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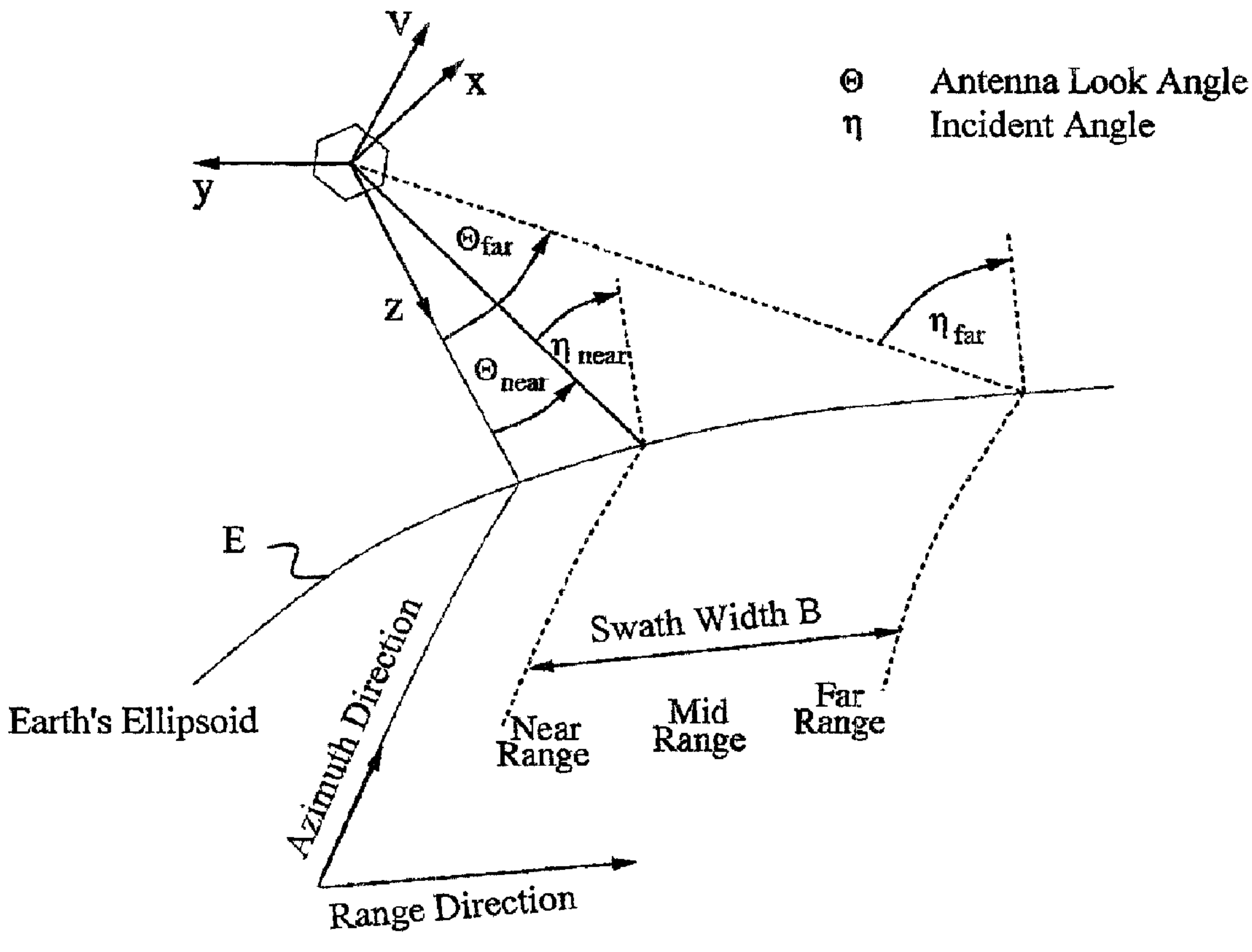
(54) Titre : METHODE DE REDUCTION DU CENTROIDE DOPPLER DANS UN SYSTEME RADAR COHERENT A IMPULSIONS
(54) Title: METHOD OF REDUCING THE DOPPLER CENTROID IN A COHERENT PULSE RADAR SYSTEM



(57) Abrégé/Abstract:
In a coherent pulse radar system supported by a spaceborne or airborne platform (S) imaging a ground swath by its antenna at nearly constant flight velocity, particularly a synthetic aperture radar (SAR) in addition to the yaw angle also the pitch angle is

(57) Abrégé(suite)/Abstract(continued):
steered to such an extent that the Doppler centroid is reduced to 0 Hz independent of the incidence angle. For use in Earth remote sensing.

Abstract

In a coherent pulse radar system supported by a spaceborne or airborne platform (S) imaging a ground swath by its antenna at nearly constant flight velocity, particularly a synthetic aperture radar (SAR) in addition to the yaw angle also the pitch angle is steered to such an extent that the Doppler centroid is reduced to 0 Hz independent of the incidence angle.

For use in Earth remote sensing.

FIG.1

Method of Reducing the Doppler Centroid in a Coherent Pulse Radar System

Technical Field

The invention relates to a method of reducing the Doppler centroid and/or the variation thereof in a coherent pulse radar system, particularly in a synthetic aperture radar system supported by a satellite or aircraft platform and which scans a swath of ground by its radar antenna in making use of yaw angle steering.

Background

Synthetic aperture radar (SAR) systems serving as instruments for remote sensing are finding ever-increasing application for imaging, monitoring and investigating the Earth's surface. Such a SAR system comprises a platform moving with approximately constant velocity, a radar antenna viewing orthogonal to the direction of motion and a coherent radar system transmitting electromagnetic pulses periodically.

FIG.1 illustrates the geometric relationships for a spaceborne SAR. The direction of motion V of the platform, in other words of a satellite S is termed the azimuth direction and the direction orthogonal thereto is termed the range direction. The extent of the scene in the range direction at the ground of the Earth's ellipsoid E is termed the swath width B and covers the areas on the ground representing the total data capture area.

The area nearest to the transmitter in the swath width B is termed near-range, that in the middle of the swath mid-range and that at the end of the swath width B far-range. The look angle 0 of the antenna is the angle between the z axis of the Cartesian xyz co-ordinate system of the satellite S and the main beam direction of the antenna. The incidence angle η at the ground is defined by the main beam direction of the antenna and the normal to the surface area of the Earth´s surface. The largest look angle of the SAR antenna is thus θ_{far} and the smallest look angle θ_{near}; correspondingly the incidence angle at the inner edge of the swath is η_{near} and at the outer edge η_{far}.

In SAR the so-called Doppler spectrum is analyzed by a point target formed from the Doppler frequencies. Doppler frequency is understood in the monostatic case to be twice the negative distance variation between radar sensor and point target per unit of time, divided by the wavelength used. The equation for this is thus

$$f_{dop} = -\frac{2}{\lambda}\frac{dr}{dt}$$

where f_{dop} is the Doppler frequency, λ the wavelength, r the distance from the radar sensor to the point target and t the time. The central frequency of the Doppler spectrum is termed Doppler centroid. A Doppler frequency of 0 Hz is also termed zero Doppler. For processing, the Doppler centroid should be as small as possible, ideally 0 Hz, which over the distance should exhibit no variation.

When the transmitter is mounted on a satellite platform it, like the satellite itself, passes through a generally elliptical orbit about the Earth. Because of the Earth´s rotation a shift occurs in the Doppler spectrum.

The co-ordinate system selected for a satellite is mostly the so-called Z system, shown in FIG. 2, or the so-called S system as shown in FIG. 3 in mostly making use of a ellipsoidal Earth reference model E with the semi-major axis R_E and the semi-minor axis R_P. It is known to define these two satellite co-ordinate systems as follows:

In the Z system as shown in FIG. 2 the Z_z axis of the co-ordinate system of the satellite S points directly towards the center of the Earth. The Y_z axis is formed by the cross product of the z axis with the velocity vector of the satellite S and the X_z axis by the cross product of the Y_z axis and the Z_z axis, resulting in a right-handed Cartesian co-ordinate system.

By contrast, in the S system as shown in FIG. 3 the Z_s axis of the co-ordinate system of the satellite S points perpendicular to the surface of the Earth usually based on an ellipsoidal Earth reference model. In this case, the Y_s axis is formed by the cross product of the Z_s axis and the velocity vector of the satellite S and the X_s axis by the cross product of the Y_s axis and the Z_s axis, resulting here too, in a right-handed Cartesian co-ordinate system.

Compensating the shift of the Doppler centroid from zero Doppler is mostly done by yaw steering, in other words a rotation around the Z-axis by the yaw angle. To minimize the variation of the Doppler centroid over the full swath width it would be of advantage to implement yaw steering for the middle of the swath width. However, this would necessitate different steering formulae for antennas looking to the left and right. This is why in current conventional SAR systems yaw steering is often implemented for a look angle of 0°. Although this results in a larger residual Doppler centroid than yaw steering to the middle of the swath width, it can be put to use the same formula for antennas looking to the left and right.

The distance to the area for which yaw steering is implemented and for which a residual Doppler centroid of 0 Hz occurs is termed reference range in the following.

In yaw steering in current conventional SAR systems the transmitting antenna is thus steered by a rotation of the yaw angle around the Z axis so that the Doppler centroid for a look angle of 0° is zero Hz.
This is given by the approximation formula

$$yaw = \arctan\left(\frac{\sin i \cos u}{N - \cos i}\right)$$

and is applicable, as mentioned, the same for antennas looking to the left and right, where i stands for the inclination, N is the number of revolutions per day and u stands for the argument of latitude and is the designation for the sum of the true anomaly υ and the argument of perigee ω. In this arrangement rotation about a vector is defined positive when rotation is counter-clockwise in the looking direction of the vector. Yaw steering can also be performed by a predefined reference range with $\theta \neq 0°$.

In this arrangement, areas at range positions other than the reference range result in a residual Doppler centroid.

This residual Doppler centroid complicates the SAR processing and can lead to image degradations.

Shown in FIG. 4 is the residual Doppler centroid in (Hz) for the Z co-ordinate system and in FIG. 5 for the S co-ordinate system, assuming an orbit with a semi-major axis of 6892.137km, an eccentricity of 0.001 and an inclination of 97.44° - for more details see Table following this parameter. For this example the yaw angle is calculated numerically, so that the Doppler centroid in the mid-range of the look angle, in this case for a look angle of 33.8°, is zero Hz. With this yaw angle the residual Doppler centroid is then calculated for a near-range look angle of 18.5° and a far-range look angle of 49.4°. These typical look angle values represent roughly the full performance incidence angle range for this spaceborne SAR system example.

