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Polarization Tracking Study of Earth Station in Satellite Communications

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Abstract

Satellite communications, in telecommunications, the use of satellite can provide communications links between various points on the earth. Typical satellite communication is composed of a communication satellite, a signal transmitter and a signal receiver. As the signal transmitter or the signal receiver, an earth station plays a vital role in the satellite communications. Accurately adjustment of antenna azimuth, elevation and polarization angles on the earth station is the key to satellite communications. In the present paper, a study of polarization tracking of earth station is presented, and a detailed adjustment procession of the polarization angle is given. Combing with observation series of MEASAT-2 satellite in geostationary orbit, the polarization tracking accuracy is verified. The method can be embeded into computer program of antenna polarization adjustment in earth station.

Keywords: satellite communications, earth station, antenna polarization, polarization tracking

1. Introduction

A communication satellite is an artificial spacecraft that relays and amplifies certain telecommunications signals with a transponder, acting as a middleman between a transmitter and a receiver. These satellites are used for television, telephone, radio, internet and military applications (International Telecommunications Union, 2002; Freeman, 2002; Elbert, 2003; Wang et al., 2004; Roddy, 2006; Pelton et al., 2012; Cochetti, 2014). Up to now, there are over 2000 communication satellites in the earth's orbit. Wireless communication uses electromagnetic waves to carry signals. These waves propagate along the line-of-sight, and are thus obstructed by the curvature of the earth. In order to communicate over great distances, satellites are used to redirect the signal. Communication satellites orbit the earth in one of three ways. One of these orbits is called geostationary earth orbit (GEO), which is about 35786 kilometers from the earth's surface. This orbit has the special characteristic in which satellites located can "stand still" with respect to a certain location on earth. Closer to the earth is the medium earth orbit (MEO). It ranges from 2000 to 35786 kilometers above the earth. With the GEO satellites (Ashby, 2003, 2005, 2014; Bertolami et al., 2012; Bertolami et al., 2011; Bertolami & Páramos, 2011; Iorio, 2014; Vespe, 2015) and the MEO satellites (Iorio, 2002, 2005, 2006, 2009, 2012a; Iorio et al., 2004, 2011, 2013; Renzetti, 2013a, 2013b, 2014, 2015), some fundamental physics including the general relativity can be tested. Below MEO is low earth orbit (LEO) and is between 160 kilometers and 2000 kilometers above the earth. MEO and LEO are not able to keep satellites "stationary" like GEO, so more satellites would be needed to cover a certain area. However, they transmit strong signals because of their relatively short distance to the earth. The main source of perturbation force for satellite orbit is combined gravitational attractions of the sun and the moon, which causes orbital inclination changes over time. The oblateness of the earth (J_2) also does change the inclination of the satellite and the effect extent relates to the coordinate system adopted in the study (Iorio, 2011). The three-body perturbation involving the earth, the moon and the sun is the largest disturbances which secularly change the orbit inclination (Cook, 2010; Iorio, 2012b; Zhao et al., 2015). According to the regulation released from the International Telecommunication Union (ITU), satellites with less than 15^{o} inclination from the equator are called GEO satellites. In Chinese Area Positioning System, the satellites with a small inclination angle, also called as slightly inclined geosynchronous orbit (SIGSO) satellite, are used to develop navigation and communication applications (Ai et al., 2008; Ai et al., 2009; Shi et al., 2009; Ma, 2011; Ma, 2014; Ma et al., 2011). The electromagnetic signals that communication satellites work with, have a large spectrum of frequencies. To keep these waves from interfering with one another, international organizations have certain rules and regulations describing which wavelength a certain company or group can use. By separating out wavelengths, communication satellites will have minimal interference and be able to communicate effectively.

A typical satellite link involves the transmission or uplinking of the signal from an earth station to a satellite. The satellite then receives and amplifies the signal and retransmits it back to the earth, where it is received and re-amplified by earth stations and terminals. The earth station plays a vital role in the satellite communications. Accurately adjustment of antenna azimuth, elevation and polarization angles on the earth station is the key to satellite communications. To ensure the earth station work reliably the antenna should accurately aim at the target satellite. Adjustment of the antenna on earth station is a process that adjusting beam center of the antenna pointing to the target satellite. This is a basis of verification tests and daily business operations for the earth station. Polarization is a property of waves that can oscillate with more than one orientation. In an electromagnetic wave, both the electric field and magnetic field are oscillating but in different directions; by convention the polarization of radio signal refers to the polarization of the electric field including linear, circular and elliptical ways. In electrodynamics, linear polarization or plane polarization of electromagnetic radiation is a confinement of the electric field vector or magnetic field vector to a given plane along the direction of propagation. The orientation of a linearly polarized electromagnetic wave is defined by the direction of the electric field vector. For example, if the electric field vector is vertical (alternately up and down as the wave travels) the radiation is said to be vertically polarized.

