THE STUDY OF REMOTE SENSING ON MONITORING ICE VELOCITIES AND FLUXES OF THE POLAR RECORD GLACIER AND THE DARK GLACIER

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ABSTRACT：The measurement of ice velocities and fluxes of the Antarctic glaciers is very significant to the study on the Antarctic ice and snow mass balance, the Antarctic environment change and its influence on the global environment. This paper discusses the principles and methods of monitoring the glacial change by means of multi-temporal satellite images of remote sensing. After performing the geometric rectification, registration and overlay processing on different temporal remotely sensed images in the Ingrid Christensen coast. It measures and calculates the average ice velocities and fluxes of the Polar Record Glacier and the Dark Glacier. Besides, it preliminarily analyzes and evaluates their changing characteristics.

Key words：The Ingrid Christensen Coast, multi-temporal remotely sensed images, the Polar Record Glacier, the Dark Glacier, glacial ice velocities and fluxes

0. Introduction

The measurement of ice velocities and fluxes of the Antarctic glaciers is very significant to the study on the Antarctic ice and snow mass balance, the Antarctic environment change and its influence on the global environment.

There are many kinds of methods to measure the ice velocities at present. The first method is to measure it in local position including traditional measurement and local measurement with GPS (Rachael Manson et al.2000). This method has high precise but there is very dangerous under the climate and environment especially squall and ice crack leading to the people and device destroyed (Abdalati and Krabill, 1999). Flag of measurement is set at Glacier for the safety of staff, and then it is observed with measure angle or intersection of distance in periodic; meantime GPS is set at Glacier, difference calculation with the stabile station is done to get velocity. In the former two methods, there would be extruded and destroyed or fall into the ice crack when glacier moves .The power provision of receiver device of GPS is still a difficult problem.

The second method is aerophotography in periodic, and then the changeable glacier is observed with photogrammetry (Brecher,1986, Krimmel, 1987). But it is influenced by climate and condition in aerophtotgraphy, moreover, there had been difficult that the reflection of ice surface is to strong and the ground control points is difficult to measure.

The third method is to use to aero laser altimeter to monitor the velocity of glacier, it is tested in Greenland (Abdalati, 1999).It is restricted by the climate and environment in Polar as areophotography.

The fourth method is to use interference synthetic aperture antenna radar (INSAR) such as interference images of the same area acquired by ERS-1 and ERS-2 satellite of European Space Bureau to measure the velocity of glacier moving (Joughin et al., 1995, Rignot, et al. 1995,Kwok and Fahnestock 1996).

The last method is to use satellite multi-spectral and multi-temporal images to measure the velocity and fluxes of the glacier moving (Scambos, et.al, 1992,Scambos and Bindschadler, 1993). This method has the advantage of safety and could choose the suitable temporal satellite images to monitor and analyze in general.

There are tens of glaciers that flow to seacoast from the land at The Ingrid Christensen Coast in southeastern polar Princess Elizabeth Land. Among the glaciers, the nearest to Zhongshan Station is Dark Glacier which lies in the east of Mirror peninsula at Larsemann Hills .It had been occurred ice crack in 1988. The broken glacier lingua, which lies in front of the glacier, flows to sea and forms many ice mountains.The largest glacier is Polar Record Glacier at the southwestern of Larsemann Hill with distance of 50Km. Its width is above 25Km.There are three research stations including China, Russia and Austria in Mirror semi-island, but it had not been reported on the velocity and fluxes of the two glaciers. This paper have monitored dynamically the Polar Record Glacier and Dark Glacier with the satellite images acquired in three dates and with three different sensors in the same area and gotten the good result.

1. Data

The used data are MSS image from Landsat-1 of U.S, TM image from Landsat-4 and SAR image from Radarsat of Canada. Table 1 shows the orbit characteristic of the above three satellites.