Parameter	**Symbol**	**Magnitude**
	Orbit parameters	
Inclination	i	97.44°
Eccentricity	e	0.001
True anomaly	υ	0° - 360°
Argument of perigee	ω	90°
Right ascension of the ascending node	Ω	88.617°
Argument of latitude	$u = \upsilon + \omega$	0° - 360°
Semi major-axis of the orbit	R_E	6892.137 km

Instrument parameters		
Full performance look angle range	Θ	18.5° - 49.4°
Full performance look incidence angle range	η	20° - 55°
Wavelength	λ	0.031 m

Table

As evident from FIG.4 and FIG.5 the residual Doppler centroid greatly differs from zero for most of the orbit. In FIG.4 and FIG.5 the residual Doppler centroid over an orbit is indicated by a dashed line for a look angle of 18.5°, by a solid line for a look angle of 33.8° and dot-dashed line for a look angle of 49.4°. In FIG.4 the satellite co-ordinate system is in accordance with the so-called Z system with its Z_z axis pointing towards the Earth's center of mass whereas in FIG.5 it is in accordance with the so-called S system with its Z_s axis pointing perpendicular to the surface of the Earth´s reference ellipsoid.

Yaw steering is performed to advantage for the mid-range to minimize the residual Doppler centroid over the full swath width. As indicated by the solid line in FIG.4 and FIG.5 the Doppler centroid for a mid-range look angle of 33.8° is zero. But for near-range and far-range, depending on the steering of the radar antenna, a relatively large residual Doppler centroid occurs in the range of approx. ±250 Hz for the Z system (FIG.4) to approx. ±1 kHz in the S coordinates system (FIG.5).

The invention is based on the object of making it possible for a spaceborne or airborne coherent pulse radar system, particularly a synthetic aperture radar (SAR) system imaging a ground swath by its antenna, to steer the satellite in an advantageous way, resulting in a residual Doppler centroid of zero Hz independent of the incidence angle.

In accordance with the invention, relating to a method of the aforementioned kind, this object is achieved to advantage in that, in addition to the yaw angle also the pitch angle is steered in such a way that the Doppler centroid and/or its variation is zero over the full width of the ground swath.

Pitch steering, in other words steering the pitch angle is understood as a rotation about the Y axis of the satellite coordinates system, cf. Y_z axis in FIG.2 and Y_s axis in FIG.3.

Summary of Invention

More specifically, the present invention provides a method for reducing the Doppler centroid in a coherent pulse radar system comprising a synthetic aperture, said system being carried by a moving satellite platform and scanning, with the aid of its radar antenna, a strip of ground at at least approximately constant flight velocity, using both yaw angle steering and pitch angle steering, wherein in the coherent pulse radar system comprising a synthetic aperture and operated on said satellite platform the Doppler centroid is reduced to a minimum over the overall width of the strip of ground in that steering of the pitch angle is carried out according to the formula

$$\cos(pitch) = \frac{1 + e\cos\upsilon}{\sqrt{1 + e^2 + 2e\cos\upsilon}}$$

and steering of the yaw angle is carried out either according to the formula

$$yaw = \arctan\left(\frac{\sin i \cos u}{N - \cos i}\right)$$

or according to a numerical calculation of the yaw angle, wherein i is the inclination, e is the eccentricity, υ is the true anomaly and N is the number of revolutions per day, and u represents the argument of the latitude and indicates the sum of the true anomaly υ and the criterion ω of the perigee, wherein this applies to use of a satellite coordinate system where one axis points in the direction of the earth's center.

The method in accordance with the invention will now be detailed with reference to the attached drawings in which:

Brief Description of Figures

FIG.1 is an illustration of the geometry of a synthetic aperture radar (SAR) as already described,

FIG.2 is an illustration of the so-called Z co-ordinate system also as already described,

FIG.3 is an illustration of the so-called S co-ordinate system likewise as already described,

FIG.4 is a graph showing the profile of the residual Doppler centroid in [Hz] for a look angle of 18.5° (dashed line), of 33.8° (solid line) and 49.4° (dot-dashed line) as a function of the argument of latitude [degree] over a full orbit, the satellite co-ordinate system points with its Z_z axis at towards the Earth's center of mass (Z system in FIG.2),

FIG.5 is a graph showing the profile of the residual Doppler centroid in [Hz] for a look angle of 18.5° (dashed line), of 33.8° (solid line) and 49.4° (dot-dashed line) as a function of the argument of latitude [degree] over a full orbit, the satellite co-ordinate system points with its Z_s axis perpendicular to the Earth´s reference ellipsoid (S system in FIG.3),

FIG.6 is a graph showing the profile of the pitch angle [degree] as a function of the argument of latitude [degree] over an orbit,

FIG.7 is a graph showing the profile of the analytically calculated yaw angle as a function of the argument of the latitude [degree] over an orbit,

FIG.8 is a illustration of a satellite co-ordinate system defined as an alternative for performing Total Zero Doppler Steering, and

FIG.9 is a graph showing the profile of the residual Doppler centroid over a full orbit for a look angle of 18.5° (near-range) as shown in a) and d), for a look angle of 33.8° (mid-range) as shown in b) and e) and for a look angle of 49.4° (far-range) as shown in c) and f), the plots a) to c) applying for left-looking antenna and the plots d) to f) for a right-looking antenna and whereby in all plots the Doppler centroid profile with analytical calculation of pitch and yaw is indicated by a solid line and with analytical calculation of pitch and numerical calculation of yaw is indicated by a dashed line.

Description of the Preferred Embodiments

In steering to zero Doppler over the full swath width there are two basic possibilities: steering first the pitch, then the yaw or, as an alternative, first the yaw, then the pitch. From an orbital-mechanical point of view there is an advantage in first steering the pitch because this will be performed within the orbital plane. This is why in the following example first the pitch is steered, followed by steering the yaw.

As the satellite co-ordinate system either the S system or the Z system can be used, the following description relating to the latter. Minor departures of the Doppler centroid from 0 Hz may result from the steering accuracy of the antenna and the satellite, any deviation of the elliptical orbit, etc.

The method in accordance with the invention features a series of advantages:

There is no, or only an extremely minor variation of the Doppler centroid over the range-coordinate within a scene, thus facilitating determining the Doppler centroid more accurately since an average can be obtained over all ranges.

Only a very minor residual Doppler centroid over the full swath occurs from near-range to far-range due to the steering accuracy.

Additionally steering the pitch of the satellite or aircraft platform can be performed within the orbital plane. This is easier to handle, orbit mechanically, than performing a steering outside of the orbital plane. In addition, pitch steering points the satellite platform in the flight direction, so that the cross-sectional surface area to be used in calculating the drag is constant over the orbit.

There is no need for different mathematical formulae for a left-looking antenna and right-looking antenna since the residual Doppler centroid over the full incidence angle range is very minor for both the left-looking antenna and right-looking antenna.

Total Zero Doppler Steering is also possible in using the S co-ordinate system.

Generating SAR interferograms is facilitated since the Doppler centroids in the two radar images which will be used are always nearly zero Hz and thus the Doppler spectra always have almost full overlap contrary to the case of different Doppler centroids in the two images used to create the interferogram.

Co-registering accuracy is substantially enhanced by the very minor Doppler centroid.

In the ScanSAR mode scalloping filters can be implemented more easily and more effectively since in the range direction the Doppler centroid is nearly constant.

An approximation of the pitch angle through which the pitch steering is rotated is calculated analytically to rotate the satellite co-ordinate system in the X-Z plane so that the X direction precisely coincides with the velocity vector. This applies for the above case of first the pitch being steered.

Deriving the approximation of the pitch steering angle can be done as follows:

As is known, using the Kepler elements an orbit position is fully described by its coordinates vector:

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = r \begin{pmatrix} \cos(\omega + \upsilon)\cos\Omega - \sin(\omega + \upsilon)\cos i \sin\Omega \\ \cos(\omega + \upsilon)\sin\Omega + \sin(\omega + \upsilon)\cos i \cos\Omega \\ \sin(\omega + \upsilon)\sin i \end{pmatrix}$$

where ω is the argument of perigee, υ the true anomaly, i the inclination, Ω the right ascension of the ascending node and r the range of the satellite from the Earth's center of mass. The time-variable range r is given by

$$r = \frac{a(1 - e^2)}{1 + e\cos\upsilon}$$

where e is the eccentricity and a the semi-major axis.

Differentiating the location vector as cited above with time the velocity vector v results in

$$v = \begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{pmatrix}$$

$$= -\sqrt{\frac{GM}{a(1 - e^2)}} \begin{pmatrix} \cos\Omega\cos\omega\sin\upsilon + \cos\Omega\sin\omega(\cos\upsilon + e) - \cos i\sin\Omega\sin\omega\sin\upsilon + \cos i\sin\Omega\cos\omega(\cos\upsilon + e) \\ \sin\Omega\cos\omega\sin\upsilon + \sin\Omega\sin\omega(\cos\upsilon + e) + \cos i\cos\Omega\sin\omega\sin\upsilon - \cos i\cos\Omega\cos\omega(\cos\upsilon + e) \\ \sin i\sin\omega\sin\upsilon - \sin i\cos\omega(\cos\upsilon + e) \end{pmatrix}$$

where the gravitational coefficient $GM = 398600.4418\ km^3/s^2$ and with the identity

$$r^2\dot{\upsilon} = \sqrt{GM(1 - e^2)}$$

The pitch angle γ for pitch steering results from the angle between the aforementioned velocity vector v_e of an eccentric orbit and the velocity vector v_k of a circular orbit for which the above formula holds with $e = 0$. The angle γ is calculated as follows:

$$\cos\gamma = \frac{\vec{v}_e \circ \vec{v}_k}{|\vec{v}_e| \cdot |\vec{v}_k|}$$

where ° stands for the scalar product.

The pitch angle γ results in

$$\cos\gamma = \frac{1 + e\cos\upsilon}{\sqrt{1 + e^2 + 2e\cos\upsilon}}$$

where e stands for the eccentricity of the satellite and υ for the true anomaly. As expected the pitch steering angle depends neither on the inclination i, the right ascension of the ascending node Ω nor on the argument of perigee ω.

The sign of the pitch angle is negative for a true anomaly υ smaller than 180° (correspondingly in the selected example to an argument of latitude between 90° and 270°) and positive for a true anomaly υ between 180° and 360°, as evident from FIG.6 showing the pitch angle [degree] as a function of the argument of latitude [degree] over a full orbit, the basis for calculation are the parameters of the Table as cited above.

