Chinese Journal of Polar Science, Vol. 9, No. 2, 118 - 124, December 1998

The extraction of elevation information of ice-sheet surface on south area of the Larsemann Hills in East Antarctica

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Received June 5, 1998

Abstract Based on the setting up of the function relation between the radiant brightness of ice-surface and the elevation control point in Antarctica, the experiments for the extraction of elevation information by using thermal infrared image of Landsat TM band 6, and the ice-surface topographical maps in area nearby Larsemann Hills have been performed.
Key words thermal infrared image, radiant brightness, elevation of ice-sheet surface, Larsemann Hills.

1 Introduction

The experiment area is located at 75° - 78°E, 69°15′ - 70°15′S in East Antarctica, or on the verge of Antarctic ice sheet. Antarctic pole is 2300 km from here. It is a big slope, rising in the southeast and bordering on the Prydz Bay in the northwest, with the height difference of 1800 m. In January of every year, the average air temperature in Larsemann Hills is 0 ℃ more or less in daytime, and drops to about −6 ℃ at night. At the height of 1000 m above the ice sheet, the average temperature is around −5 ℃ in daytime, and below −10 ℃ at night. The elevation of ice sheet surface and the ice surface temperature are closely correlated (NIPR 1988; Sun 1997).

The satellite image acquired from thematic mapper of Landsat 4 on January 20, 1989 was used for the experiment. Its orbit number is 124/109. The total amount is divided into seven bands. TM band 6 is a thermal infrared image, with the wavelength range from 10.4 μm to 12.5 μm. Its spacial resolution is 120 m and noise equivalent temperature difference (NEΔT) is 0.5 K.

2 The extraction of elevation information of ice-sheet surface

2.1 *Image radiant characteristics*

According to the Planck law, on Antarctic ice-sheet, the ice surface radiant power in TM6 band's range is:

$$W = \varepsilon\int_{10.4}^{12.5}\left(\frac{2\pi hc^2}{\lambda^5}\frac{1}{e^{hc/\lambda KT}-1}\right)d\lambda = \varepsilon\left(\frac{2\pi hc^2}{11^5}\frac{1}{e^{hc/11KT}-1}+\frac{2\pi hc^2}{12^5}\frac{1}{e^{hc/12KT}-1}\right) \quad (1)$$

For local area around Larsemann Hills, emissivity ε is a constant, so the ice surface radiant power is only the function of the ice surface temperature(T):

$W = f_1(T)$ (2)

The relationship between the image brightness value (I) and the radiant power (W) in ice surface is:

$I = KW$ (3)

Where K is sensor's response coefficient. So, the ice-sheet surface image brightness value also is the function of the ice surface temperature:

$I = f_2(T)$ (4)

2.2 The relationship between the ice-sheet surface elevation and the radiant brightness value in TM6

Temperature descends along with altitude ascending (NIPR 1988), and there is a function relation between elevation (H) and the ice surface temperature (T):

$H = f_3(T)$ (5)

According to formula (4) and formula (5), the elevation H is also the function of TM6 image brightness value(I):

$H = f_4(I)$ (6)

The known control points coordinates are gotten from 1:1000000 map of the Prydz Bay published by USAF(United States Air Force), and the brightness values of these points are measured from TM6 image (see Table 1). From Table 1, the function relationship between the elevation (H) and the brightness value (I) is obviously shown.

Table 1. The relationship between elevation and radio brightness

Elevation /m	Longitude	Latitude	Brightness value
300	76°41′55″	69°21′38″	72.0
600	76°37′28″	69°28′08″	66.0
700	76°35′51″	69°31′39″	63.0
800	76°32′49″	69°37′04″	61.0
900	76°26′51″	69°47′04″	60.0
1000	76°28′25″	69°51′24″	58.8
1100	76°22′02″	69°56′48″	57.3
1200	76°19′17″	70°00′32″	56.4

2.3 Extracting the ice surface elevation information

The relationship between the ice surface elevation and the TM6 image brightness value can be imitated by using a high order polynomial (Sun 1997):

$$H = \sum_{i=0}^{k} C_i I^i \quad (7)$$

Where C_i is indeterminacy coefficients. Because there are many observation values, it is possible to use Least-Squares Procedure. Error equation is:

$$V = A\Delta - M \tag{8}$$

Normal equation is:

$$[A^T A]\Delta = A^T M \tag{9}$$

Indeterminacy coefficient is:

$$\Delta = [A^T A]^{-1} A^T M \tag{10}$$

Where $V = [V_1 \quad V_2 \quad \cdots \quad V_n]^T$ is error vector, $n = 8$. $\Delta = [C_1 \quad C_2 \quad \cdots \quad C_k]^T$ is indeterminacy coefficient vector.

$$A = \begin{bmatrix} I_1 & I_1^2 & \cdots & I_1^k \\ I_2 & I_2^2 & \cdots & I_2^k \\ \cdots & & & \\ I_n & I_n^2 & \cdots & I_n^k \end{bmatrix}$$

Where A is the brightness value matrix of the known elevation control point in TM6 image. $M = [H_1 \quad H_2 \quad \cdots \quad H_n]^T$ elevation value vector, $n = 8$.