The linear polarization can be divided into horizontal and vertical polarizations. The radio signal with the linear polarization way is widely used to apply for satellite communications. The polarization angle is how the antenna is oriented based on the polarization way of the signal, which is affected by the curvature of the earth. Some studies show polarization matching is crucial for effectively receiving weak signal from the satellite (Lin, 2004; Ma et al., 2010). In this work, the authors present a polarization tracking study of earth station, and verify its accuracy with MEASAT-2 satellite observation series.

2. Definition of Polarization Angle

When the antenna on earth station receives electromagnetic wave with horizontal linear polarization from the satellite, polarization angle is an angle between orientation of the electric field for electromagnetic wave from the satellite and orientation of intersecting line between local level and receiving antenna aperture. After adjusting the azimuth and elevation angles of the antenna, there is an intersecting line between local level and antenna aperture on earth station. The angle between the intersecting line and orientation of satellite electric field is defined as polarization angle. In the next section, several coordinate systems used in this work are given a brief introduction.

3. Several Coordinate Systems

3.1 Earth-Centered Earth-Fixed Coordinate System

The Earth-centered Earth-fixed (ECEF) is a geographic coordinate system and Cartesian coordinate system. It represents positions as an X, Y, and Z coordinate. The point (0, 0, 0) is defined as the center of mass of the earth, hence the name earth-centered. Its axes are aligned with the International Reference Pole and International Reference Meridian that are fixed with respect to the surface of the earth, hence the name earth-fixed.

The z-axis is pointing towards the north but it does not coincide exactly with the instantaneous earth rotational axis. The slight "wobbling" of the rotational axis is known as polar motion. The x-axis intersects the sphere of the earth at 0° latitude (Equator) and 0° longitude (Greenwich longitude). This means that ECEF rotates with the earth and therefore, coordinates of a point fixed on the surface of the earth do not change (Xie, 2009).

3.2 Earth-Centered Inertial Coordinate System

The Earth-centered inertial (ECI) coordinate frames have their origins at the center of mass of the earth. ECI frames are called inertial in contrast to the ECEF frames which rotate in inertial space in order to remain fixed with respect to the surface of the earth. It is convenient to represent the positions and velocities of terrestrial objects in ECEF coordinates or with latitude, longitude, and altitude. However, for objects in space, the equations of motion that describe orbital motion are simpler in a non-rotating frame such as ECI. The ECI frame is also useful for specifying the direction toward celestial objects.

ECI coordinate frames are not exactly inertial since the earth center of mass itself is accelerating as it travels in its orbit about the Sun. In many cases, it may be assumed that the ECI frame is inertial without adverse effect.

However, when computing the gravitational influence of a third body such as the Moon on the dynamics of a spacecraft, the acceleration of the ECI frame must be considered. For example, when computing the acceleration of an earth-orbiting spacecraft due to the gravitational influence of the Moon, the acceleration of the earth itself due to the Moon's gravity must be subtracted (Xia & Huang, 1995).

3.3 Topocentric Coordinate System

There are two main topocentric coordinate frames one is based on the direction of the local vertical, which defines the plane of the horizon; the other is based on the direction of the earth's axis of rotation, which defines the plane of the celestial equator. The local meridian, which contains the direction of the local vertical and the direction of the axis of rotation, is common to both frames.

The angular coordinates in the topocentric coordinate frame of the horizon and local meridian are known as azimuth is measured from 0º to 360º from north in the direction of the east; that is, in the negative sense with respect to the direction of the zenith. Altitude is measured positively from the horizon toward the zenith. Both the altitude and the azimuth of any celestial object change rapidly as the earth rotates, and therefore, for many purposes it is more convenient to use the topocentric frame of the celestial equator and the local meridian. The direction of the north celestial pole is parallel to the earth's axis of rotation, and the altitude of the pole is equal to the geographic latitude of the point of observation (Urban & Seidelmann, 2013).