For subsequent yaw steering the approximation formula as already cited above

$$yaw = \arctan\left(\frac{\sin i \cos u}{N - \cos i}\right)$$

is used. The analytical calculated profile of yaw steering angle in [degree] as a function of the argument of latitude in [degree] over a full orbit is shown in FIG.7. Here again, the basis for calculation thereof is the parameters of the Table.

The new method leads to a significant reduction in the residual Doppler centroid. Using the given formulae of which the formulae for the pitch angle and for the yaw angle are approximations, a residual Doppler centroid of approx. ±25 Hz results, which is a significant improvement over prior art. In this case it is to be noted that a numerical calculation of the yaw angle and the pitch angle produces a still further improvement in the residual Doppler centroid of less than 0.05 Hz.

For illustration, a few trivial cases will now be discussed to highlight the statement of the achievement forming the basis of the method in accordance with the invention. The examples are based on the parameters as listed in the Table above. This is followed by a proposal for suitably selecting the satellite co-ordinate system for efficiently performing yaw steering.

For an assumed ellipsoidal Earth and a circular orbit, rotation of the Earth results in a Doppler centroid between approx. 10 kHz in the near-range and approx. 24 kHz in the far-range. Under these assumptions conventional yaw steering is capable of compensating the Doppler centroid as cited above over the full swath width. The near-range and far-range residual Doppler centroids are zero. When assuming an ellipsoidal Earth and a circular orbit the resulting Doppler centroid are of the same order of magnitude.

In the realistic case of an ellipsoidal Earth and an elliptical orbit a residual Doppler centroid results as a function of the range and argument of latitude. The Doppler centroid for a swath width corresponding to a look angle in the range 18.5° to 49.4° is approx. 10 kHz to 24 kHz. When using conventional yaw steering the residual Doppler centroid in the near-range and far-range can be reduced to approx. ±250 Hz for the Z system and approx. ±1 kHz for the S system as already described above.

It is evident that the residual Doppler centroid results due to deviation of the X direction of the satellite co-ordinate system from the direction of the velocity vector. The starting point for the novel method can also be appreciated in that due to the additional pitch steering the satellite co-ordinate system is rotated in the X-Z plane so that the X direction coincides with the velocity vector v.

By a suitable alternative definition of the satellite co-ordinate system pitch steering may already be integrated to advantage there in thus merely requiring yaw steering to steer the residual Doppler centroid to zero over the full swath width and for left- and right-looking systems.

As already described above the method in accordance with the invention now makes it possible to rotate the satellite co-ordinate system, i.e. the S system, for instance, by additional pitch steering in the X-Z plane so that the X direction precisely coincides with the velocity vector *V*.

Referring now to FIG.8 there is illustrated how this can be done to advantage in the definition of the co-ordinate system by the velocity vector *V* forming the X_T axis of the satellite coordinates system. The Z_T axis stands perpendicular to the X_T axis and is laying in the orbital plane and the Y_T axis stands perpendicular to the plane formed by the X_T axis and Z_T axis in complementing the Cartesian co-ordinate system. In FIG.8 this alternative definition of the satellite co-ordinate system is depicted in achieving Total Zero Doppler Steering.

Example aspects of the novel method and its advantages will now be described.

The parameters used in evaluating the formulae as cited above and those as listed in the above Table, whereby yaw steering is assumed for a mid-range look angle of 33.8°.

Referring now to FIG.9 there is illustrated firstly how the formulae as cited above represent a good approximation by way of the combination of analytical and numerical yaw steering with pitch steering in near-range, mid-range and far-range, FIGs. 9a) and 9d) showing the profile of the residual Doppler centroid over an orbit for a near-range look angle of 18.5°, FIG.9b) and 9c) for a mid-range look angle of 33.8° and FIGs. 9a) and 9f) for a far-range look angle of 49.4°. Note that the profiles 9a) to 9c) are those for a left-looking antenna whilst those of FIGs. 9d) to f) are for a right-looking antenna. This look angle range corresponds to an incidence angle range 20° to 55°. The solid profile lines of the Doppler centroid in the six plots a) to f) of FIG.9 are the result of an analytical calculation of both pitch steering and yaw steering, whilst the dashed lines of the Doppler centroid relate to an analytical calculation of pitch steering and numerically calculation of yaw steering.

In the numerical calculation at each point on the orbit the yaw angle is calculated so that it results in a minimum residual Doppler centroid, e.g. $< 10^{-5}$ Hz. Using the orbit parameters as listed in the above Table the residual Doppler centroid is calculated.

As readily appreciated from FIG.9 the approximation by the formulae as cited above is satisfactorily appropriate. The maximum residual Doppler centroid is negligible with 26 Hz. Furthermore, as evident from the FIGs. 9a - 9f the residual Doppler centroid is practically identical for a left-looking antenna and right-looking antenna interchanged in sign.

Due to the various tangential velocities at the Earth's surface within the illuminated swath, a further minimum change is caused, which in this case is negligible, but which expediently could be taken into account by an improved yaw steering formula.

The method working in accordance with the invention may also be employed for reducing variation of the Doppler centroid in an airborne or spaceborne squint SAR system. Furthermore, the method can also be put to use for other kinds of coherent radar systems other than with a synthetic aperture. For instance, it can be put to use to advantage also in remote sensing radar systems operating with a real aperture, such as e.g. for an altimeter for sensing the spacing between supporting platform and ground, for a scatterometer in sensing ground profiles or roughness of the sea or for a weather radar in establishing cloud coverage and other weather features.

For support, any kind of platform is suitable, such as e.g. satellites, shuttles, aircraft, drones etc. Steering the pitch and yaw angle may also be achieved by changing the position of the platform and/or by electronically and/or mechanically steering the radar antenna itself.

CLAIMS

1. A method for reducing the Doppler centroid in a coherent pulse radar system comprising a synthetic aperture, the method comprising the steps of:

supporting said system by a moving satellite platform;

scanning, with the aid of a radar antenna of the system, a strip of ground at at least approximately constant flight velocity, using both yaw angle steering and pitch angle steering; and,

reducing the Doppler centroid in said coherent pulse radar system to a minimum over the overall width of the strip of ground by controlling the pitch angle according to the formula

$$\cos(pitch) = \frac{1 + e\cos\upsilon}{\sqrt{1 + e^2 + 2e\cos\upsilon}}$$

and controlling the yaw angle either according to the formula

$$yaw = \arctan\left(\frac{\sin i \cos u}{N - \cos i}\right)$$

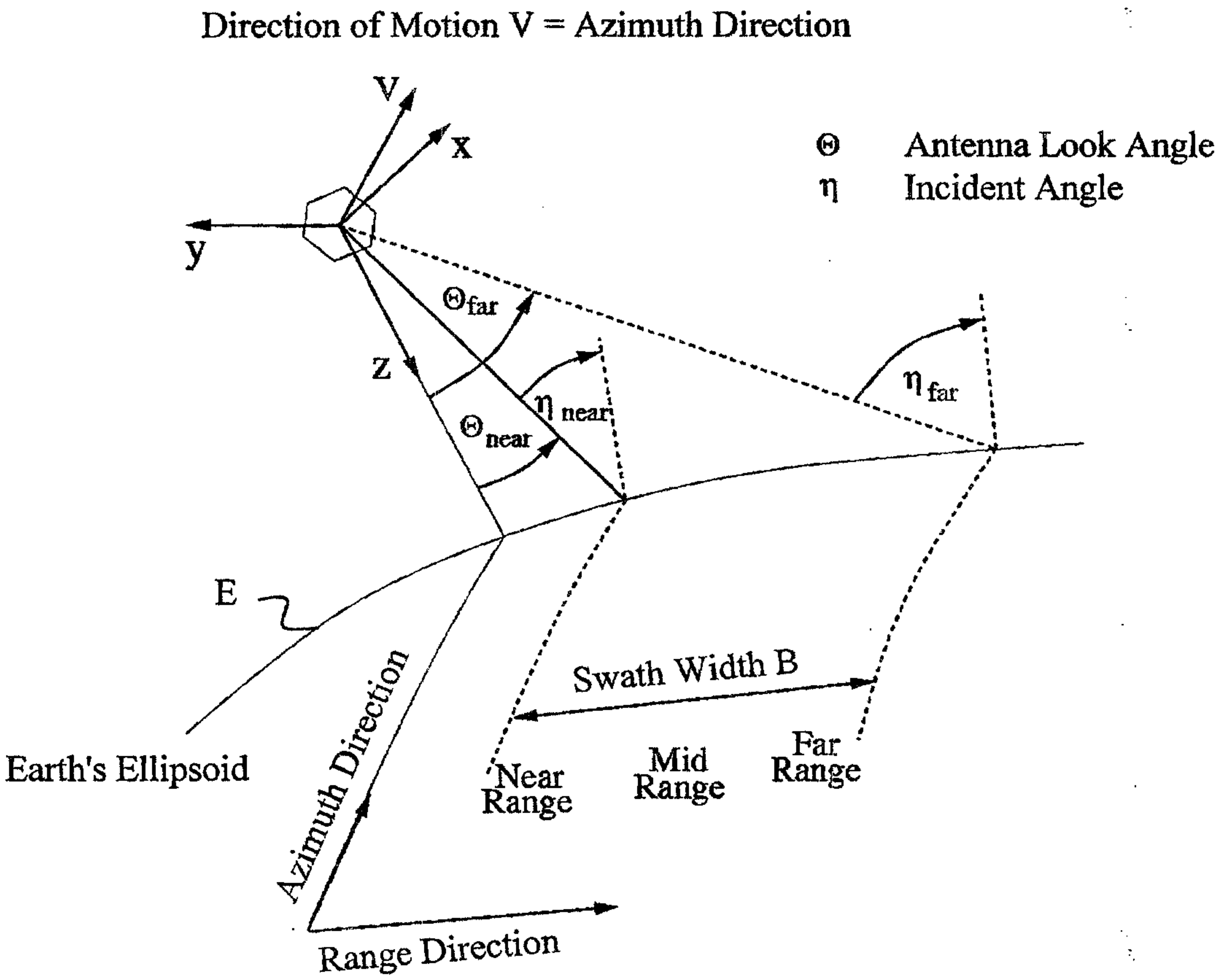
or according to a numerical calculation of the yaw angle, wherein i is the inclination, e is the eccentricity, υ is the true anomaly and N is the number of revolutions per day, and u represents the argument of the latitude and indicates the sum of the true anomaly υ and the criterion ω of the perigee, wherein this applies to use of a satellite coordinate system where one axis points in the direction of the earth's center.

