A Two-dimensional Attitude Steering Method to Compensate for the Doppler Centroid in Moon-based SAR

G Q Chen, Y X Ding, M Y Lv, H D Guo, and J Wu

1 Key Laboratory of Digital Earth Science, Aerospace Information Research Institute, Chinese Academy of Sciences, Beijing 100094

Correspondence: chengq@radi.ac.cn

Abstract. The rising attention to Moon-based Earth observation provides a new way to monitor Earth. Among Moon-based detectors, the SAR method has the advantage of long-term, stable, unique observations compared to space-borne SAR. Unlike space-borne SAR, however, the complicated relative motion of a Moon-based sensor makes its Doppler centroid estimation more difficult. This paper proposes a method for two-dimensional attitude steering to compensate for the Doppler centroid of Moon-based SAR. In the periodic movement between Earth and the Moon, the track speed of sites distributed around the near side of the Moon are almost perpendicular to vectors from the sites to the Earth centroid. This situation indicates the feasibility of attitude steering to guide antennas into a zero Doppler plane intersecting Earth’s surface. Therefore, this paper proposes a method for two-dimensional attitude steering to compensate the Doppler centroid to zero. In this method, the Moon is no longer deemed as a point but a natural celestial body with an average radius. Sites distributed around the hemisphere of the near side are also considered separately because of differences in spatial position and speed. Through the proposed method, the pointing of SAR antennas will be steered to a place on Earth where the Doppler centroid is compensated to zero. The JPL DE430 and EOP data are closer to reality and are used for accurate simulation. In this paper, the two-dimensional attitude steering method is compared with no attitude steering and a one-dimensional attitude steering method, and the results show its effectiveness.

1. Introduction

During the past decades, humankind’s appetite for lunar exploration and public interest in lunar research has risen again [1]. Several countries and astronomical institutions, including CNSA in China, NASA in the USA, and ESA in Europe, have announced programs (e.g., Chang’e, the Artemis landing mission, and the Moon Village program) for lunar exploration. Among these lunar exploration programs, better performance in Earth observation from the Moon has been one of the main tasks. Earth observation research, including that from Moon-based SAR (MBS), is of great scientific potential in deep space exploration [2, 3], with potential to have a huge role in the sustainable development of humanity [4]. As the only natural satellite of Earth, the Moon has an average distance of $3.8 \times 10^6$ km, giving it a field of view (FOV) of the entire Earth disc at a small angle of just 1.8°. An MBS distributed around the Moon’s near side would have advantages over space-borne SAR in long-term, stable monitoring of global phenomena, e.g., solid tides, radiation balance, and plasma/magnetosphere, [5, 6].
The literature mainly focuses on the system structure and potential applications of MBS; few studies have analyzed the Doppler centroid steering of MBS. Similar to space-borne SAR, especially geostationary satellites, the rotation of Earth also contributes to the Doppler centroid. Unlike space-borne SAR, which has free rotation in space [7], the Moon is a celestial body with an average radius of 1,738 km [8, 9], and SAR antennas may have occlusion constraints that mainly come from the spherical curvature and irregular topography [10]. The Moon’s rotation and its revolution also contribute to the Doppler centroid. The long synthetic aperture time caused by the long distance between Earth and the Moon, together with the nonzero Doppler centroid, will result in high coupling of the azimuth and range signal, increased complexity in signal processing, and lower quality of the imaging formulation [11,12,13], all of which are unfavorable for MBS observation. Therefore, calculating and minimizing the Doppler centroid are the inevitable first steps in further research on signal processing of MBS. In order to simulate the real motion of MBS with an Earth ground target (EGT), the MBS is no longer considered to coincide with the Moon centroid. A high-precision ephemeris named JPL DEM430 and EOP data will be used [14,15].

