

THE INFLUENCE OF THE CLUSTER SATELLITE SYSTEM PARAMETER TO IMAGING PRECISION

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ABSTRACT

The Cluster Micro-Satellite Synthetic Aperture Radar (SAR) System is an innovative SAR system brought forward recently. In the Cluster Micro-Satellite System, technology of cross-track interferometric SAR (INSAR) imaging processing is studied. Analyze the influence of the rotating of the cluster micro-satellite to the baseline and the phase of INSAR. Derive the corrected formula of the baseline and the INSAR phase. By computer simulation, compare the errors between corrected and uncorrected height measurement. The analysis results verify the correction of the formula and necessity to correct the baseline and the phase.

Key words Cluster Micro-Satellite System, Synthetic Aperture Radar (SAR), INSAR phase, available baseline, height error

INTRODUCTION

The Cluster Micro-Satellite Synthetic Aperture Radar (SAR) System is an innovative SAR system brought forward recently to face to 21st century, which is constituted by a group of satellites work and cooperate to complete the function of a single satellite. This kind of combination can extend the usage of the SAR system, enhance the flexibility and reliability, and reduce the expense of launch. It can also apply much more mode of baseline combination and gain more data sources that include the data of the direction of along the orbit and across the orbit.

Now there are mainly two ways by which the data of interferometric SAR (INSAR) are acquired. The one method is using repeat-orbit SAR system to collect INSAR data; another is using the double-antenna SAR system to collect INSAR data. The disadvantage of repeat-orbit SAR system is that it's difficult to estimate baseline accurately, which will badly affect the precision of measure height. The return-wave data collected at different time is easy to bring the temporal non-relativity, and this is disadvantageous to the short-wave band (such as X band). And the double-antenna SAR system will make the load equipment more complicated, which will be a badly obstacle to satellite flat. The Cluster Micro-Satellite SAR system can avoid the disadvantage of the two methods above, and can apply accurate baseline combination needed by the NSAR. Using the technology of cross-track interferometric SAR (CT-INSAR), the height message of SAR image can be extracted. The technology of along-track interferometric SAR (AT-INSAR) can be also used to

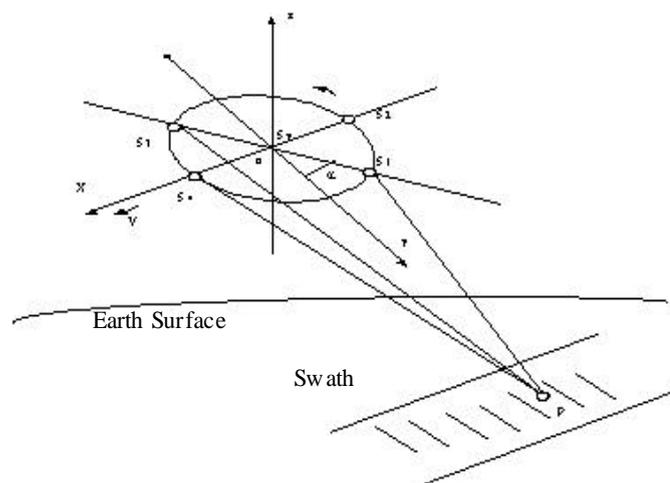


Fig.1 The Cluster Micro-Satellite SAR geometric sketch map

THE INFLUENCE OF THE CLUSTER SATELLITE SYSTEM PARAMETER TO IMAGING PRECISION

detect movement target and to extract velocity of slow-move target. This is just a very important contribution of the cluster satellite combination to SAR system performance.

The Cluster Micro-Satellite system is made up of several satellites (such as 8 or 4 micro- satellites), which distribute in a same plane (fig. 1). When the combined satellites run along the earth orbit, they rotate around the center (Sv) along their circle and the cycle of rotation just equal to the one rotating the earth orbit. The relative geometric relation between every micro-satellite will keep unchangeable. These micro-satellites rotate around the center point (Sv) that will influence the INSAR imaging precision necessarily. The paper analyzes mostly the influence of the rotation of the cluster micro-satellite to the height precision when CT-INSAR imaging technique is applied in the system.