2. The method according to claim 1, characterized in that steering of the pitch and yaw angle is performed electronically and/or mechanically by steering the radar antenna.

3. The method according to claim 1, characterized in that steering of the yaw and/or pitch angle is performed by changing the position of the platform.

4. The method according to claim 1, characterized in that first steering of the pitch angle is performed before steering of the yaw angle.

5. Use of the method according to any one of claims 1 to 4 for remote sensing of the earth's surface.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y
z
Θ Antenna Look Angle
η Incident Angle
Θfar
Θnear
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E
Earth's Ellipsoid
Swath Width B
Near Range
Mid Range
Far Range
Azimuth Direction
Range Direction

Fig.1

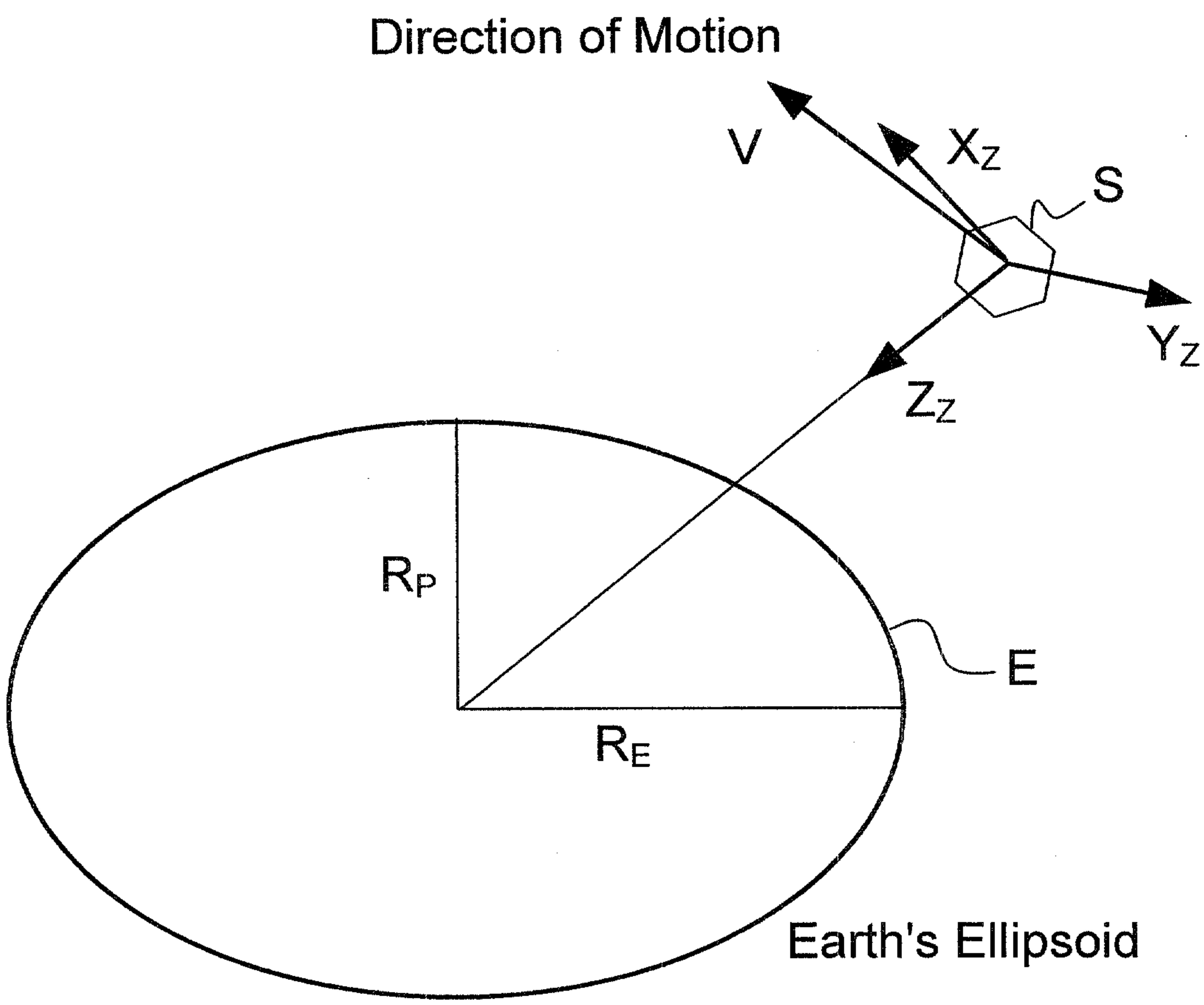


Fig.2

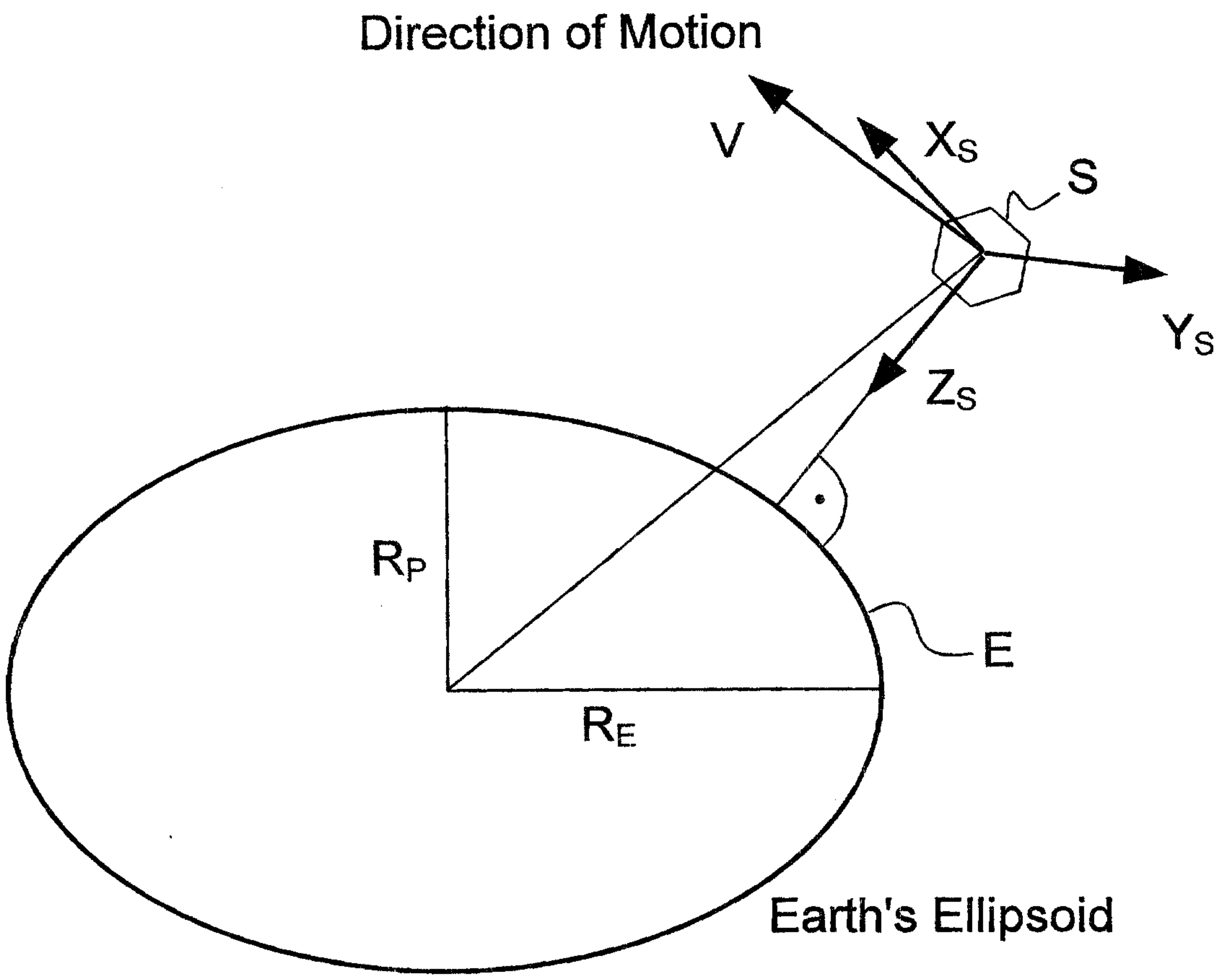
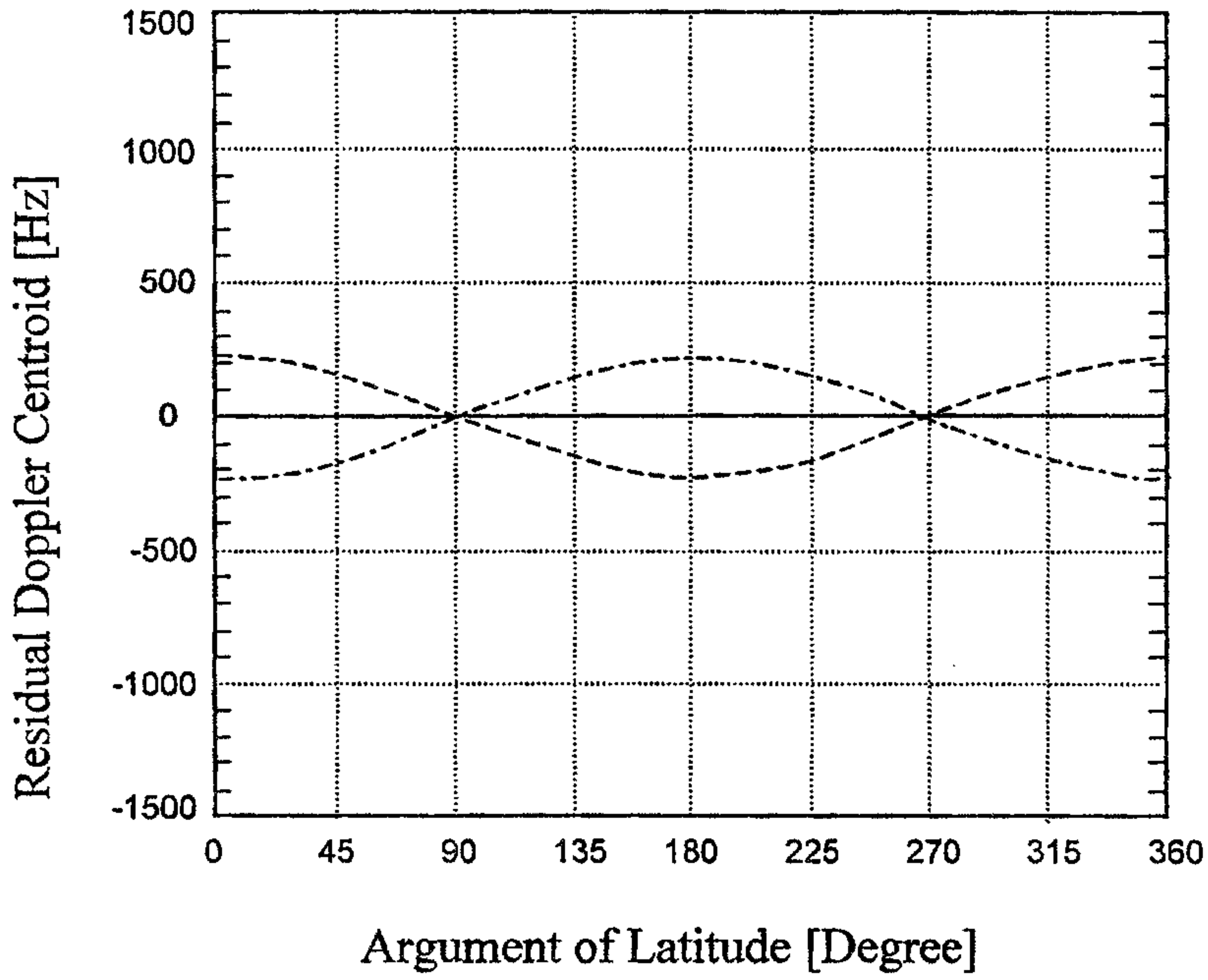