This paper proposes an analytical approach to estimate the Doppler properties of MBS according to the geometrical model. On the surface of the Moon itself, craters, hills, and other uplifts are unevenly distributed, thus making the topography very complicated [16, 17]. The FOV of MBS might be partly sheltered, the slope of the lunar site might be too steep to construct MBS, and a site’s buffer area might not satisfy the need for avoiding falling rocks. In order to reduce computational costs, the influence of topography on MBS is ignored in this study. Generally speaking, the Moon curvature will have an adverse influence on attitude steering because of its occlusion.

The rest of this letter is organized as follows. Section 2 gives a description of the Doppler centroid and attitude steering method of MBS; section 3 studies the performance of the Doppler centroid on the near side of the Moon and the differences between two-dimensional attitude steering, no attitude steering, and one-dimensional attitude steering; and section 4 gives a brief conclusion.

2. Method

To study an MBS, it is necessary to conduct attitude steering to reduce its Doppler centroid, because a nonzero Doppler centroid will increase the complexity of signal processing and lower the quality of image formulation, all of which are unfavorable for MBS. In this section, three parts are presented to indicate the performance of MBS attitude steering. Section 2.1 indicates the calculation and decomposition method of Doppler. Section 2.2 indicates the MBS attitude steering method, in which the Doppler centroid is reduced to zero to satisfy the purpose of this paper. Section 2.3 indicates the probability distribution of attitude steering for the near side of the Moon.

In the paper, vectors are expressed in bold; scalars are expressed in italics; position and speed vectors are expressed in the Earth Central Rotational Coordinate System (ECR), which is related to the Earth Central Inertial Coordinate System (ECI), the Moon Central Moon Fixed Coordinate System (MCMF), and others [18,19]; the symbol ‘∥’ indicates the norm of a vector; the symbol ‘⟨,⟩’ indicates the inner product of two vectors; and the symbol ‘×’ indicates the cross product of two vectors.

2.1 Calculation and decomposition method of Doppler

As shown in Figure 1, the dark Earth surface coverage area, determined by angle in range, angle in azimuth, and look angle of MBS, changes along relative motions between Earth and the Moon. The synthetic aperture length (e.g., the ‘Ls’ in Figure 1) can reach hundreds of kilometers because of its longer synthetic aperture time than space-borne SAR. Considering the revolution of the Moon and rotation of the Moon and Earth, an MBS space trajectory relative to Earth’s centroid is not exactly a straight line but an arc of smaller curvature. The real zero Doppler line, shown as a green dotted line in Figure 1, moves on the curved Earth surface; that is to say, the zero Doppler pointing and squint angle is changing along synthetic aperture time, and the zero Doppler plane rotates along the MBS space trajectory. Thus, for an accurate estimation of MBS Doppler performance, the motion between Earth
and the Moon cannot be determined from air-borne flight or space-borne orbit. Once the pointing of MBS intersects with the zero Doppler line, the frequency of the Doppler centroid can be reduced to the desired value: zero.

In this paper, the position and speed of researched objects are calculated based on JPL DE430 and EOP data.

\[ \text{Figure 1. Space trajectory of MBS (a), and the angle of MBS parameters (b).} \]

For MBS and its achievable EGT, the frequency of the Doppler centroid caused by the relative motion between them are expressed as:

\[
f_{dc} = \frac{2}{\lambda} \cdot \frac{dR}{dt} = -\frac{2}{\lambda} \cdot \frac{( \mathbf{R}_{mp} - \mathbf{R}_{ep} ) \cdot ( \mathbf{V}_{mp} - \mathbf{V}_{ep} )}{\sqrt{\mathbf{R}_{mp} - \mathbf{R}_{ep}}} \]

where \( \mathbf{R}_{mp} \) and \( \mathbf{R}_{ep} \) are the positions of MBS and GET; \( \mathbf{V}_{mp} \) and \( \mathbf{V}_{ep} \) are the corresponding speed in the same coordinate system, such as ECR; and \( \lambda \) is the wavelength of MBS.