4. Calculation of Polarization Angle

4.1 Unit Vector of Orientation of Satellite Electric Field

The diagrammatic sketch of orientation of satellite electric field is given in Figure 1. Where the point O_e is the center of the earth and the point P is the place of receiving antenna. The satellite is located at points S_t and S_{t-1} at time t and $t-1$, respectively. In the orbital plane a tangent line through point S_t is made. The line is the unit vector of orientation of satellite electric field.

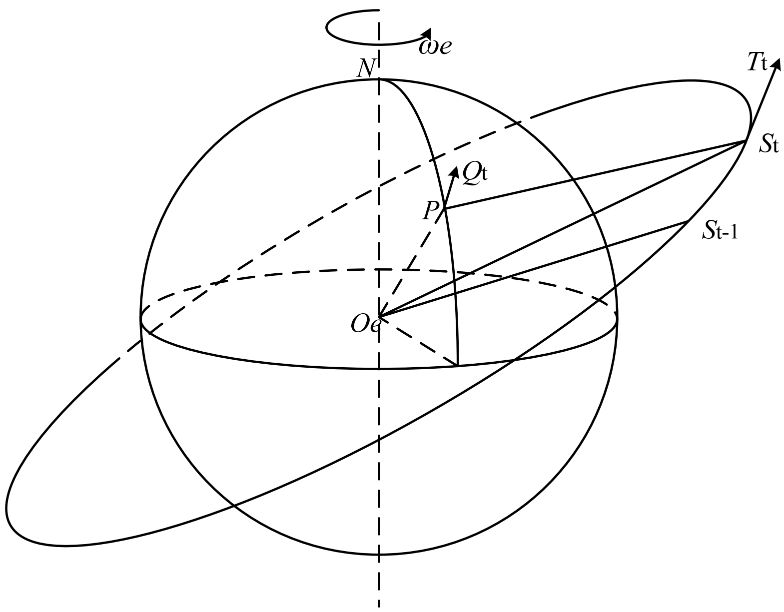

Figure 1. The diagrammatic sketch of orientation of satellite electric field

Under the spatial inertial rectangular coordinate system, normal vector of the orbital plane can be described as $\overrightarrow{O_eS_t} \times \overrightarrow{O_eS_{t-1}} / \left|\overrightarrow{O_eS_t} \times \overrightarrow{O_eS_{t-1}}\right|$. Unit vector $(\overrightarrow{N_1})$ of orientation of satellite electric field is perpendicular to the above the normal vector, meanwhile, it is also perpendicular to the vector $\overrightarrow{O_eS_t}$. So $\overrightarrow{N_1}$ is equal to $(\overrightarrow{O_eS_t} \times \overrightarrow{O_eS_{t-1}}) \times \overrightarrow{O_eS_t} / \left|(\overrightarrow{O_eS_t} \times \overrightarrow{O_eS_{t-1}}) \times \overrightarrow{O_eS_t}\right|$.

4.2 Unit Vector of Intersecting Line between Local Level and Antenna Aperture

Convenient understanding, here the topocentric coordinate system is adopted. After the antenna azimuth and elevation angles are adjusted, an analytic equation of antenna aperture can be described by one plane with a line from satellite to station as a norm and through point P. According to spatial geometry, a plane equation with a norm vector $(l,\ m,\ n)$, and through a point $(x_0,\ y_0,\ z_0)$ is given as follows.

$$l(x - x_0) + m(y - y_0) + n(z - z_0) = 0 \tag{1}$$

The origin of the topocentric coordinate system is located at point P, meanwhile the analytic equation of the local level is $z = 0$. Furthermore the horizontal coordinate of some point in the intersection line is set as 1, the coordinate of the point is $(1,\ -l/m,\ 0)$. Therefore unit vector of intersecting line between local level and antenna aperture expressed as follows

$$\overrightarrow{n_2} = \left(\frac{1}{\sqrt{1+l^2/m^2}},\ \frac{-l}{\sqrt{l^2+m^2}},\ 0\right) \tag{2}$$

4.3 Calculation of Polarization Angle

Here all coordinates are adopted with the topocentric coordinates. Firstly the topocentric coordinates of unit vector of orientation of satellite electric field is calculated. According to Equation (3), the ECI coordinates of unit vector $(\overrightarrow{N_1})$ of orientation of satellite electric field are transformed into the ECEF coordinates.

$$\begin{bmatrix} x_{ecef} \\ y_{ecef} \\ z_{ecef} \end{bmatrix} = \begin{bmatrix} \cos(GAST + \omega_e(t - t_0)) & \sin(GAST + \omega_e(t - t_0)) & 0 \\ -\sin(GAST + \omega_e(t - t_0)) & \cos(GAST + \omega_e(t - t_0)) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_{eci} \\ y_{eci} \\ z_{eci} \end{bmatrix} \tag{3}$$

Where, *GAST* is the Greenwich Apparent Sidereal Time, and ω_e is the mean angular velocity of earth rotation.

