Zenith Pass Problem of Inter-satellite Linkage Antenna Based on Program Guidance Method

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Abstract

While adopting an elevation-over-azimuth architecture by an inter-satellite linkage antenna of a user satellite, a zenith pass problem always occurs when the antenna is tracing the tracking and data relay satellite (TDRS). This paper deals with this problem by way of, firstly, introducing movement laws of the inter-satellite linkage to predict the movement of the user satellite antenna followed by analyzing the potential pass moment and the actual one of the zenith pass in detail. A number of specific orbit altitudes for the user satellite that can remove the blindness zone are obtained. Finally, on the base of the predicted results from the movement laws of the inter-satellite linkage, the zenith pass tracing strategies for the user satellite antenna are designed under the program guidance using a trajectory preprocessor. Simulations have confirmed the reasonability and feasibility of the strategies in dealing with the zenith pass problem.

Keywords: satellite; antenna; tracking and data relay satellite; zenith pass; program guidance

1 Introduction

Antennas of the elevation-over-azimuth type are always subject to there being a zenith pass problem[1-3], which means that when the elevation approaches 90°, the demand for azimuth velocity becomes very large and because of the limitation imposed on the velocity of servo mechanisms of a real antenna, the antenna will be incapable of tracing the target.

To tackle this problem, two methods are usually adopted: mechanical tilting and program guidance. The former[4] is to locate a tilting mechanism below the standard elevation-over-azimuth pedestal. It realizes stable tracking in the zenith pass course by changing the hardware structure of the antenna, but it is too expensive and might exert negative influence on the pointing accuracy of the antenna. The latter[5-6] only needs to change the software program of the antenna’s controller with no need for altering its hardware structure hence lowering the cost.

Mounted on the user satellite of the tracking and data relay satellite (TDRS), an inter-satellite linkage antenna, a load antenna, serves to point, acquire and track TDRS and usually uses the elevation-over-azimuth architecture characterized by compactness in structure. A reasonable pointing accuracy demands a very high yet small allowable velocity of its servo mechanisms to reduce the influences of its movement on the satellite, which poses a very severe zenith pass problem to the inter-satellite linkage antenna.

The relative space relationship between the user satellite and the TDRS complicates efforts to analyze the zenith pass problem of the user satellite.

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This is the reason why the researches concerning the zenith pass problem of the inter-satellite linkage antenna are so far not well-documented. This paper will discuss this problem and describe a strategy to deal with it using the program guidance method.

2 Movement Laws of Inter-satellite Linkage

The laws governing the TDRS to track the user satellite are called movement laws of the inter-satellite linkage, which involve the rotating laws of the azimuth axis and elevation axis of the user satellite antenna for tracing TDRS [7].

TDRS is moving in a geosynchronous orbit with a radius, \( R \), equal to 42 164 km. \( \Omega \) is the angle between the vernal equinox and the TDRS. The user satellite is moving in an elliptic orbit mode—relatively close to the Earth at an average altitude of approximately 200-1 200 km. Let the orbit parameters be: \( a, e, \Omega, w, i, f \). At the beginning moment, the user satellite antenna points to the positive direction of y-axis of the satellite body fixed frame, while the azimuth axis which is parallel to and points to the negative direction of its z-axis. The elevation axis is parallel to and points to the negative direction of the x-axis of the satellite body fixed frame (for detailed definitions see Ref.[7]). Then is obtained

\[
\begin{align*}
    2(1) & = \cos a - c o s f = + (1) \\
    \beta & = \beta \\
    \beta & = \beta \\
    \beta & = \beta \\
    \beta & = \beta \\
\end{align*}
\]

By differentiating the above equations with respect to \( t \), the angular velocities are

\[
\begin{align*}
    \phi_1 & = \frac{d_x \nu_x - d_y \nu_y}{d^2_x + d^2_y} \\
    \phi_2 & = \frac{d_x (d_x \nu_x - d_y \nu_y) + d_y (d_y \nu_y - d_x \nu_x)}{(d^2_x + d^2_y + d^2_z)(d^2_x + d^2_y)} \\
\end{align*}
\]

where \( \nu_x, \nu_y \) and \( \nu_z \) are the time derivatives of \( d_x, d_y \) and \( d_z \) respectively.

3 Potential Zenith Pass Moment

When the elevation of the user satellite antenna approaches 90°, the demand on azimuth velocity becomes very large, but because of the limitation imposed on the velocity of servo mechanisms of the real antenna, the antenna will be incapable of tracing TDRS. Then a blindness zone will form around the elevation of 90°. The moment is called the zenith pass moment when the elevation approaches 90°, and the azimuth velocity becomes infinite. The zenith pass moment appears when the user satellite lies on the orbit node, and TDRS just arrives at the point of intersection of the extended node line with the TDRS orbit (see Fig.1).