The speed of EGT is perpendicular to its position, so \( \mathbf{R}_{ep} \cdot \mathbf{V}_{ep} = 0 \). Through properties of vector operations, Equation (1) can be simplified to:

\[
f_{dc} = -\frac{2}{\lambda} \cdot \frac{\mathbf{R}_{mp} \cdot \mathbf{V}_{mp} - \mathbf{R}_{mp} \cdot \mathbf{V}_{ep} - \mathbf{R}_{ep} \cdot \mathbf{V}_{mp} + \mathbf{R}_{ep} \cdot \mathbf{V}_{ep}}{\sqrt{\mathbf{R}_{mp} - \mathbf{R}_{ep}}} \]

where \( \mathbf{w}_e \) is the angular velocity vector of Earth’s rotation, \( \mathbf{A} \) is the pointing vector of the MBS center, and \( \mathbf{B} \) is the track speed caused by relative motion.

Through trigonometric formulas, Equations (2) – (5) can be rewritten as Equation (5):

\[
f_{dc} = -\frac{2}{\lambda} \cdot \frac{\mathbf{A} \cdot \mathbf{B}}{\sqrt{\mathbf{A} \cdot \mathbf{B}} \cdot \cos \left( \frac{\pi}{2} - \theta \right)}
\]

where \( \theta \) is called the equivalent squint angle between \( \mathbf{A} \) and \( \mathbf{B} \). If parameter \( \theta \) is reduced to zero, the frequency of the Doppler centroid can be minimized to zero.

The above equations explain the frequency of the Doppler centroid from MBS pointing and track speed, but does not reflect the direct influence of MBS motion and Earth’s rotation. The Doppler centroid in Equation (2) can also be rewritten as:
\[ f_{dc} = -2 \frac{(\mathbf{R}_{mp} - \mathbf{R}_{ep}) \cdot \mathbf{V}_{mp}}{\lambda \left\lVert \mathbf{R}_{mp} - \mathbf{R}_{ep} \right\rVert} \left( \frac{2 \cdot (\mathbf{R}_{mp} - \mathbf{R}_{ep}) \cdot (\mathbf{R}_{mp} \times \mathbf{w}_e)}{\lambda \left\lVert \mathbf{R}_{mp} - \mathbf{R}_{ep} \right\rVert} - \mathbf{R}_{mp} \times \mathbf{w}_e \right) \]

where \( \mathbf{R}_{me} \) is the vector from the EGT position to MBS position. The first term on the right side of Equation (6) shows the Doppler centroid caused by the motion of MBS, which can be represented as \( f_{dc}^m \). The second term on the right side shows the Doppler centroid caused by Earth’s rotation, which can be represented as \( f_{dc}^r \).

As Earth’s rotation and the Moon’s revolution are not equal, the specific ground target is always changing and should be renewed. The unit direction of \( \mathbf{R}_{me} \) is equal to \( \mathbf{A} \), shown in Equation (3) in the Antenna Coordinate System (ACS). The Z-axis in ACS is parallel to the vector from MBS to Earth’s centroid, the Y-axis is parallel to the angular momentum of MBS, and the X-axis obeys the right hand rule together with the Y-axis and Z-axis.

### 2.2 Attitude steering method of MBS

Parameters \( \mathbf{A} \) and \( \mathbf{B} \) in Equation (3) and (4) are in ACS. If Doppler centroid \( f_{dc} \) must be reduced to zero, the track speed should be perpendicular to the direction of the beam center. In the initial orientation of the SAR antenna in ACS, parameter \( \mathbf{A} \) can be expressed as:

\[
\mathbf{A} = k \cdot \sin \varphi_1 \cdot \cos \varphi_2 \cdot \mathbf{u}_x + k \cdot \sin \varphi_1 \cdot \sin \varphi_2 \cdot \mathbf{u}_y + \cos \varphi_1 \cdot \mathbf{u}_z
\]