According to the calculated indeterminacy coefficient Δ, each pixel elevation in TM6 image can be calculated by its brightness value through formula (7), then the 100 m contour can be interpolated from the raster topography map, and through raster to vector, the vector topography map is obtained (see Fig. 1).

3 Influence factors discussing

3.1 *Emissivity influence*

The emissivity of the ice-sheet surface in the middle part of East Antarctica is 0.70 (Hall and Martinec 1985; Richard and Hudson 1969). The ice-sheet surface in the south of Zhongshan Station is similar to that in East Antarctica, so their emissivity are also identical. Emissivity changing in the whole do not effect the calculation of elevation, but formula(2) may be invalidated if the surface is not ice-sheet but other substances, such as bare rock of hill, sea water in the Prydz Bay, because their emissivities are very different to the ice's one. There is a bare hill with the highest altitude (160 m) called Friendship Peak. In order to prevent the influence of the different emissivity of these substances on the extraction of elevation, we only survey the contour lines starting from 200 m upwards.

3.2 *Reflex influence*

On the Antarctic ice surface the intensity of the reflect radiation is much stronger. The reflectivity is over 90% in 0.5 μm, but descends sharply in infrared spectrum range, and becomes very low after 1.4 μm, even to 0% (Wiscombe and warren 1980, Fig. 2). The snow under the irradiation of the sun absorbs the radiation energy of the spectrum near 0.5 μm and reemit the energy in the spectrum of 10 μm(Richard and Hudson 1969). According to Verne law, wavelength of radiation peak value will increase along with the descending of temperature. Among the temperature's range of the earth surface, the waves with the strongest emissive radiation intensity are between 8 - 14 μm, corresponding to lower reflectivity (Wiscombe and warren 1980). By this token, though the reflect intensity is very strong on the