THE PRINCIPLE OF INSAR THREE-DIMENSIONAL IMAGING

The figure 2 is the geometrical graphic of INSAR. S_1 and S_2 denote the position that are vertical to the orbit direction, B is the baseline length, α is the angle between the baseline and the plane, H_0 is the relative height of S_1 to the earth surface, and q is the incident angle of the target T. h is the relative height of the target T. The interferometric phase of two plural image conjugating of S_1 and S_2 is:

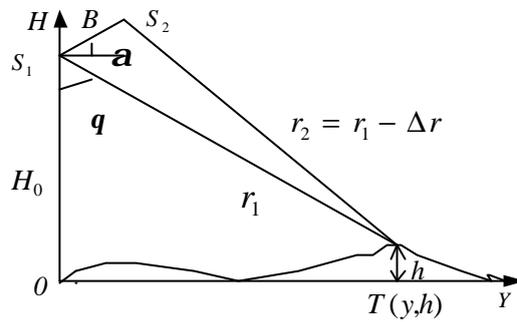


Fig.2 INSAR geometrical graphic

$$j = j_1 - j_2 = \frac{4p}{l}(r_1 - r_2) = \frac{4p}{l} \Delta r$$

(1)

When $r_1 \gg B$, then:

$$\sin(q - \alpha) = \frac{r_1^2 + B^2 - (r_1 - \Delta r)^2}{2r_1 B} \approx \frac{\Delta r}{B} - \frac{\Delta r^2}{2r_1 B} \quad (2)$$

From this that:

$$q = \alpha + \arcsin\left(\frac{\Delta r}{B} - \frac{\Delta r^2}{2r_1 B}\right) = \alpha + \arcsin\left(\frac{l j}{4p B} \left(1 - \frac{l j}{8p r_1}\right)\right) \quad (3)$$

So the relative height h of the target T is:

$$h = H_0 - r_1 \cos q = H_0 - r_1 \cos\left(\alpha + \arcsin\left(\frac{l j}{4p B} \left(1 - \frac{l j}{8p r_1}\right)\right)\right) \quad (4a)$$

In the cluster micro-satellite system, because one satellite transmits and the others receive signal, the formula (4a) should be modified as:

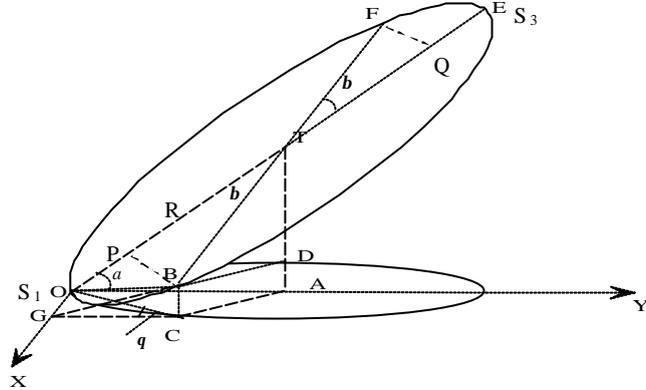
$$h = H_0 - r_1 \cos q = H_0 - r_1 \cos\left(\alpha + \arcsin\left(\frac{l j}{2p B} \left(1 - \frac{l j}{4p r_1}\right)\right)\right) \quad (4b)$$

So the target height from the interferometric phase can be estimated if the orbit parameters are known. In the above formula (4a), the influence of the earth's spherical surface is not thought over. But in the practical appliance, the spherical-surface effect to H_0 in the spaceborne INSAR system should be considered.