In the analysis of this paper, \( \varphi_2 \) is always set to an angle that makes the MBS left-looking (\( \varphi_2 = 90^\circ \)) or right-looking (\( \varphi_2 = -90^\circ \)). If MBS is left-looking, \( k = 1 \), and if MBS is right-looking, \( \varphi_2 = -1 \). The vectors of the X-axis, Y-axis, and Z-axis in ACS are \( \mathbf{u}_x \), \( \mathbf{u}_y \), and \( \mathbf{u}_z \). If parameter \( \mathbf{A} \) is perpendicular to \( \mathbf{B} \), then the Doppler centroid will be reduced to zero, which meets the purpose of antenna attitude steering. Generally speaking, antenna attitude steering has three methods: the first is no attitude steering, the second is one-dimensional attitude steering, and the third is two-dimensional attitude steering. They consist of three basic methods: roll and then yaw steered, roll and then pitch steered, and yaw and then pitch steered. The calculation of attitude steering angles of the three methods are basically the same.

Here, the pitch steer then yaw steer method is introduced. In this method, the rotation matrix is expressed as:

\[
\Xi = R_y(\varphi_2) \cdot R_x(\varphi_1) = \begin{bmatrix} \cos \varphi_2 & 0 & -\sin \varphi_2 \\ 0 & 1 & 0 \\ \sin \varphi_2 & 0 & \cos \varphi_2 \end{bmatrix} \begin{bmatrix} \cos \varphi_1 & \sin \varphi_1 & 0 \\ -\sin \varphi_1 & \cos \varphi_1 & 0 \\ 0 & 0 & 1 \end{bmatrix}
\]

where \( \varphi_1 \) and \( \varphi_2 \) are the angle of pitch steer and yaw steer, respectively.

After attitude steering, the unit axis vectors in ACS will be changed into the parts below:

\[
\mathbf{u}_x' = \cos \varphi_2 \cdot \cos \varphi_1 \cdot \mathbf{u}_x - \sin \varphi_1 \cdot \mathbf{u}_y + \sin \varphi_2 \cdot \cos \varphi_1 \cdot \mathbf{u}_z
\]

\[
\mathbf{u}_y' = \cos \varphi_2 \cdot \sin \varphi_1 \cdot \mathbf{u}_x + \cos \varphi_1 \cdot \mathbf{u}_y + \sin \varphi_2 \cdot \sin \varphi_1 \cdot \mathbf{u}_z
\]

\[
\mathbf{u}_z' = -\sin \varphi_2 \cdot \mathbf{u}_x + \cos \varphi_2 \cdot \mathbf{u}_z
\]
For left-looking or right-looking MBS, parameter $A$ in Equation (8) after attitude steering in ACS can be rewritten as Equation (11):

$$A' = k \cdot \sin \phi \cdot u'_y + \cos \phi \cdot u'_z$$

$$= k \cdot \sin \phi \cdot (\cos \sigma_2 \cdot \sin \sigma_1 \cdot u_y + \cos \sigma_1 \cdot \sin \sigma_2 \cdot u_z) + \cos \phi \cdot (-\sin \sigma_2 \cdot u_y + \cos \sigma_2 \cdot u_z)$$

$$= \begin{bmatrix} k \cdot \sin \phi \cdot \cos \sigma_1 \\ k \cdot \sin \phi \cdot \cos \sigma_1 \\ k \cdot \sin \phi \cdot \cos \sigma_2 \end{bmatrix} : \begin{bmatrix} u_x \\ u_y \\ u_z \end{bmatrix}$$

where the upper right subscript ‘$T$’ indicates the transpose of a vector. The track speed in ACS is $B = \xi_x \cdot u_x + \xi_y \cdot u_y + \xi_z \cdot u_z$, and should be perpendicular to the changed unit axis vectors $u'_y$ and $u'_z$. That is to say, the Doppler centroid result should be subject to the equations below:

$$B \cdot u'_y = 0$$

$$B \cdot u'_z = 0 \quad (11)$$

Therefore, the variable equations are changed again as:

$$\begin{cases} \xi_x \cdot \cos \sigma_2 \cdot \sin \sigma_1 + \xi_y \cdot \cos \sigma_1 + \xi_z \cdot \sin \sigma_2 \cdot \sin \sigma_1 = 0 \\ -\xi_x \cdot \sin \sigma_2 + \xi_z \cdot \cos \sigma_2 = 0 \end{cases} \quad (12)$$