Table 1. The orbit characteristics of Landsat-1, Landsat-4 and Radarsat satellites

Name of RS satellites	Orbit Altitude	Slant Angle of Orbit	Run Cycle	Revisit Time (day)	Time passing the equator (local time)	Sensors in Satellite
Landsat-1	915	99.125^0	103.26’	18	$9^h 42^m$, $21^h 42^m$	MSS, RBV
Landsat-4	705	98.22^0	98.9’	16	9^h 45,$21^h 45^m$	MSS, TM
Radarsat	814	98.6^0	101’	24	6^h ,18^h	SAR

Table 2 the sensor characteristics of Landsat-1, Landsat-4 and Radarsat satellite

Table 2 shows the characteristic of three sensors.

Name of RS Satellites and sensors	Spatial resolution	Bands	Bands range
Landsat-1 MSS	80 240(hot IR)	4(5)	MSS4 0.5-0.6 μ MSS5 0.6-0.7 μ MSS6 0.7-0.8 μ MSS7 0.8-1.1 μ (MSS8 10.4-12.6 μ)
Landsat-4 TM	30 120(hot IR)	7	TM1 0.45-0.52 μ TM2 0.52-0.60 μ TM3 0.63-0.69 μ TM4 0.76-0.90 μ TM5 1.55-1.75 μ TM6 10.4-12.5 μ TM7 2.08-2.35 μ
Radarsat SAR	Multi-beam 80-100	1	C-band 5.6cm Polarize HH

SAR of Radarsat is a multi-beam radar, the relation between different beam and resolution, incident angle shows in table 3

Table 3. The relation of beam, resolution and incident angle of the multi-beam SAR on the Radarsat satellite.

Beam name	Incident angle (degree ^{0})	Resolution (m)
Standard beam	20-49	25*28
Width Beam	20-31	(30-48)*28
Width Beam	31-39	(25-32)*28
High resolution beam	37-48	(9-11)*9
Scan SAR (N)	20-40	50*50
Scan SAR (W)	20-49	100*100
High incident angle	50-60	(19-22)*28
Low incident angle	10-23	(28-63)*28

It is necessary to use Satellite images data acquired in different time to monitor the velocity and fluxes of the glacier. With the development of new sensors, dismiss of old sensors, application of new sensors and the influence of photography and condition, such as the images acquired with MSS, TM should be run in day under the condition of no cloud; While Radarsat is not influenced by climate and time, but to photography polar image, the right-side looking of SAR designed primary must be changed an angle of 180 degree to left side looking. The antenna of SAR was turned to left looking on carrying Polar mission with RADARSAT between Sep. 09, 1997 to March 11, 1997 by Canada. So the polar images are acquired only in this time. Satellite images acquired in three times were selected to monitor the velocity and fluxes, on the basis of former reasons, images acquired with three kinds remote sensing satellites and different sensors were selected. The resolution, acquisition data is shown in table 4.

Table 4. The acquisition date, resolution, band and wavelength of the satellite images

Name of RS satellites and sensors	Acquired date	Resolution (m)	Bands	Wavelength(μ)
Landsat-1 MSS	Feb. 4,1973	80	MSS7	0.8-1.1
Landsat-4 TM	Jan. 20,1990	30	TM4	0.76-0.90
Radarsat SAR	Sep. 14,1997	50	C band	5.6cm

2. Images processing

2.1 Enhancement

2.1.1 Contrast adjustment

Velocity of glacier moving is monitored by shape and texture of glacier. Only single band is adopted among the images acquired with three sensors on three different dates (shown in table 4). The NR band was selected in MSS and TM for the display of ice is the best and the character of texture of SAR is better than other bands. The difference is large between the ice surface and seawater in this region with large area. A three-segment contrast stretch (see Fig. 1) is adopted to stretch middle hue.

$$I' = \begin{cases} A_1 I + B_1 & when \quad a < I < b \\ A_2 I + B_2 & when \quad b < I < c \\ A_3 I + B_3 & when \quad c < I < d \end{cases} \qquad (1)$$

Where a,b,c,d is threshold, judged by the primary image.