In Fig.1, \( P_{nd1} \) and \( P_{nd2} \) are the orbit nodes, \( P_{q1} \) and \( P_{q2} \) are the points of intersection of the extended
node line with the TDRS orbit. When TDRS arrives at the point $P_{q1}$ or $P_{q2}$, the zenith pass problem is likely to appear. The moment when TDRS arrives at the point $P_{q1}$ or $P_{q2}$ is called the potential zenith pass moment. Thus,

$$\Omega = \Omega_M - 180n_i$$  \hspace{1cm} (7)$$

Fig.1 Sketch map for the zenith pass.

where $\Omega_M$ approximately equals $360.9856 \degree/d$, is the derivative of $\Omega_M$, $n_i$ the serial number of the potential zenith pass moment. This paper assumes the user satellite in an sun synchronous orbit. When the inclination is greater than $90\degree$, $\Omega$ is equal to $0.9856 \degree/d$, where $(\degree)/d$ represents the variation radio of degree to a day. $M_{\Omega}$ and $\Omega$ are the values of $\Omega_M$ and $\Omega$ at $t_0$ and $M_{\Omega0}$, $\Omega_0 < 360\degree$. According to Eq.(7), can be obtained

$$n_i = \frac{t - \Omega_0 - \Omega_{M0}}{180}$$  \hspace{1cm} (8)$$

From Eq.(8) some conclusions can be drawn as follows: When $\Omega_{M0} - \Omega_0 = -180\degree$, $0\degree$ or $180\degree$, three potential zenith pass moments may appear in one day with the beginning moment being the 1st potential zenith pass moment, while under other conditions, there are only two. If $-360\degree < \Omega_{M0} - \Omega_0 \leq -180\degree$ and $n_i = -1, 0, 1, \cdots$, the 1st potential zenith pass moment appears when TDRS arrives at $P_{q1}$. If $-180\degree < \Omega_{M0} - \Omega_0 \leq 0\degree$ and $n_i = 0, 1, 2, \cdots$, it occurs when TDRS at $P_{q2}$. If $0\degree < \Omega_{M0} - \Omega_0 \leq 180\degree$ and $n_i = 1, 2, 3, \cdots$, it takes place when TDRS at $P_{q3}$. Finally if $180\degree < \Omega_{M0} - \Omega_0 < 360\degree$ and $n_i = 2, 3, 4, \cdots$, it appears when TDRS at $P_{q2}$.

According to Eq.(7), the potential zenith pass moment is calculated by

$$t_{q_i} = 240(\Omega_0 - \Omega_{M0} + 180n_i)$$  \hspace{1cm} (9)$$

Eq.(9) shows that $t_{q_i}$ obeys an arithmetical progression with a tolerance of $0.5 \degree$, which means the potential zenith pass moment appears once every half day.

At the potential zenith pass moment, Eq.(4) and Eq.(6) can be expressed as

$$\phi_1 = 0\degree$$
$$\phi_2 = \arctan \left( \frac{-r + R \cos u \cos \beta}{R \sin u \cos \beta} \right)$$  \hspace{1cm} (10)$$

$$\phi_i = \frac{\sin u}{\sin \beta}$$  \hspace{1cm} (11)$$

Let the potential zenith pass moment be the zenith pass moment, can be obtained

$$u = 180n_i + 360n_2$$  \hspace{1cm} (12)$$

where $n_2$ is an integer. Eq.(12) can be expressed as

$$n_2 = 240\omega(\Omega_0 - \Omega_{M0}) + 180n_i(240\omega - 1)$$  \hspace{1cm} (13)$$

where $u_0$ is the value of $u$ at $t_0$ and $0\degree \leq u_0 < 360\degree$, $\omega$ the angular orbit velocity of the user satellite. Whether a potential zenith pass moment is a zenith pass moment depends upon whether $n_2$ is an integer.

At the zenith pass moment, Eq.(4) and Eq.(6) can be expressed as

$$\phi_1 = 0\degree, \phi_2 = 90\degree$$  \hspace{1cm} (14)$$

$$\phi_1 = \infty$$  \hspace{1cm} (15)$$

4 Some Special Orbits for User Satellite

At the potential zenith pass moment, can be obtained

$$u_{q_i} = u_0 + 240\omega(\Omega_0 - \Omega_{M0}) + 43200\omega n_i$$  \hspace{1cm} (16)$$

Eq.(16) shows that $u_{q_i}$ obeys an arithmetical progression with a tolerance of $43200 \omega$.