THE INFLUENCE OF THE CLUSTER SATELLITE SYSTEM PARAMETER TO IMAGING PRECISION

THE INFLUENCE OF THE SATELLITE'S ROTATING TO THE PRECISION OF HEIGHT-MEASURE

When the micro-satellites move along the earth-orbit, they rotate along the cluster circumference at the same time. It is necessary to produce interferometric phase error and baseline error. In convenience, here just analyze position-change of the two satellites with the longest baseline(such as S_1 & S_3).



The Derivation of the Satellites' Position Change

Fig.3 The system sketch map of the cluster-satellite

As the figure 3 show, points O and E are the original position of the satellites S_1 and S_3 , namely the baseline between the satellite S_1 and S_3 is cross track orientation, R is the radius of the satellites rotation circumference, point B is the position after S_1 rotate β angle, point C is the position when B project on the horizontal, and a is the angle between the cluster-satellite plane and the horizontal. Axes X is the azimuth orientation and Y is the range orientation of the satellites. Supposing $L = OB$, the point C's coordinate can be obtained.

The x-coordinate of the point C is:

$$L = \sqrt{R^2 + R^2 - 2R^2 \cos b} = 2R \sin(b/2).$$

The y-coordination is:

$$OC \cdot \cos q = \frac{L}{2R} \sqrt{4R^2 - L^2 \sin^2 a} \cdot \frac{L \cos a}{\sqrt{4R^2 - L^2 \sin^2 a}} = \frac{L^2 \cos a}{2R} = 2R \cos a \sin^2 \frac{b}{2}$$

And the distance from B to C can be deduced as follow: $BC = 2R \sin a \sin^2 \frac{b}{2}$. Then the coordinate of B is:

X-coordinate: $R \sin b$

Y-coordinate: $2R \cos a \sin^2 \frac{b}{2}$

Z-coordinate: $H_1 = H_0 + BC = H_0 + 2R \sin a \sin^2 \frac{b}{2}$

In which: H_0 is the height of satellite S_1 at O point.

Supposing the coordinate of the target at the terrain is $(0, y_0, h)$, then the slant ranges from the O and B to the target respectively are:

$$r_1 = \sqrt{y_0^2 + (H_0 - h)^2} \quad (5)$$

$$r_1' = \sqrt{R^2 \sin^2 b + (y_0 - 2R \cos a \sin^2 \frac{b}{2})^2 + (H_0 - h + 2R \sin a \sin^2 \frac{b}{2})^2} \quad (6)$$

In figure 3, point F is the satellite S_3 's place after rotating, we can acquire the point F coordinate alike:

X-coordinate: $-R \sin b$

THE INFLUENCE OF THE CLUSTER SATELLITE SYSTEM PARAMETER TO IMAGING PRECISION

$$\text{Y-coordinate: } 2R \cos \mathbf{a} \cos^2 \frac{\mathbf{b}}{2}$$

$$\text{Z-coordinate: } H_2 = H_0 + 2R \sin \mathbf{a} \cos^2 \frac{\mathbf{b}}{2}$$

Then the slant ranges from the E and F to the target respectively are:

$$r_2 = \sqrt{(y_0 - 2R \cos \mathbf{a})^2 + (H_0 + 2R \sin \mathbf{a} - h)^2} \quad (7)$$

$$r_2' = \sqrt{R^2 \sin^2 \mathbf{b} + (y_0 - 2R \cos \mathbf{a} \cos^2 \frac{\mathbf{b}}{2})^2 + (H_0 + 2R \sin \mathbf{a} \cos^2 \frac{\mathbf{b}}{2} - h)^2} \quad (8)$$

The formulas (5) to (8) show the distance change after the satellites rotate a certain angle. Now analyze the influence of the rotation to the height precision.

The Influence of the Satellites' Rotation to the CT-INSAR Phase and Baseline

According to the imaging principle of the INSAR, the rotation of the cluster-micro-satellite system will cause error of the phase, baseline size, slant range etc. These parameters can influence the CT-INSAR height precision, especially the phase and the baseline.