The results are altered again as:

$$\begin{cases} \sigma_1 = -\arctan \left( \frac{\xi_y}{\xi_x \cdot \cos \sigma_2 + \xi_z \cdot \sin \sigma_2} \right) \\ \sigma_2 = \arctan \left( \frac{\xi_z}{\xi_x} \right) \end{cases} \quad (13)$$

The calculation of rotation angle for the other two steering methods is similar to the equations above.

In the no attitude steering method, the attitude of the antenna will always be consistent, as in ACS. In the one-dimensional attitude steering method, only the first rotation angle of the corresponding two-dimensional attitude steering method is introduced.

### 2.3 Probability distribution of attitude steering for the near side of the Moon

Theoretically, MBS can be distributed anywhere on the near side of the Moon and as long as the Doppler centroid has at least one intersection on Earth’s surface, the intersections on Earth’s surface can be called Intersections Perpendicular to Track Speed (ISPT). However, there are reasons why there might not be such an intersection.

The ISPT of MBS in some regions do not exist because of occlusion from the Moon’s curvature if we consider the Moon a smooth sphere with an average radius of 1,738 km. In addition to its curvature, the complex topography of the Moon will also cause occlusion on the orientation of MBS after attitude steering, but the influence of lunar topography will be ignored for a simplified calculation in this paper.

While analyzing whether ISPT exists or not, we can devise three situations based on the observable Earth disc. The first situation is when the entire Earth disc can be observed by MBS, the second when part of the Earth disc can be observed by MBS, and the third when no Earth disc can be observed by MBS.

For the region of the Moon where the entire Earth disc can be observed, ISPT exists if Equation (14) is subjected, and the Doppler centroid can be effectively reduced to zero:
\[ \alpha \leq \frac{\pi}{2} - \beta, \quad \left| \phi - \frac{\pi}{2} \right| \leq \beta \]  

where \( \alpha \) is the angle between the normal vector of the MBS ground plane and the vector from MBS to Earth’s centroid; \( \beta \) is the angle between the edge of the Earth disc and the vector from MBS to Earth’s centroid; and \( \phi \) is the angle between the track speed and the vector from MBS to Earth’s centroid. The three angles are shown in Figure 1(b).

In Equation (14), formula \( \alpha \leq \frac{\pi}{2} - \beta \) indicates that the entire Earth disc, about 1.8°, can be observed. Formula \( \left| \phi - \frac{\pi}{2} \right| \leq \beta \) indicates MBS always has a zero Doppler line on Earth’s surface, and its corresponding frequency of the Doppler centroid can be minimized to zero after attitude steering.

For the region of the Moon where only part of the Earth disc can be observed, there also exists ISPT if Equation (15) and (16) are subjected, and the Doppler centroid can be also effectively reduced to zero.

\[ \alpha > \frac{\pi}{2} - \beta \quad \text{and} \quad \alpha \leq \frac{\pi}{2} + \beta \]  

\[ \left| \phi - \frac{\pi}{2} \right| \leq \beta \]  

Equation (15) indicates only part of the Earth disc can be observed because occlusion of the Moon’s curvature caused by the MBS location far away from the center of the near side of the Moon. Equation (16) indicates MBS has a zero Doppler line on Earth’s surface after attitude steering.