Secondary how to transform the ECEF coordinates to the topocentric coordinates is presented in Equation (4).

$$\begin{bmatrix} x_{lv} \\ y_{lv} \\ z_{lv} \end{bmatrix} = \begin{bmatrix} -\sin B_0 \cos L_0 & -\sin B_0 \sin L_0 & \cos B_0 \\ -\sin L_0 & \cos L_0 & 0 \\ \cos B_0 \cos L_0 & \cos B_0 \sin L_0 & \sin B_0 \end{bmatrix} \begin{bmatrix} x_{ecef} - x_o \\ y_{ecef} - y_o \\ z_{ecef} - z_o \end{bmatrix} \tag{4}$$

Where $(B_0,\ L_0)$ and $(x_0,\ y_0,\ z_0)$ are geodetic and ECEF coordinates of point P, respectively. Then the unit vector $(\overrightarrow{n_1})$ can be obtained under the topocentric coordinate system.

From mentioned previously, the unit vector of intersecting line between local level and antenna aperture is calculated under the topocentric coordinate system. The polarization angle of earth station receiving radio signal can be solved with

$$\theta = \cos^{-1}(\overrightarrow{n_2} \cdot \overrightarrow{n_1}) \tag{5}$$

Specially, when the longitude of orbital slot for some satellite is less than that of earth station, the value of Equation (5) is taken negative. Additionally, considering the orthogonal characteristics between horizontal and vertical radio signal, when the antenna on earth station receives vertical linear polarization signal, and the polarization angle is equal to the value of Equation (5) adding $\pi/2$.

4.4 Calculation Flow of Polarization Angle

The calculation flow of polarization angle is shown in Figure 2. Using the calculation flow, polarization tracking of the antenna for earth station can be achieved.