Using formula (5)? (7) and(1), the interferometric phase of the satellites S_1 and S_3 is:

$$\mathbf{j} = \frac{2\mathbf{p}}{\mathbf{l}} \Delta r = \frac{2\mathbf{p}}{\mathbf{l}} (r_1 - r_2) \quad (9)$$

When the satellites S_1 and S_3 rotate a certain angle \mathbf{b} , the interferometric phase can be acquired by formula (6) and (8). Namely:

$$\mathbf{j}' = \frac{4\mathbf{p}}{\mathbf{l}} \Delta r' = \frac{4\mathbf{p}}{\mathbf{l}} (r_1' - r_2') \quad (10)$$

Basing on INSAR imaging principle, the height is extracted by the phase of the two satellites which baseline is vertical to the azimuth orientation. After the satellites rotate a certain angle, the phase and baseline values cannot be directly used for estimating height, otherwise can cause the height-error. So the phase and baseline need be timely corrected.

If the baseline is projected onto the cross-track direction (the point P and Q of the figure 3), the effective baseline is:

$$B' = B \cos \mathbf{b} \quad (11)$$

The slant range from projection point to the target shall be also recount. By figure 3, the coordinate of the point P and Q are respectively:

$$P(0, R(1 - \cos \mathbf{b}) \cos \mathbf{a}, R(1 - \cos \mathbf{b}) \sin \mathbf{a} + H_0)$$

$$Q(0, R(1 + \cos \mathbf{b}) \cos \mathbf{a}, R(1 + \cos \mathbf{b}) \sin \mathbf{a} + H_0)$$

$$\text{Then } r_1' = \sqrt{[y_0 - R(1 - \cos \mathbf{b}) \cos \mathbf{a}]^2 + [H_0 - h + R(1 - \cos \mathbf{b}) \sin \mathbf{a}]^2} \quad (12)$$

$$r_2' = \sqrt{[y_0 - R(1 + \cos \mathbf{b}) \cos \mathbf{a}]^2 + [H_0 - h + R(1 + \cos \mathbf{b}) \sin \mathbf{a}]^2} \quad (13)$$

The interferometric phase between P and Q is:

$$\mathbf{j}' = \frac{2\mathbf{p}}{\mathbf{l}} \Delta r' = \frac{2\mathbf{p}}{\mathbf{l}} (r_1' - r_2') \quad (14)$$

By formula (10) and (14), the corrected interferometric phase is:

THE INFLUENCE OF THE CLUSTER SATELLITE SYSTEM PARAMETER TO IMAGING PRECISION

$$\mathbf{j}'' = \frac{r_1'' - r_2''}{r_1' - r_2'} \cdot \mathbf{j}' \quad (15)$$

If the phase and the baseline are considered at one time, the corrected height formula is:

$$h_2 = H_0 - r_1'' \cos(\mathbf{a} + \arcsin \frac{l}{2pB \cos \mathbf{b}} \cdot \frac{r_1' - r_2'}{r_1' - r_2'} \mathbf{j}') \quad (16)$$

In which: the phase \mathbf{j}' is the interferometric phase when the rotation angle is \mathbf{b} . So the phase and baseline should be real-time corrected to reduce INSAR height-measure error.

THE RESULT OF THE EXPERIMENTATION-SIMULATION AND THE ANALYSIS

In order to analyze the influence of the phase and baseline shift to the height measurement after the rotation, here suppose the most large distance of cluster satellites is 240 meters, the height of satellite to the earth surface is 800km, the incidence angle is 35 degree, and the cluster satellite rotation cycle is 90 minutes.

Figure 4 simulates the height section map when the rotation angle \mathbf{b} is 0^0 . Figure 5 and 6 are separately the height map when \mathbf{b} is 0.24 and 1 degree.