For the region of the Moon where no Earth disc can be observed, there is no ISPT, which is to say, no intersection on Earth can make the vector from the MBS center to the intersection perpendicular to the track speed of MBS. We can obtain the distribution of ISPT for all sites on the near side of the Moon, and for Earth observation from MBS, it is better to establish the MBS someplace where more ISPT exists.

3. Results

3.1 Distribution of ISPT for the near side of the Moon

Different sites distributed around the near side of Moon have different rotation and revolution speeds. After unifying the two speeds into the same coordinate system (the ECR) and superimposing them, we noticed that the angle between the vector from the lunar site to the Earth centroid and its corresponding track speed fluctuated slightly around 90°. Table 1 shows maximum, average, and minimum values of the angle between the track speed and the vector from MBS (on the near side of the Moon) to the Earth centroid at different latitude and longitude lines in a sidereal year. In the annual motion of the Moon around Earth, the maximum and minimum values of the angles at different latitude and longitude lines fluctuated slightly around 90°. In this time period, the average apogee of the Moon’s orbit was about 4.05 \times 10^7 \text{ km}, the average perigee of the Moon’s orbit was about 3.63 \times 10^5 \text{ km}, and the angle between the edge of the Earth disc and the vector from the MBS center to Earth’s center fluctuated between about 0.9° and 1° without considering the influence of the irregular ellipsoidal Earth. The maximum value of the angle was 90.02°, and the minimum was 89.98°, as shown in Figure 2. Its fluctuation range does not exceed half the FOV (e.g., 0.9°) of the entire Earth disc, so any site on the near side of the Moon is able to find ISPT of the MBS most of the time without considering the impact of Moon curvature.
Figure 2. Average degree between the track speed and vector from MBS (distributed around the near side of the Moon) to Earth’s centroid in 18.6 years

Table 1. The maximum, average, and minimum values of the angle between the track speed and the vector from MBS (on the near side of the lunar surface) to Earth’s centroid at different latitude and longitude lines in a sidereal year:

| Latitude line | Maximum (°) | Average (°) | Minimum (°) | Longitude line | Maximum (°) | Average (°) | Minimum (°) |
|---------------|-------------|-------------|-------------|----------------|-------------|-------------|-------------|
| 80°N          | 90.0032°    | 90°         | 89.9968°    | 80°W           | 90.0202°    | 90.0128°    | 90°         |
| 60°N          | 90.0099°    | 90°         | 89.9901°    | 60°W           | 90.0179°    | 90.0113°    | 90°         |
| 30°N          | 90.0175°    | 90°         | 89.9825°    | 30°W           | 90.0106°    | 90.0067°    | 90°         |
| 0°            | 90.0204°    | 90°         | 89.9796°    | 0°             | 90.0004°    | 90.0002°    | 90°         |
| 30°S          | 90.0178°    | 90°         | 89.9822°    | 30°E           | 90°         | 89.9937°    | 89.9900°    |
| 60°S          | 90.0105°    | 90°         | 89.9895°    | 60°E           | 90°         | 89.9889°    | 89.9825°    |
| 80°S          | 90.0039°    | 90°         | 89.9960°    | 80°E           | 90°         | 89.9873°    | 89.9800°    |

However, Moon curvature is an important factor in occlusion of the MBS line of sight after attitude steering. The average probability distribution of ISPT is shown in Figure 2. ISPT will always exist inside the area shown in Figure 3(a), where the ranges from about 80°W to 80°E and 80°S to 80°N during the Moon’s nutation period is the region of interest for attitude steering (IRAS). But ISPT does not exist at all during 0.3~0.6 of the Moon’s nutation period outside of IRAS, as shown in Figure 3(b). From the point of reducing the Doppler centroid to zero while considering Moon curvature, the area inside IRAS is more suitable than outside.