Fig.3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1000
500
0
-500
-1000
-1500
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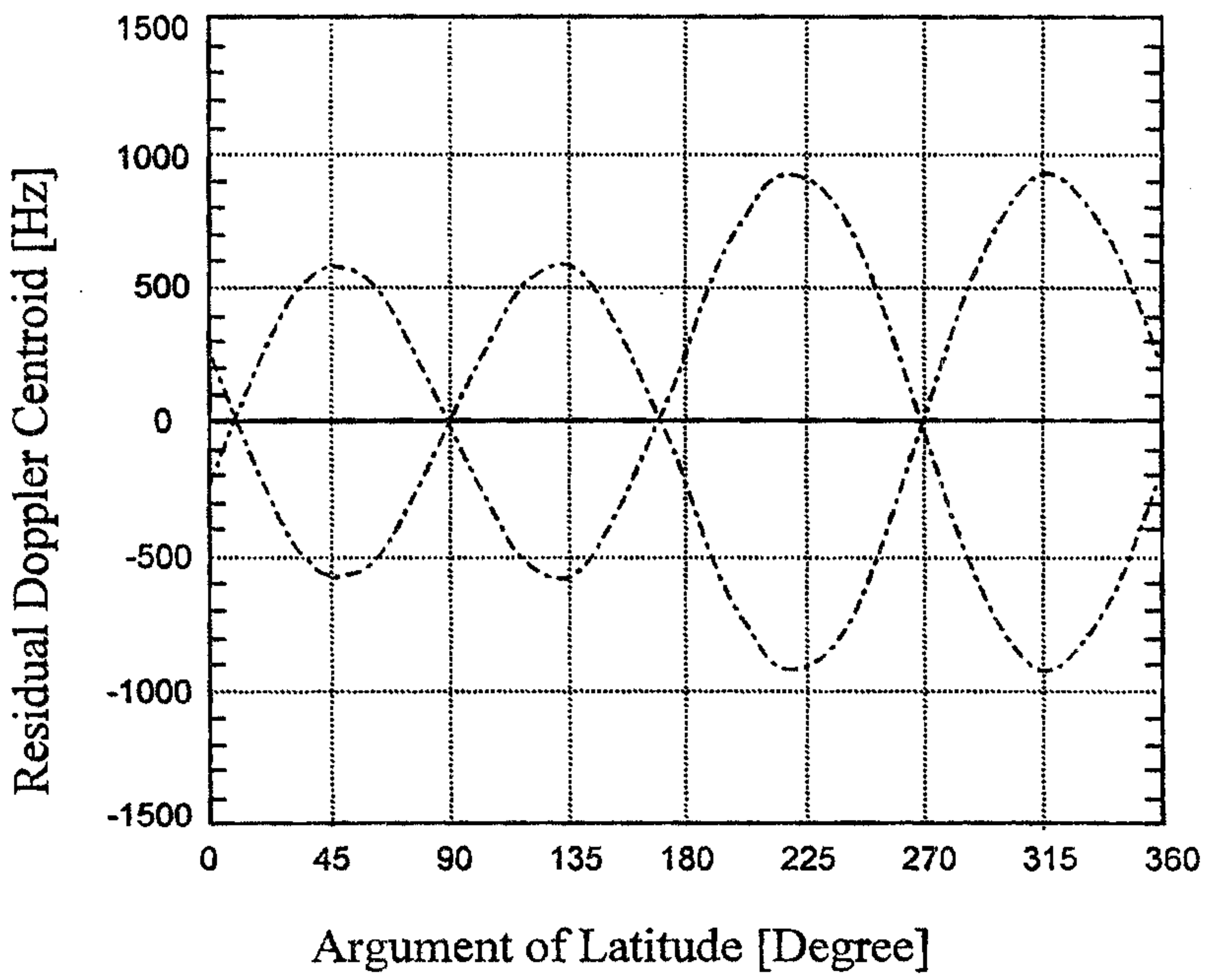
45
90
135
180
225
270
315
360
Residual Doppler Centroid [Hz]
Argument of Latitude [Degree]

Fig.4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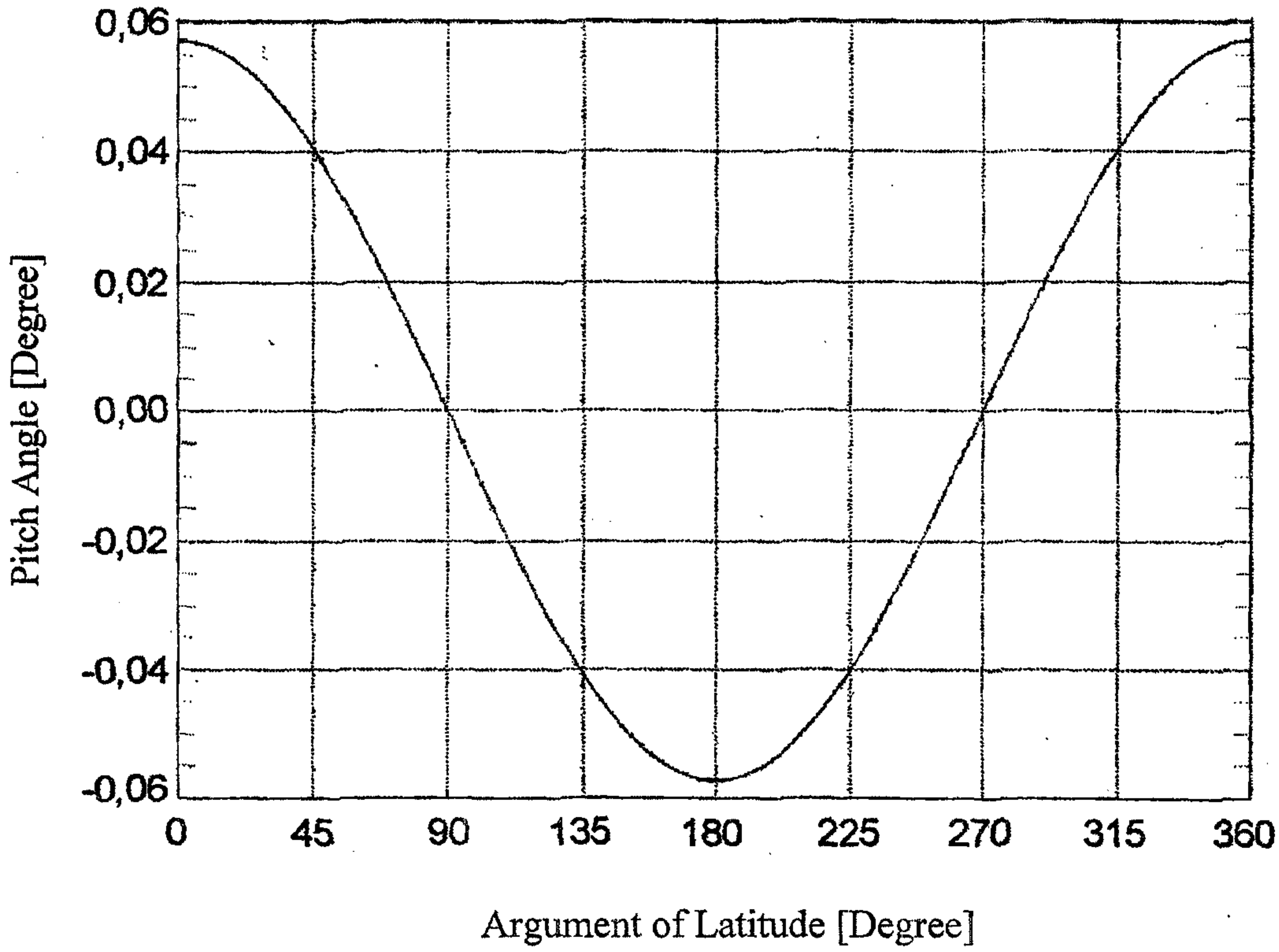
Residual Doppler Centroid [Hz]
Argument of Latitude [Degree]