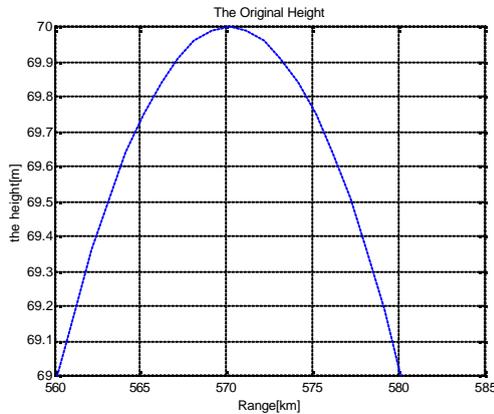


Fig.4 the simulating original height

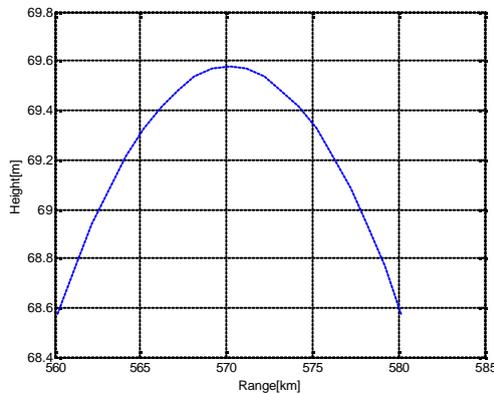


Fig.5 the height of rotation $\beta=0.24^0$
(No correction)

Because of no correcting baseline and phase, there are apparently height error in figure 5 and 6. The height error when the rotation angle is 1 degree is bigger than that when the angle is 0.24 degree. Figure 7 present the relation between the rotation angle and the height error. Now take a few representative values in table 1.

THE INFLUENCE OF THE CLUSTER SATELLITE SYSTEM PARAMETER TO IMAGING PRECISION

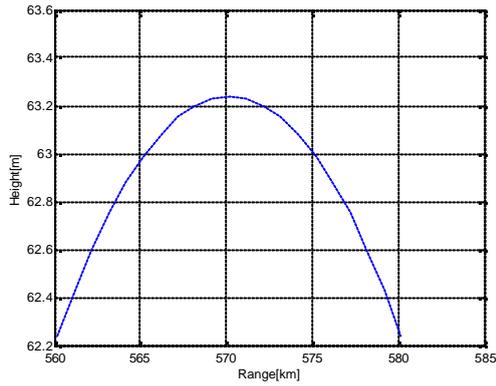


Fig.6 the height of rotation $\beta=1^\circ$
(No correction)

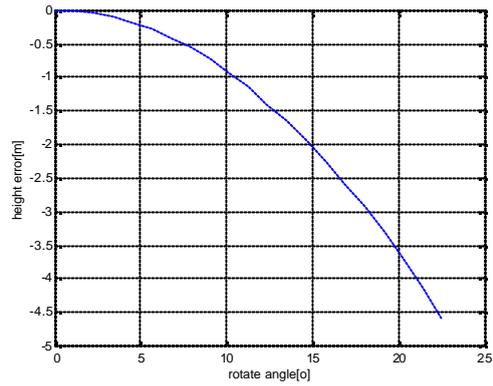


Fig.7 the relation between rotation angle and
the height error

Table 1

Rotate Angle β (°)	Height Error? h(m)
0.06	0.03
0.12	0.11
0.18	0.24
0.24	0.42
0.48	1.69
0.71	3.80
1.00	7.4

We can see that the bigger the rotation angle, the bigger the height error. When the runtime is under 4 second ($\beta \leq 0.24^\circ$), the height error is low than 1 meter. But when the angle increase, the height error increase along with it. By table 1, when the rotation angle is 1 degree, the height error will reach 7.4 meter. Therefore the phase and the baseline must be corrected along with the rotation angle increase.

When the phase correction is considered only, the error is decreased apparently, But a certain error exist yet, and error increase along with the increase of the range. When the baseline correction is considered at the same time, the height error will decrease more. Figure 8 and 9 is the result when the phase and the baseline correction are considered at one time.