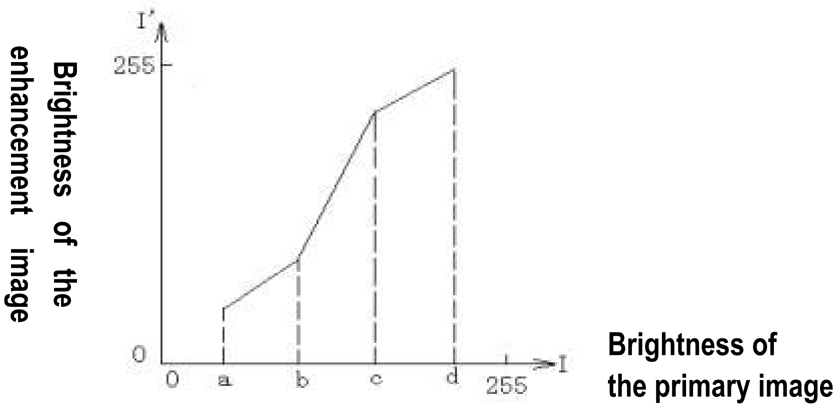

Fig. 1. The multi-linear contrast stretch in three segments

2.1.2. Enhancement of edge

Laplacian algorithm is used to crisp the image to enhance the shape and texture of glacier.

$$g(x,y)=\nabla^2 f(x,y) \tag{2}$$

In practice, the neighbor area of the primary image is done with quadric differential

$$\nabla^2 f(x,y)=f(x+1,y)+f(x-1,y)+f(x,y+1)+f(x,y-1)+f(x,y-1)-4f(x,y) \tag{3}$$

Formula 3 is extraction of edge, and the result should be added to the image, at last the enhancement image is gotten:

$$g'(x,y)=2f(x,y)+g(x,y) \tag{4}$$

2.2. Rectification of image

The TM images with the highest resolution (30m) is regarded as the basis images, it should be rectified and adopted with Gauss projection. 7-ground control points distributed on the Larsemann Hill are measured (Altazimuth and Laser Ranger). Its geodesic and image coordinate is shown in table 5.

Table 5. The geodesic and image coordinates of ground control points

Points no.	Image coordinates		Geodesic coordinate	
	L	P	Y	X
1	2934	3226	2289479	514754
2	3003	3323	2286627	516334
3	3017	3295	2286617	515472
4	3052	3291	2285773	514960
5	3007	3225	2287694	513850
6	2976	3181	2289026	513099
7	3100	3202	2285695	512208

Polynomial with one order is adopted to

$$X=a_0+a_1L+a_2P$$

$$(5)$$

$$Y=b_0+b_1L+b_2P$$

The coefficient of polynomial is calculated after the least squares adjustment with normal equation:

$$\triangle=[A^TA]^{-1}[A^TA] \tag{6}$$

According to the formula of accuracy assessment:

$$\delta = \pm\sqrt{\frac{[VV]}{m - f}} \tag{7}$$

The adjusted residual errors of ground control points is shown in table 6

Table 6. The table of residual errors (unit: meter)

	1	2	3	4	5	6	7	Total residual errors
δX	-15.8	15.6	-19.8	19.4	2.9	-12.4	10.1	12.452285477
δY	21.3	-0.8	-7.6	-24.3	-14.4	-3.0	-3.8	12.26208591

Bilinear interpolation is used to resample when rectified.

$$Ip = \sum_{i}^{2}\sum_{j}^{2} W_{ij} I_{ij} \tag{8}$$

Due to the low resolution of MSS and SAR image; the resample pixel size is 50m*50m.

2.3. Image matching

Image Matched with image is that MSS and SAR image is added compulsory to the rectified TM image. The obvious image points is chosen as the matching points. The shape of object above the land has changed little, especially the small and large semi-island and islands at the Larsemann Hill, For being the same area in different time, glacier has stretched and ruptured. The parts on the land have obvious feature and it is easy to choose the matched points, because the glacier has flowed from the land every year, moreover due to the relief under the ice, the shape has changed little.