Fig.5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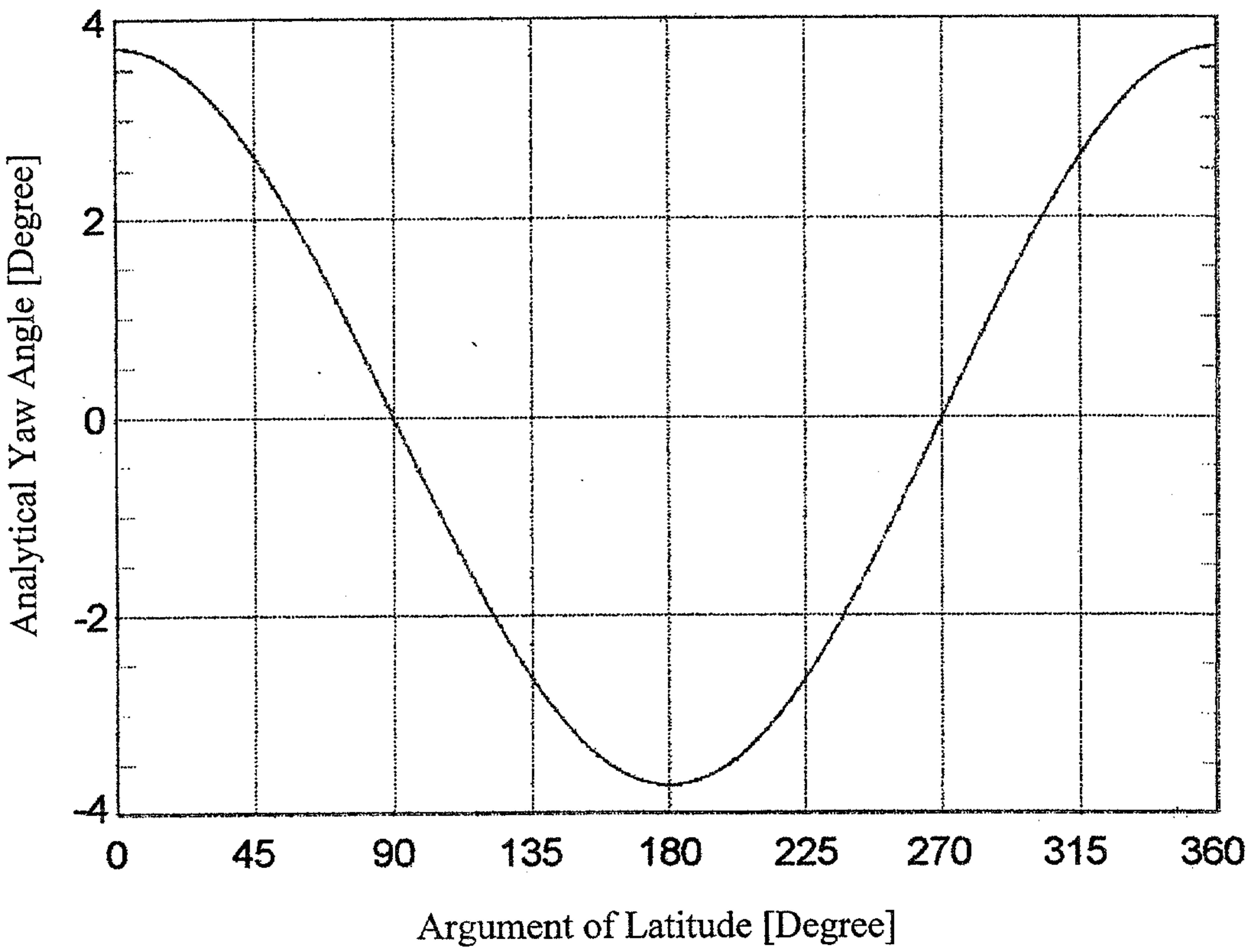
Pitch Angle [Degree]
Argument of Latitude [Degree]

Fig.6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135
180
225
270
315
360
Argument of Latitude [Degree]

Fig.7

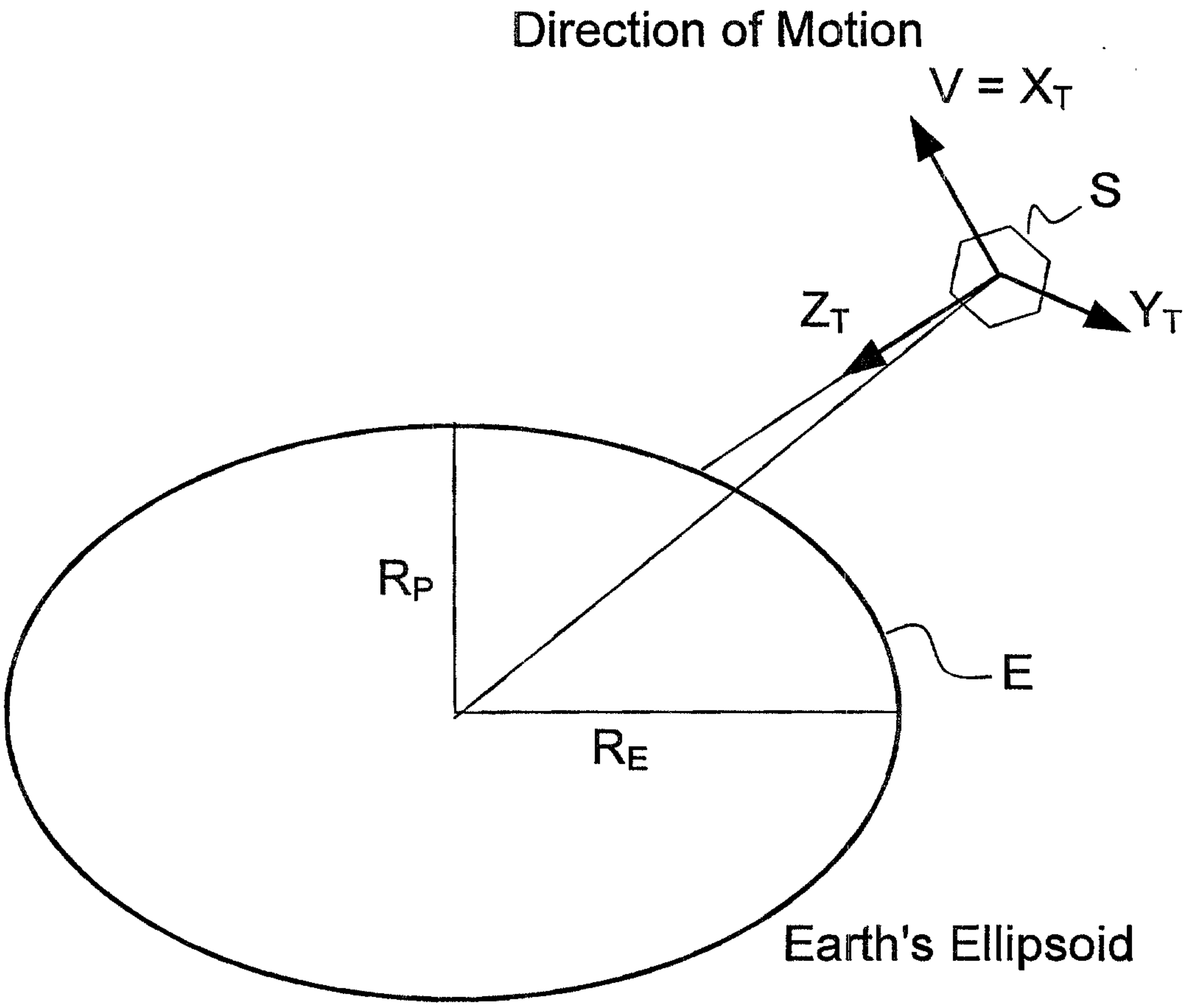

Fig.8

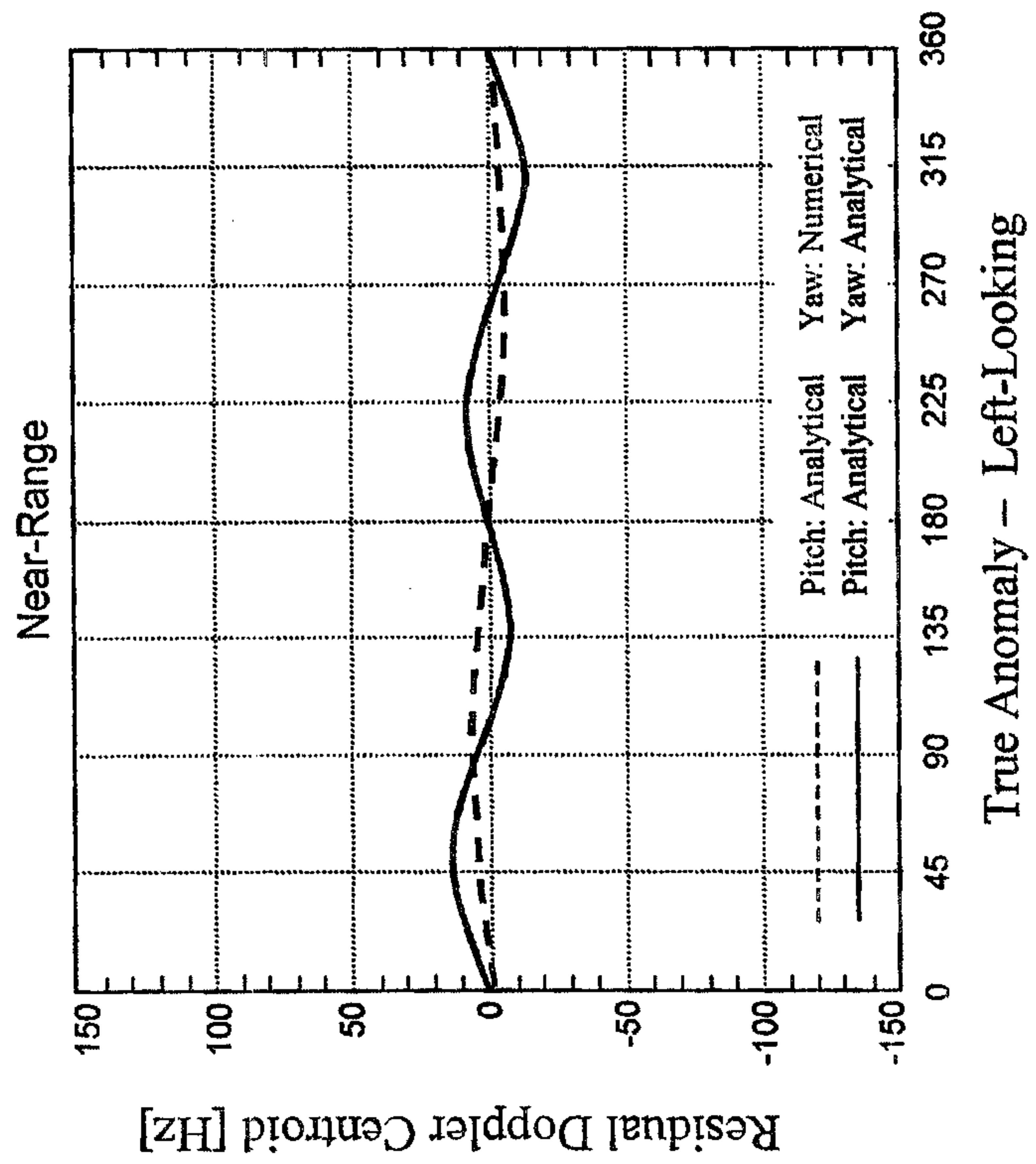
Near-Range
Residual Doppler Centroid [Hz]
150
100
50
0
-50
-100
-150
0
45
90
135
180
225
270
315
360
Pitch: Analytical Yaw: Numerical
Pitch: Analytical Yaw: Analytical
True Anomaly – Left-Looking

