

By the experimental study of the Damxung-Yangbajain area, the conclusion can be drawn that InSAR is a very effective surveying method specially in the areas which are difficult for people to reach, and DEM can be generated by InSAR more automatically compared with other surveying methods.

The main steps of data processing include the co-registration, resampling of the SAR image pair, calculation of the phase interferometric pattern, phase unwrapping, calculation of baseline, geometry transformation and geocoding. Among them, phase unwrapping and calculation of parameters and models of the baseline are need to be further studied.

The ways to improve the precision of interferential DEM include: ① increasing the temporal correlation which relies on the design of hardware system; ② controlling the baseline decorrelation and decreasing the ambiguity height which depends on the selection of interferential pair eclectically, i.e., the baseline should not be too large or too small, and 200–300 m is appropriate for ERS-1/2 system (Zeng and Jiao, 1998); ③ the models and parameters should be calculated precisely; ④ methods of correcting atmospheric phase delay should be improved.

The technology of InSAR including arithmetic, software, analysis method and hardware can meet the requirements of practical application. However, accuracy of the data should be improved. The data in use is acquired from the same secondary planet imaging in two

adjacent orbits, and it is effected by excursion, aviation change and earth motion in certain period, which can cause errors. The precision of InSAR can be highly improved along with the launch of bi-antenna radar system.

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References

- Atlantis Scientific Inc. (2004). *EV-InSAR User's Guide*. Version 3.1. Atlantis Scientific Inc., Nepean, Ontario, Canada, 39–40.
- Institute of Geology, State Seismological Bureau (1992). *Active Faults in the Central Tibet*. Seismological Press, Beijing, 93–96 (in Chinese with English abstract).
- Li D R, Zhou Y Q and Ma H C (2000). Principle and applications of interferometric SAR. *Survey Science* **25**(1): 9–12 (in Chinese).
- Liao M S and Lin H (2003). *Interferometric SAR—Principle and Data Processing*. Surveying and Mapping Press, Beijing, 38–41 (in Chinese).
- Liu G X, Ding X L and Liu Y Q (2000). New and potential technology for observation of earth from space: Synthetic aperture radar interferometry. *Advance in Earth Sciences* **15**(6): 734–740 (in Chinese with English abstract).
- Ning S Z, Ren J W, Shan X J, Tao W and Zhou M D (2006). Application of spaceborne synthetic aperture radar interferometry on morphotectonic research in Bengcuo area of Tibet. *Seismology and Geology* **28**(1): 111–118 (in Chinese with English abstract).
- Shan X J and Ye H (1998). The InSAR technique: Its principle and applications to mapping the deformation filed of earthquakes. *Acta Seismologica Sinica* **11**(6): 759–769.
- Tang X M, Lin Z J and Wu L (1999). Estimation of DEM precision based on counters and elevation point. *Remote Sensing Information* **55**(3): 7–10 (in Chinese).
- Wang C, Zhang H and Liu Z (2002). *Secondary Planet Interferometric Synthetic Aperture Radar*. Science Press, Beijing, 46–50 (in Chinese).
- Wang Y P (1998). Principal features of the active tectonics in Qinghai-Xizang Plateau. In: Institute of Geology, China Seismological Bureau eds. *Study on Tectonic Faults* (6). Seismological Press, Beijing, 22–26 (in Chinese).
- Zebker H A and Goldstein R M (1998). Topographic mapping from interferometric SAR observations. *J Geophys Res* **91**(9): 4 993–4 999.
- Zeng Q M and Jiao J (1998). *Principles and Applications of SAR*. 4th ed. *Remote Sensing Information* **4**: 42–46 (in Chinese).
- Zhang J F and Shao Y (1998). InSAR and its applications. *Seismology and Geology* **20**(3): 277–287 (in Chinese).