The size of the image is 80Km*80Km, it is smaller than that of TM image (185Km*185Km), so polynomial with one order is adapted to

MSS image is matched with the TM image:

$$\begin{aligned} L_T &= a_{m0}+a_{m1}L_M+a_{m2}P_M \\ P_T &= b_{m0}+b_{m1}L_M+b_{m2}P_M \end{aligned} \tag{9}$$

For SAR is slant ranging projection, the direction of emission has lead to quadratic distortion, quadratic polynomial is used to match the TM image.

$$\begin{aligned} L_T &= a_{s0}+a_{s1}L_S+a_{s2}P_S + a_{s3} L_S^2 + a_{s4} L_S P_S + a_{s5}P_S^2 \\ P_T &= b_{s0}+b_{s1}L_S+b_{s2}P_S + b_{s3} L_S^2 + b_{s4} L_S P_S + b_{s5}P_S^2 \end{aligned} \tag{10}$$

Bilinear interpolation is adopted in resampling, the pixel size is 50m*50m after matched, the gridline is 10Km*10Km in order to measure conventionally at the coordinate of 10Km.

3.Interpretation and measurement of glaciers

3.1.Interpretation

The Polar Record Glacier is stretching continuously from the MMS image acquired in Feb. 4,1973(see Fig. 2) to sea about 50 Km (Plydz Bay) and floated on the sea. With the glacier flowing outside, the surface of sea can not sustain the weight of the large glacier, it occur to collapse in 1990,the large ice mountains which form from collapse glacier has the same area as three Wuhan of China (the east-southern parts of ice mountains is shown in west TM image acquired in 1990,the shape is correspond to the east-southern parts in 1997,the ice mountains is smaller than the actual size, which is replaced according to matched ice mountains, is not in image, see Fig. 3). Slide outside and collapse, the size of image acquired in1997 has the same area as two Wuhan city(about 360 Km^2) .

The ice mountains is always circuiting in the gulf and had not left because the large ice mountains and lies in the Publications Ice Shelf, almost in frozen in a year the side of seacoast is shallow .The Polar Record Glacier continuously flow out with it's constant speed there is an interval between the ice mountains (see Fig. 3) in the TM image acquired in 1997,the fore edge of Polar Record Glacier had met the ice mountains on the SAR image (see Fig. 4)

The fore edge of ice mountains of SAR image acquired in1997 is different from that of MSS image acquired in 1973(collapse for discrete), but the texture is still correspond, the peak of glacier fore edge in 1973 could be found, it is shown that there was only one collapse of ice collapse, there is the same shape ice mountains between the image acquired in 1990 and the SAR image in 1997,the fore shape of glacier after broken is the same, there is no other ice mountains between the ice mountains and glacier, glacier had stretched 6 Km from 1990 to 1997,while the glaciers had stretched to sea 50 Km from 1973.It can be seen that there is no ice collapse in 7 years ,it can be calculated the velocity and fluxes of the Polar Record Glacier.

The Dark Glacier lies in the east of the Mirror semi-island, which has the width about 3 KM and is more small than that of Polar Record Glacier, is near to the three research stations of Russia Austria and China. Every year research ships of the three countries anchor at the gulf of the Dark Glacier. It is important if there have had ice collapse for its high research value, the time interval of ice collapse is shorter than that of Polar Record Glacier for the small scale. It cannot be seen because the east edge of MSS image acquired in 1973 lies at the west of the Dark Glacier, the TM image acquired in 1990 is clear. It maybe have been occurred several ice collapses after 17 years, for example It occurred once in 1988, the fore edge shrink, the fluxes could not be calculate from the image acquired in 1973 and in 1990 even the Dark Glacier can be shown in the image acquired in 1973. So it is no real useful to study the fluxes of the Dark Glacier with image acquired in 1973,there are no ice collapse in Dark Glacier between 1973 to 1990(China Russia Austria research stations are established there, especially Russia has annual station, it is no reported on the large ice collapse), so it is reasonable to survey and calculate the velocity and fluxes.