Fig.9a

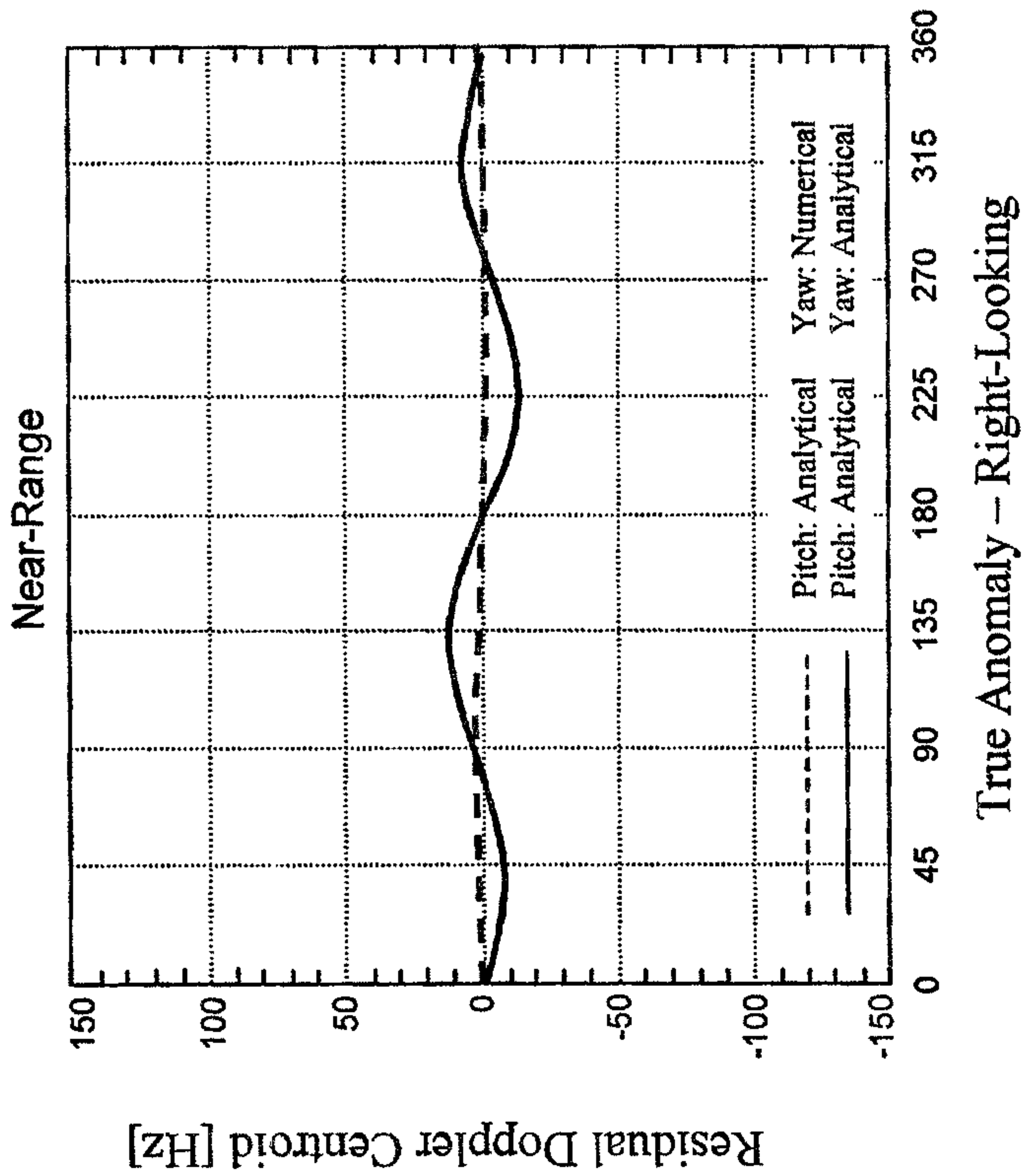
Near-Range
Residual Doppler Centroid [Hz]
150
100
50
0
-50
-100
-150
0
45
90
135
180
225
270
315
360
Pitch: Analytical Yaw: Numerical
Pitch: Analytical Yaw: Analytical
True Anomaly – Right-Looking

Fig.9d

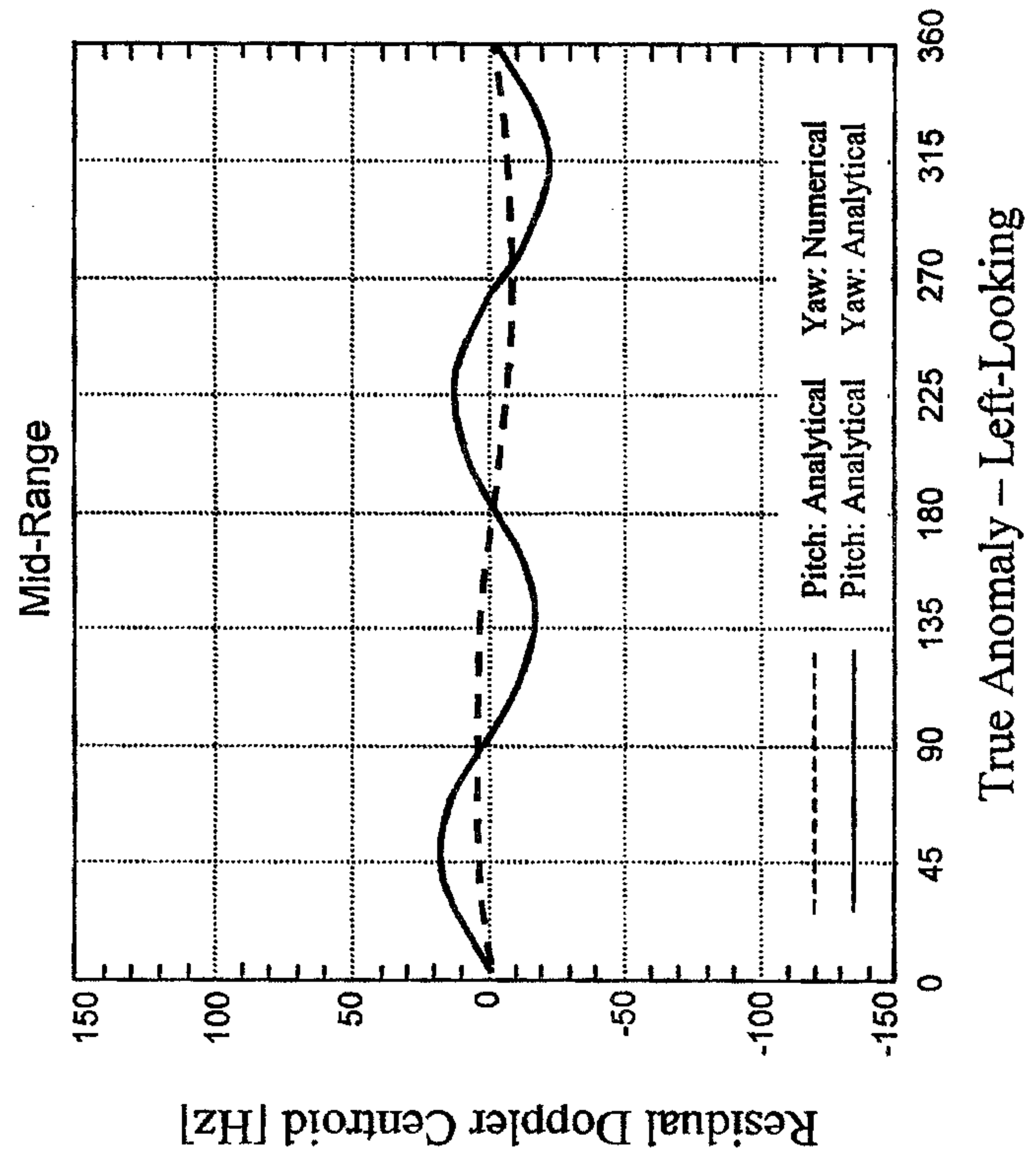
Mid-Range
Residual Doppler Centroid [Hz]
150
100
50
0
-50
-100
-150
0
45
90
135
180
225
270
315
360
True Anomaly – Left-Looking
Pitch: Analytical Yaw: Numerical
Pitch: Analytical Yaw: Analytical