According to Eq.(11), with a too small value of $\sin u$ at the potential zenith pass moment, the value of $\phi_i$ turns very large meaning there to be a peak value of $\phi_i$ around about the potential zenith pass
moment. With the peak value larger than the allowable velocity of the servo mechanism, the antenna will be incapable of tracing TDRS resulting in a blindness zone. Therefore, the value of $\sin u$ should be small enough at the potential zenith pass moment to get rid of the appearance of the blindness zone. If, at each potential zenith pass moment, the user satellite is located in the regions denoted by thick arcs in Fig.2, the blindness zone could be removed.

![Fig.2 Sketch map for avoidance the blindness zone.](image)

The region enclosed by thick arcs involves the allowable velocity of the servo mechanism. With the allowable velocity is equal to $2 \, ^\circ$/s, $\beta$ can be chosen up to $60^\circ$. Then can be obtained

$$
\omega = \frac{n_3}{240}, \quad n_3 = 1, 2, 3, \ldots
$$

(17)

Because the orbit altitude of the user satellite ranges from 200 km to 1 200 km, the angular orbit velocity ranges from $5.858 \, ^\circ$/d to $4.783 \, ^\circ$/d. According to Eq.(17), the value of $n_3$ can be 14, 15 or 16, and the value of $\omega$ is $5.040 \, ^\circ$/d, $5.400 \, ^\circ$/d or $5.760 \, ^\circ$/d, which corresponds the orbit altitudes 893.8 km, 566.9 km or 274.4 km respectively.

If the user satellite is at one of the above-mentioned three orbit altitudes, it can be located in the thick-arcs-enclosed region of Fig.2 by reasonable choice of the values of $u_0$, $\Omega_{M0}$ and $\Omega_a$ at the 1st potential zenith pass moment thereby leading to permanent avoidance of the blindness zone. In turn, if a reasonable choice of the values of $u_0$, $\Omega_{M0}$ and $\Omega_a$ makes the 1st potential zenith pass moment the zenith pass moment when the user satellite is at one of the orbit altitudes mentioned above, every potential zenith pass moment will be zenith pass moment.

5 Zenith Pass Tracing Based on Program Guidance

The basic idea of the program guidance method is as follows: in the process of an antenna automatically tracking TDRS, before TDRS enters the blindness zone, the antenna is moving under the program guidance, and after the antenna traverses the blindness zone, the antenna resumes its automatic tracking. This method can help the antenna catch and track TDRS again as quickly as possible after it has lost TDRS thus reducing the blindness zone. If the pointing error of the antenna is smaller than the allowable tracking error in the process of program guidance, TDRS is in the field of the antenna’s radio-frequency sensor throughout. Otherwise, TDRS will be lost during this period of time.

The key of the program guidance method is to design a proper antenna movement trajectory through the blindness zone. In Ref.[6], a method was proposed as follows: firstly, the trajectory of the azimuth axis is programmed with the intention of making the azimuth error small enough, then the trajectory of the elevation axis is calculated by

$$
\phi_2' = \tan^{-1}\left[\frac{\tan \phi_2}{\cos(\phi_1 - \phi_1')}\right]
$$

(18)

where $\phi_1'$ and $\phi_2'$ are the azimuth and elevation of the antenna under the program guidance respectively.

In this paper, the azimuth trajectory is designed using the trajectory preprocessor arithmetic[8] with the known movement laws of the inter-satellite linkage. According to the above-mentioned conclusions, the blindness zone should appear at the moment around about the potential zenith pass moment. Therefore, a peak value of the azimuth velocity will appear around about the potential zenith pass moment. When this peak value is larger than the allowable velocity of the servo mechanism, $t_m$, the moment when the peak value appears is the middle
moment of the blindness zone. This can be confirmed by the movement laws of the inter-satellite linkage.

The way to find $T$, an acquisition time of the trajectory preprocessor, is the key to use the trajectory preprocessor. In this paper, the trajectory preprocessor uses the sinusoidal acceleration pattern to make the final position and velocity match against the expected values. It could be found that the sign of the 1st region of the trajectory preprocessor and that of the 3rd region are opposite in this application. In such case, can be obtained

$$\varphi\left(t_0 + \frac{T}{2}\right) - \varphi\left(t_0 - \frac{T}{2}\right) = \nu_{\text{lim}} T - \frac{\left(\nu_0 - \nu_{\text{lim}}\right)^2 + \left(\nu_f - \nu_{\text{lim}}\right)^2}{2a_1}$$

$$\nu_0 = \varphi\left(t_0 - \frac{T}{2}\right)$$

$$\nu_f = \varphi\left(t_0 + \frac{T}{2}\right)$$

(19)

(20)

The left side of Eq.(19) is the azimuth that has been passed during the period of time $T$ around about the moment $t_m$, the right side of Eq.(19) is the angle that has been passed using the designed trajectory preprocessor during the period of time $T$. $\nu_{\text{lim}}$ is the allowable angular velocity of the antenna’s servo mechanisms, $\nu_0$ the initial angular velocity, $\nu_f$ the final angular velocity and $a_1$ the angular acceleration of the 1st region.