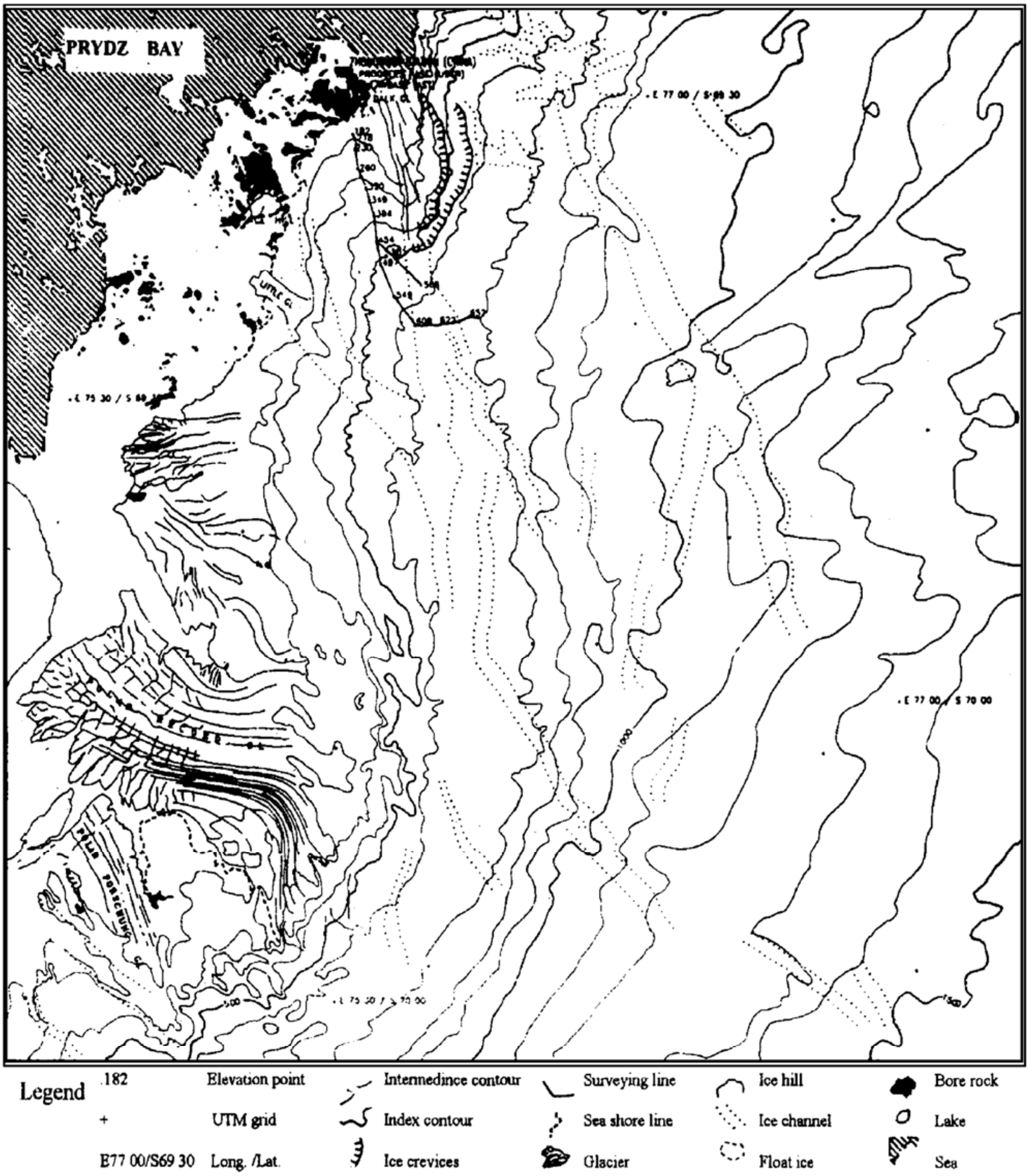

Fig. 1. Ice-sheet surface topographic map.

ice surface of the Antarctica, the influence is needed to be considered only on the range of the visual and near-infrared spectrums and can be ignored on the range of the spectrums with 10.4 – 12.5 μm.

3.3 Sea water influence

The temperature of the sea water is higher than that of the ice surface and will influence the seacoast area. The temperature varies at the different place with the same elevation because of the different distances off the seashore, especially the tem-

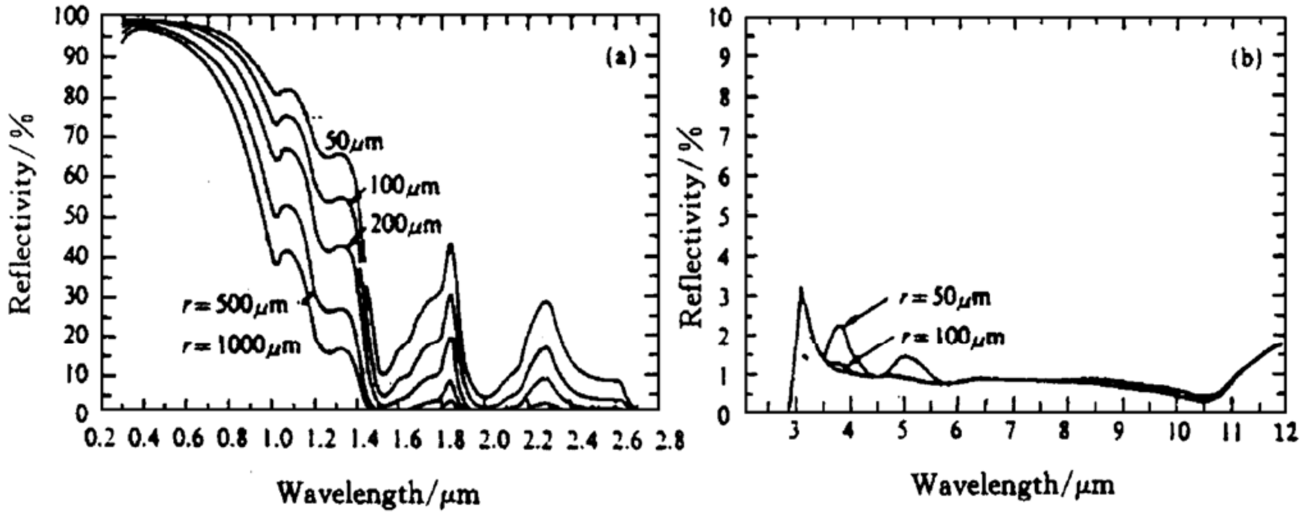

Fig. 2. The relationship between ice surface reflectivity and wavelength(Wiscombe and warren 1980).

perature of the ice surface layer. As a result, the error comes into being in the process of calculating elevation. In order to determine the connection between the elevation and the distances off the seashore, we get other group of eastern elevation control points from 600 m to 1500 m on the same USAF map, measuring their distances off the seashore, reading out their pixel brightness values from TM6 image respectively (see Table 2), and comparing to the elevation control points and their distances off the seashore in Table 1. We found that the differences of the pixel brightness values in TM6 image are not distinct in spots with the same elevation which are near seashore and that the differences of the pixel brightness values in TM6 image are clear if the differences of the spots' distances are large. The distances off seashore of the same elevation points are among 10 – 15 km and their pixel brightness values' differences are less than 1 in this test area. Thus, we can remove the influence after simple linear interpolation according to the distances off seashore.