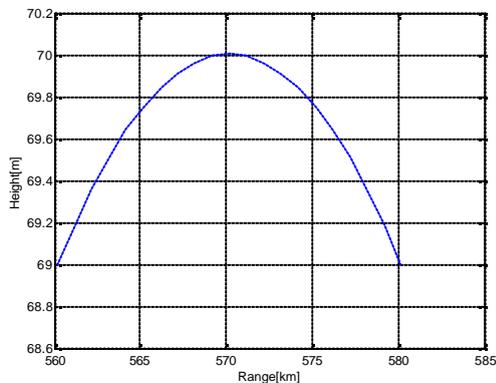


Fig.8 the corrected height of $\beta=0.24^\circ$

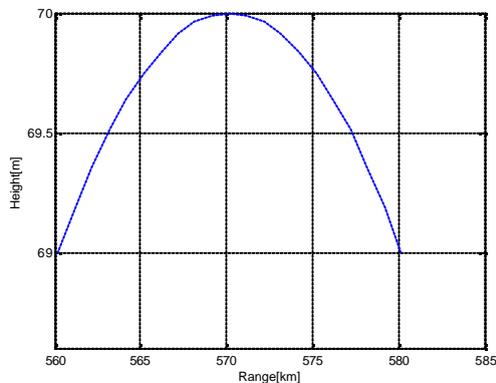


Fig.9 the corrected height of $\beta=1^\circ$

THE INFLUENCE OF THE CLUSTER SATELLITE SYSTEM PARAMETER TO IMAGING PRECISION

The height of the baseline and the phase corrected compare with the original height. Table 2 shows error result when the rotation angle is difference.

Table 2

Rotation Angle β ($^{\circ}$)	Height Error Δh (m)
0.06(1 ?)	2.65e-7
0.12(2 ?)	2.25e-7
0.18(3 ?)	2.08e-7
0.24(4 ?)	7.11e-8
0.48(8 ?)	1.49e-7
0.71(12 ?)	2.56e-8
0.95(16 ?)	1.65e-8

As fig.8? fig.9 and table 2 show, when the baseline and the phase are corrected at one time, the height error is very small no mater how big the rotation angle.

Based on above simulation results, we can obtain some conclusions:

- When the satellites' rotation angle is small, the change of baseline and phase produce little the height error. For example, when the angle is 0.24 degree, the height error is little than 0.5 meter. So the influence of the satellites' rotation to CT-INSAR height-measure can be not considered.

- When the rotation angle is big, the baseline and the interferometric phase should be corrected all together, otherwise a big height error will be presented. As in figure 3, when the rotation angle is 45 degree, there is the biggest error (when the angle exceed 45 degree, another two satellites will take the place). The corrected height error is small, and the result is satisfaction.

- The rotating velocity of the cluster satellites will be an important parameter. The rotation can keep the totalization of the cluster satellites. But if the rotating velocity is out of reason, it is difficultly to obtain the accurate interferometric phase-measure data. According to spending time of a frame SAR image acquired, we can reasonably choose the velocity of the satellite rotation.

SUMMARY

The Cluster Micro-Satellite SAR System can offer more baseline combination modes. The cross-track interferometric SAR(CT-INSAR) can extract the height information, and the along-track interferometric SAR (AT-INSAR) can detect moving target and obtain the velocity of the slow-move target. This paper analyzes the image problem of CT-INSAR in the system, and aim mostly at the influence of the satellites' rotation to the height precision. Analyze and deduce the baseline and the phase etc. parameters shift because of the rotation, and give the formula of the height correction and simulation relation curve. The results of simulation indicate that the height error increase along with the increase of the rotation angle, and the baseline and the phase must be corrected rational in order to improve the height precision. In additional, based on spending time of a frame SAR image acquired, we can reasonably choose the velocity of the a. satellite rotation to reduce the inaccuracy of the interferometric phase-measure data.

THE INFLUENCE OF THE CLUSTER SATELLITE SYSTEM PARAMETER TO IMAGING PRECISION

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