The value of $T$ can be obtained by solving Eq.(19) and Eq.(20).

6 Simulations and Analyses

Let the orbit parameters of the user satellite and TDRS at the initial time be: $a_0 = 6978$ km, $i_0 = 97.79^\circ$, $e_0 = 0.0013$, $\Omega_0 = 225.4^\circ$, $u_0 = 138.1^\circ$, $M_0 = 328.5^\circ$; the azimuth ranges from $-180^\circ$ to $180^\circ$ while the elevation from $-25^\circ$ to $90^\circ$; $\nu_{\text{lim}} = 2 (^\circ)/s$; the field of the antenna’s radio-frequency sensor is $0.4^\circ$.

According to the movement laws of the inter-satellite linkage, the expected rotating laws of the azimuth axis and the elevation axis of the user satellite antenna during one day can be obtained (see Fig.3 and Fig.4).

From Fig.3 and Fig.4, there exist two stations, at which the expected azimuth velocity is larger than $2 (^\circ)/s$ in one day meaning there to be two blindness zones meantime. According to the movement laws of the inter-satellite linkage, the middle moment of the 1st blindness zone is $18105.9$ s and that of the 2nd blindness zone $61671.1$ s.

According to Eq.(19) and Eq.(20), the acquisition time of the trajectory preprocessor for the two blindness zone is $45.015$ s and $90.152$ s respectively, which are rounded up into $46$ s and $91$ s. Besides, $\nu_{\text{lim}} = 2 (^\circ)/s$ and $a_m = 2 (^\circ)/s^2$.

The simulations are carried out for two options with or without program guidance in two blindness zones with the step time $0.01$ s. The results are shown in Figs.5- 12.
Fig. 5  Curves of the azimuth for the 1st blindness zone.

Fig. 6  Curves of the elevation for the 1st blindness zone.

Fig. 7  Curves of the azimuth velocity for the 1st blindness zone.

Fig. 8  Pointing error for the 1st blindness zone with program guidance.

Fig. 9  Curves of the azimuth for the 2nd blindness zone.

Fig. 10  Curves of the elevation for the 2nd blindness zone.
Fig. 11 Curves of the azimuth velocity for the 2nd blindness zone.

Fig. 12 Pointing error for the 2nd blindness zone with program guidance.

7 Conclusions

There exists a blindness zone when the inter-satellite linkage antenna of the user satellite moves to point and acquire TDRS. Defined as a moment when the blindness zone appears, the potential zenith pass moment occurs once a half day, which means, in the worst situation, a blindness zone can appear once a half day. Of the three specific orbit altitudes in this paper, if the user satellite chooses one as its own, the blindness zone may be avoided forever, or the zenith pass problem may become most serious.

The program guidance proves to be a kind of effective method to deal with the zenith pass problem of the antenna. In this paper, the azimuth trajectory of the antenna is programmed using the trajectory preprocessor. Then the elevation trajectory of the antenna is obtained based on the principle of making the pointing error as small as possible. The results out of simulations confirm that in some situations, using the program guidance method could have the zenith pass problem of the antenna completely solved, while in other situations, it could not though, the blindness zone gets shrunk obviously with the antenna able to catch and track TDRS again as quickly as possible after moving through the blindness zone.

Nevertheless, the program guidance is unable to compensate for the tracing error and incapable of curbing the jamming. The structural and/or mounting error of the antenna, the measuring error of the radio frequency sensor and the controlling error of the driving machine—all these will bring influences.

could be seen that the azimuth velocity of the antenna is smaller than 2 (°)/s in the 2nd blindness zone under the program guidance. Fig. 12 shows that the pointing error is larger than 0.4° for some length of time in the 2nd blindness zone, which implies that TDRS is lost during this period. However, the 2nd blindness zone is shrunk obviously under the program guidance, and the antenna is able to catch and track TDRS again as quickly as possible after moving through the blindness zone.
to bear on the tracing accuracy. Future engineering experiments are needed to make an insight into these influences.

References


Biography:
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