Figure 3. Average probability distribution of ISPT in all observed situations (a), and in no observed situation (b) in 18.6 years

3.2 Attitude steering of selected MBS inside IRAS

Research on the distribution of ISPT in section 3.1 will contribute to attitude steering of specific MBS. Three evenly distributed MBS inside the IRAS will be selected to study attitude steering. The first site, labeled A, is in (30°S, 30°W), B is in (30°S, 30°E), C is in (30°N, 30°W), D is in (30°N, 30°E), and E is in (0°, 0°). As the angle between the edge of Earth’s disc and the vector from MBS to Earth’s
centrroid fluctuates between about 0.9° and 1°, the angle $\varphi_1$ in Equation (7) of MBS can set a middle number 0.3°.

Under a normal ionosphere environment, the L-band has less influence on MBS imaging [20], so the carrier frequency of MBS can be set at 1.5 GHz. In section 2.2, the angle of attitude steering is mainly related to track speed of MBS when it is left-looking or right-looking. The attitude steering angles for the five evenly distributed MBS in an orbital period are shown in Figure 4.

![Figure 4](image)

**Figure 4.** Attitude steering of (a) yaw angle and (b) pitch angle for the five evenly distributed MBS under 0.3° looking angle.

In Figure 4, the angle change of attitude steering is continuous and the values of MBS are very similar because the rotation speed of MBS is much smaller than its revolution speed. The revolution speed of the Moon fluctuates between 960 m/s and 1,100 m/s, and the maximum rotation speed of the lunar equatorial region is only about 4.6 m/s, so the influence of Moon rotation on attitude steering is much smaller compared to the Moon’s revolution. Figure 4 also indicates that the difference in MBS attitude steering is small in IRAS. This characteristic avoids huge jumps in the process of attitude steering, especially for MBS that contains huge antennas and swivel structures.

Because the angle changes of the five sites are similar, the fifth, labeled E, in (0°, 0°) can be selected to simply analyze the Doppler centroid before steering and after steering. In Figure 5(a), the MBS motion and Earth rotation all contribute to the Doppler centroid. If there were no attitude steering, such a large Doppler centroid would lower the quality of imaging formulation at a great scale, but if there were only one-dimensional attitude steering, the Doppler centroid would be minimized but not to zero, as shown in Figure 5(b), so it is necessary to introduce two-dimensional attitude steering for MBS. After two-dimensional attitude steering, the residual Doppler centroid in (0°, 0°) can be reduced to almost zero, as shown in Figure 6(a).

![Figure 5](image)

**Figure 5.** Doppler centroid related to MBS motion and Earth’s rotation (a), and the difference in the Doppler centroid with no attitude steering or one-dimensional attitude steering (b).
Parameter $\theta$ in Equation (5) is the equivalent squint of MBS. Compare Figure 5(b) with Figure 6(b), though MBS’s equivalent squint is far less than 1° under no or one-dimensional attitude steering, its corresponding Doppler centroid is still hundreds of hertz. The pointing accuracy is of great importance along the long distance between MBS and achievable EGT. After two-dimensional attitude steering, the Doppler centroid of MBS can be reduced to a small number very close to zero. In this case, the Doppler centroid is usually regarded as zero, and the equivalent squint angle in Equation (5) can also be reduced to zero as shown in Figure 6(b).

Figure 6. Doppler centroid of MBS in (0°, 0°) with two-dimensional attitude steering (a) and the equivalent squint angle with no/one-dimensional/two-dimensional attitude steering (b)

4. Conclusions

Not all of the near side of Moon has intersections perpendicular to the track speed (ISPT) of Moon-based SAR (MBS), and the area outside the region of interest for attitude steering (IRAS) is not better for MBS to be established. Because of the complex motion of MBS and Earth, the Doppler centroid is not always zero, which has adverse effects on imaging. Therefore, a method of two-dimensional attitude steering should be introduced to eliminate the effect, and this paper clarifies a two-dimensional attitude steering method and compares it with no attitude steering and one-dimensional attitude steering. The results indicate no attitude steering and one-dimensional attitude steering methods cannot reduce the Doppler centroid to zero, which shows the necessity of a two-dimensional attitude steering method.

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