Fig.9b

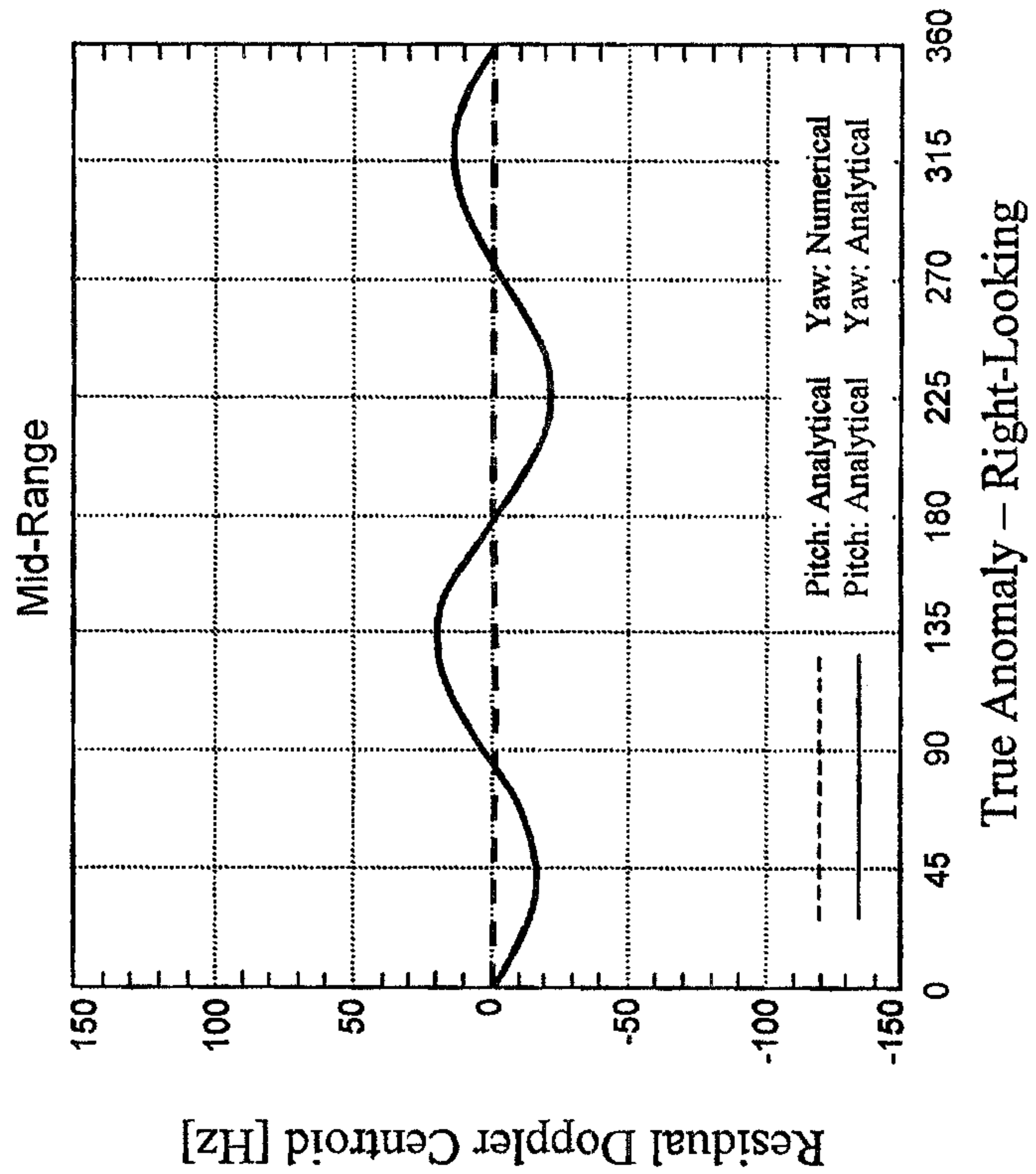
Mid-Range
Residual Doppler Centroid [Hz]
150
100
50
0
-50
-100
-150
0
45
90
135
180
225
270
315
360
True Anomaly – Right-Looking
Pitch: Analytical Yaw: Numerical
Pitch: Analytical Yaw: Analytical

Fig.9e

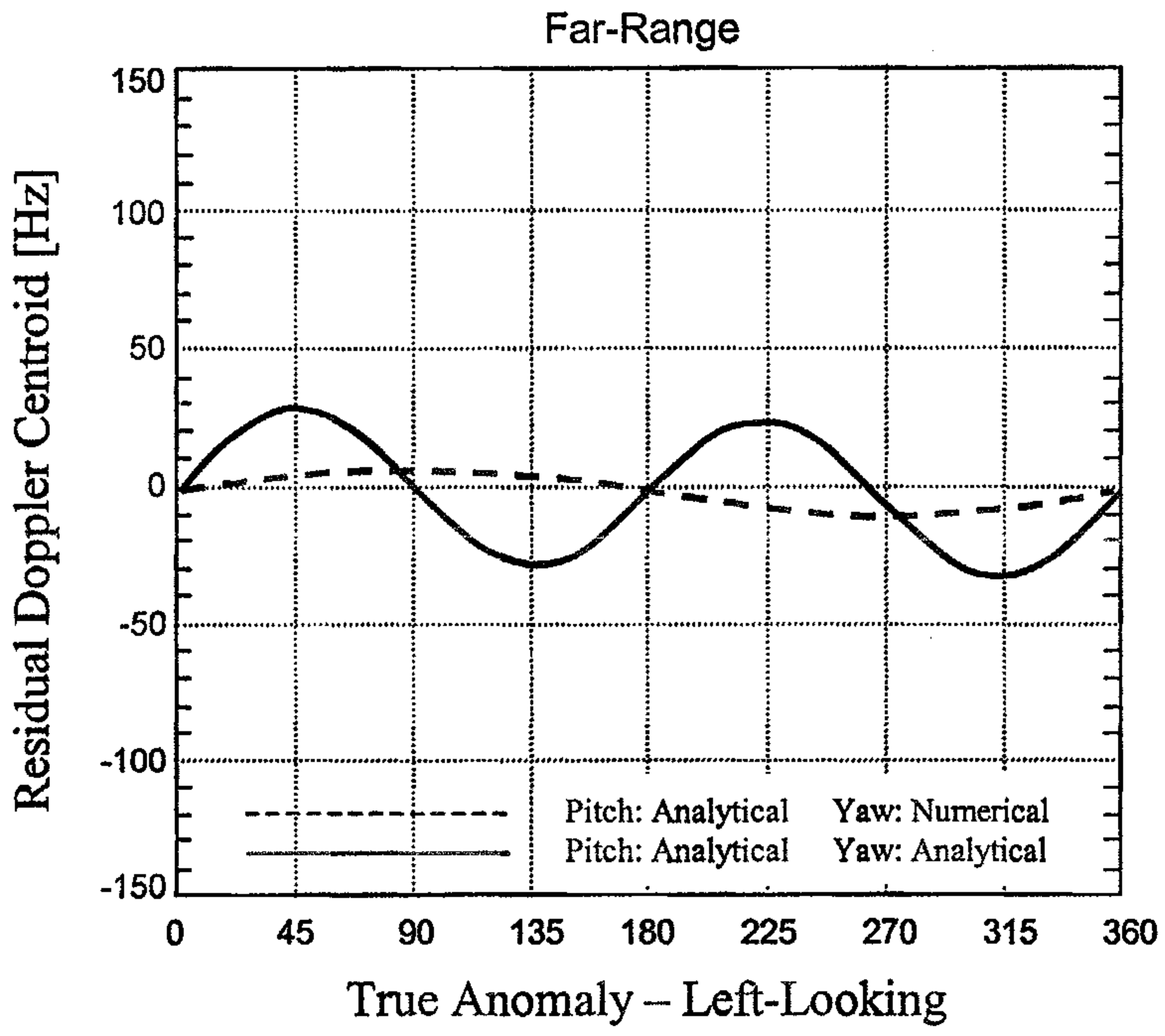
Far-Range
150
100
50
0
-50
-100
-150
0
45
90
135
180
225
270
315
360
Residual Doppler Centroid [Hz]
True Anomaly – Left-Looking
Pitch: Analytical Yaw: Numerical
Pitch: Analytical Yaw: Analytical

Fig.9c

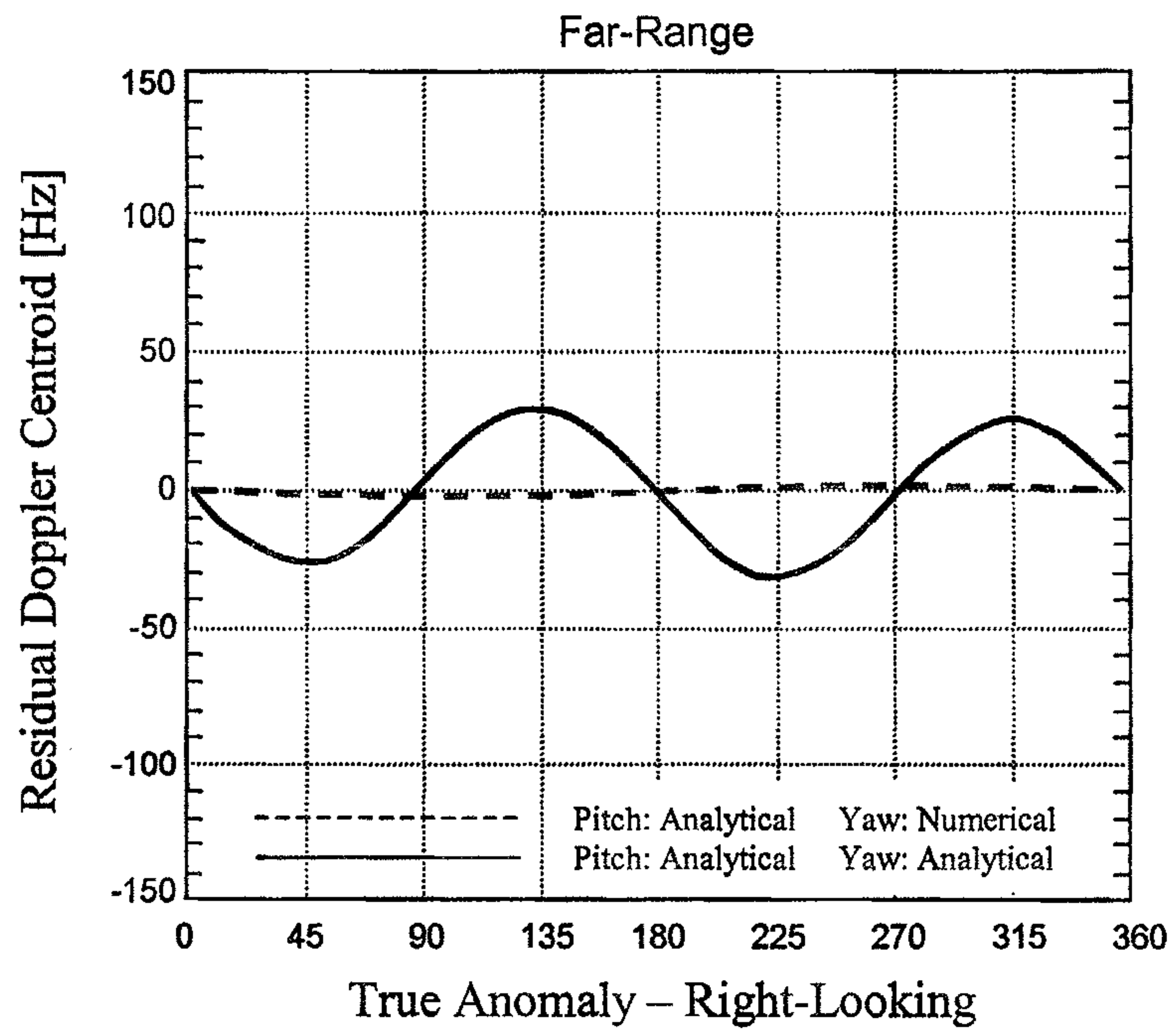
Far-Range
150
100
50
0
-50
-100
-150
0
45
90
135
180
225
270
315
360
Residual Doppler Centroid [Hz]
True Anomaly – Right-Looking
Pitch: Analytical Yaw: Numerical
Pitch: Analytical Yaw: Analytical

Fig.9f

Direction of Motion V = Azimuth Direction