3.2.Measurement and calculation the velocity and fluxes

The image acquired in three different time is matched and the resolution after resample is the same, to measure the change is only that add the two images, in general, the position of changeable object to the position of unchangeable is outlined and added to the another image, edge line of the Polar Record Glacier of MSS image acquired in 1973 is added to the TM image acquired in 1990(see Fig. 5). The edge line of lingua at Polar Record Glacier and Dark Glacier of TM image acquired in 1990 is outlined added to the SAR image acquired in 1997(see Fig. 6). The matched points of images is interpreted after two years, the distance of between matched points is measured. It should be noticed that before 1990, the large collapsed Ice Mountains is flowing from glacier and form middle space. The distance between the matched points from 1973 to 1990, should be minus the interval distance, is the real distance of glacier moving distance. There is no ice crack after 1990,so the distance of matched points is equal to the distance of glacier moving .the velocity calculation formula is:

$$V=D/\Delta t \qquad (11)$$

Where: D is a real distance of glacier;

T is the difference of two images acquired time.

The ejected area is first calculated in measurement of fluxes, then the fluxes is calculated in an unit time (ejected area), the minus area due to collapse after ice break should be outlined with old time image when the shape is restoration, for example, The head of Ice Mountains in 1990 is difference from that in 1973 duo to collapse. The shape of lingua of glacier in 1973 is restored to head of mountains, and then outlined the changeable area after getting the matching points (see Fig. 7). There is no large changeable for the lingua of glacier from 1973 to 1990,the fluxes is outlined directly (see Fig. 8). The fluxes is the actual fluxes in an unit time (ejected area).

With the measurement with RS methods, the deep of Polar Record Glacier in coast is 150 m, while the deep of Dark Glacier is 80m,

The velocity, fluxes of Polar Record Glacier and Dark Glacier is measured in RS image is shown in table 7,8,9.

Table 7. The motion distance and ejected area and volume of the Polar Record Glacier from 1973 to 1990

	Feb. 4,1973-Jan 20,1990 (16.96 years)	Average volume a year	Average a day
Distance	13258.58(13.26Km)	781.76m	2.14m
Area	211007500 m^2 (211 Km^2)	12441479.95 m^2 (12.4 Km^2)	34086.25 m^2
Volume	31.65 Km^3	1.81 Km^3	0.0051 Km^3

Table 8. The motion distance and ejected area and volume of the Polar Record Glacier from 1990 to 1997

	Jan 20,1990-Sep. 14,1997 (7.65 years)	Average volume a year	Average a day
Distance	6380.635m(6.4Km)	834.1m	2.29m
Area	79340000 m^2 (79.34 $m^{2)}$	10371241.83 m^2 (10.4 $m^{2)}$	28414.36 m^2
Volume	11.90 Km^3	1.56 Km^3	0.0043 Km^3

Table 9 The motion distance and area and volume of the Dark Glacier from 1990 to 1997

	Jan 20,1990-Sep. 14,1997 (7.65 years)	Average volume a year	Average a day
Distance	1457.74m	190.55m	0.52m
Area	3610000m^2	471895.42m^2 (0.47Km^2)	1292.86m^2
Volume	0.289 Km^3	0.038 Km^3	0.0001Km^3

From the above table, the average velocity, fluxes of Polar Record Glacier is 781.76m per second from 1973 to 1990;the average velocity a day is 2.14 m. The average velocity is 834.1m per year from 1990 to 1997,the average velocity a day is 2.29m, from the result the average velocity is equal, it is faster in 1990 than that in 1997. The reason is the lingua of glacier is long, it stop the glacier move and make velocity slowly between 1973 to 1990 .the Polar Record Glacier in 1990 had broken, the lingua had gotten shorter, the velocity had gotten fast from lands. The ejected ice area 12.4Km^2 a year in the period from 1973 to 1990, it is larger than the ejected ice area of 10.4 Km^2 a year from 1990 to 1997. The reason is that the glacier is long from 1973 to 1990 and had expanded to two side and lead to enlarge the area, while the expand to two sides is not large for the short glacier lingua and short time from 1990 to 1997. The fluxes (no exclude the crack ice) are separately 1.87 Km^3 a year and 1.56 Km^3 a year.

With the same method, the average velocity of Dark Glacier moving is 190.55 m a year, the day average velocity is 0.52 m, the average ejected ice area is 0.47 Km^2 a year, average fluxes is 0.0038Km^3 a year. It is smaller than that of Polar Record Glacier, but the average stretch outside 190m is considerable.

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