Table 2. The relationship between the brightness values and the distance off the seashore in the eastern and western groups of elevation points

Elevation /m	Eastern elevation point				Western elevation point			
	Longitude	Latitude	Distance off the seashore /km	Brightness value	Longitude	Latitude	Distance off the seashore /km	Brightness value
300				72.0	76°41′55″	69°21′38″	4.5	72.0
600	76°53′55″	69°25′43″	13	66.0	76°37′28″	69°28′08″	11	66.0
700	76°58′36″	69°26′00″	18	63.0	76°35′51″	69°31′39″	17	63.0
800	77°07′24″	69°26′30″	24	61.0	76°32′49″	69°37′04″	25	61.0
900	77°20′16″	69°27′20″	29.5	60.0	76°26′51″	69°47′04″	28.5	60.0
1000	77°35′04″	69°28′10″	32	58.6	76°28′25″	69°51′24″	30	58.8
1100	78°19′38″	69°24′07″	40	56.8	76°22′02″	69°56′48″	35	57.3
1200	78°22′26″	69°29′17″	50	55.6	76°19′17″	70°00′32″	37	56.4
1300	78°25′43″	69°34′33″	59	54.5				
1400	78°27′26″	69°38′40″	65	53.5				
1500	78°35′51″	69°52′03″	90	52.0				

3.4 *Shadow influence*

Because reflex is very weak in the snow surface in TM Band 6, there is only sensitivity on the infrared spectrum emission from snow surface temperature. There is a large slope in the south of the Larsmann Hills, with less terrain undulation, wide and shallow ice channels, unclear channel outline and less temperature difference between positive slope and negative slope, so it seems unnecessary to correct the influence in many areas. Only on the sea mouth of the Dark glacier, there is a east-side steep slope (300 m fall), and the shadow will affect accuracy of elevation in the lower part of this area with the errors being about 100 m.

3.5 *Time and climate influence*

The changes of time and climate influence largely the snow surface temperature, but the formation time of an image is within 30 s, and all information is gotten synchronously, so the relative relation is steady. There is a violent katabatic wind from inland to sea in Antarctic area, beginning from 22 – 24 in the evening, ending till 7 – 8 on the next morning. The ice surface temperature changes sharply, the lowest temperature at 2 – 4 in the early morning and warming gradually after 6 in the morning. Because the formation time is synchronous and after 7 – 8 in the morning, the time influence can be ignored. The katabatic wind's direction is the same as the altitude changing direction and its influence is presented at pixel brightness values in Table 1 and needs not to be corrected any more.

3.6 *Noise influence*

The noise equivalent temperature is 0.5 K in TM6. According to Planck formula and the relationship between the temperature differences and the elevation in this area, the noise equivalent temperature (0.5 K) may affect the accuracy of surveying elevation when altitude difference is less than 50 m. In order to avoid the noise influence, the survey of contour is made at 100 m of contour-interval.

4 Contour accuracy assessment

Finally, check it with 40 elevation points on the ice surface measured with the transit traverse in Polar Research Institute of China in Jan., 1991. Each point's error is listed in Table 3. The following formula may be used to calculate its mean-squared error:

$$\delta = \pm \sqrt{\frac{[VV]}{n-1}} \tag{11}$$

It is ± 13.34 m, not more than 1/2 contour interval, which reaches the elevation accuracy regulated by National Bureau of Surveying and Mapping of China.

Acknowledgments This project was supported by the National Science and Technology Committee of China (C85-03-07). We would like to thank Prof. E Dongchen, Lin Kaiyu, Gan Xinzheng and Mr. Guo Xiaogang for their support and help.

Table 3. Elevation errors list

Point No.	Survey in elevation /m	Interpolation elevation in map /m	Error /m	Point No.	Survey in elevation /m	Interpolation elevation in map/m	Error /m
1	182	182	0	21	515	530	+15
2	204	200	−4	22	524	540	+16
3	218	210	−8	23	549	571	+22
4	230	229	−1	24	551	590	+39
5	260	278	+18	25	566	604	+38
6	286	301	+15	26	609	613	+4
7	320	314	−6	27	613	614	+1
8	335	335	0	28	618	618	0
9	344	341	−3	29	622	634	+12
10	349	353	+4	30	623	646	+23
11	375	374	−1	31	641	665	+24
12	386	381	−5	32	689	688	−1
13	394	389	−5	33	700	700	0
14	423	413	−10	34	501	508	+7
15	444	438	−6	35	511	518	+7
16	454	456	+2	36	523	523	0
17	478	483	+5	37	531	537	+6
18	475	482	+7	38	552	549	−3
19	497	511	+14	39	554	563	+9
20	512	525	+13	40	566	580	+14

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