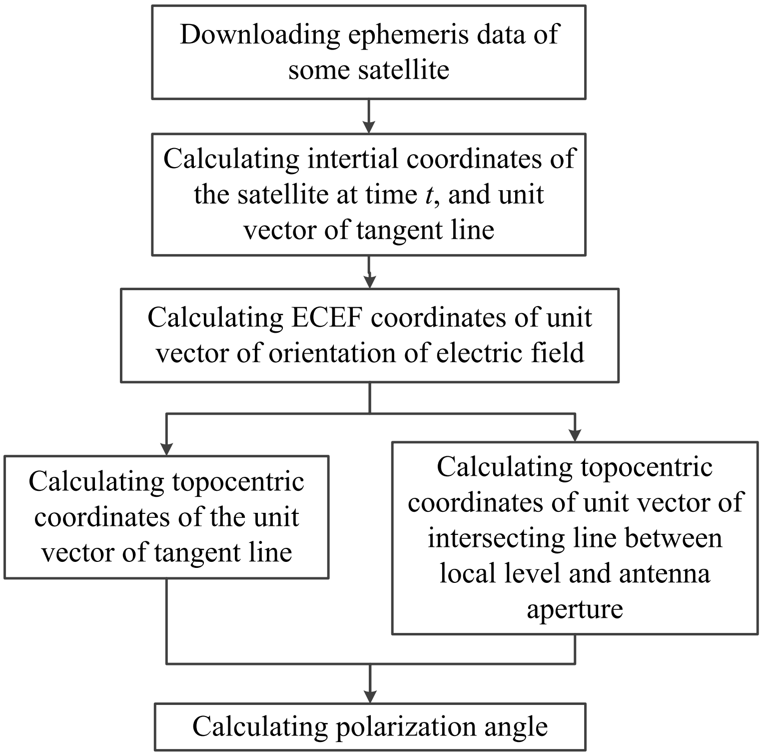

Figure 2. The calculation flow of polarization angle

5. Simulation Analysis

Once some satellite is launched into the space, the North American Aerospace Defense Command (NORAD) will include it in special number catalog. It is tracked all life time. Using satellite ephemeris data released by NORAD the coordinate and velocity with higher precision of any satellite can be determined. The satellite ephemeris is typically expressed with a Two-Line Element (TLE) form. Using the TLE data, the position and velocity of MEASAT-2 satellite at any time can be achieved (Kelso, 1998). Here the following Figure 3 gives MEASAT-2 satellite TLE data at 105.88346166 day, 2015 (April 15, 2015 21:12:11.087 UTC).

```
AFRICASAT-2 (MEASAT-2)
1 24653U 96063B   15105.88346166 -.00000242  00000-0  00000+0 0  9996
2 24653   6.1891  56.0904 0003635 162.0308  91.5264  1.00266671 67467
```

Figure 3. The TLE data of MEASAT-2 satellite

With the above TLE series, position and velocity of MEASAT-2 satellite can be achieved at any time. Meanwhile the azimuth, elevation and polarization angles on a visible station can be calculated. Supposing that earth station in Tianjin of China receives radio signal with vertical polarization transmitted by MEASAT-2 satellite. The polarization angle during 4:00 on April 16 to 4:00 on April 17, 2015 (UTC time) is solved according to calculating flow from Figure 2. The daily change of polarization angle is plotted in Figure 4. It is obvious that polarization angle remarkably changes over time and the daily change is similar to sinusoidal wave. The maximum value with -51.11 degrees and the minimum value with -64.89 degrees appear at about 14:20 (UTC) and about 2:50 (UTC), respectively. The amplitude of daily change is 13.78 degrees.

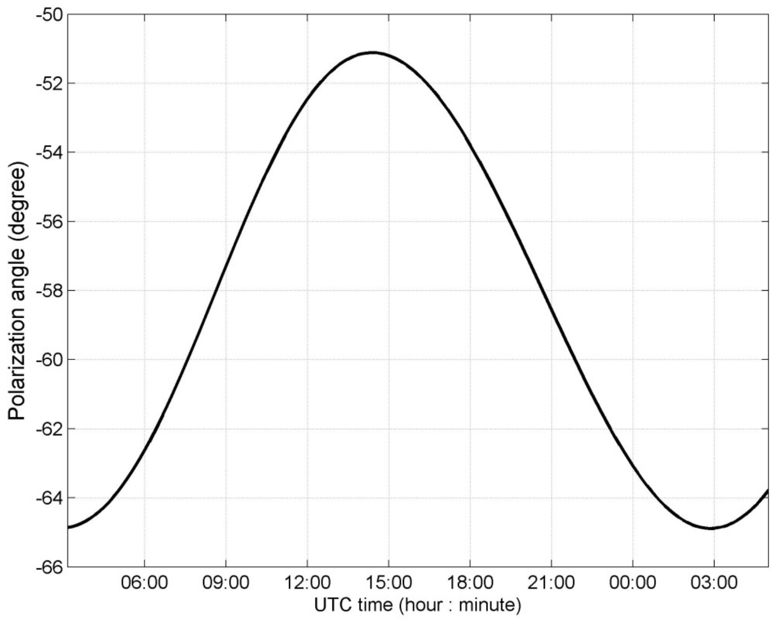

Figure 4. Simulation result of daily change for the polarization angle

6. Observation Series

To verify the simulation result, observation was carried out from April 16 to April 17, 2015 on earth station in Tianjin of China, where the beacon signal at 4199.125 MHz with vertical polarization was received by the 16 meters antenna system. The spectrum analyzer simultaneously monitors the power intensity of reverse polarized signal. The observation series is listed in Table 1.

Table 1. Observation series of MEASAT-2 satellite

UTC time	Polarization angle (°)	Power intensity of beacon signal (dBm)	Power intensity of reverse polarized signal (dBm)	Difference of power intensity of beacon and reverse polarized signals (dBm)
4/16/2015 04:00	-63	-14.77	-59.13	44.36
4/16/2015 06:01	-60	-14.76	-56.43	41.67
4/16/2015 08:07	-58	-13.97	-54.65	40.68
4/16/2015 10:05	-55	-12.78	-50.60	37.82
4/16/2015 13:04	-51	-11.54	-50.21	38.67
4/16/2015 14:33	-51	-11.32	-49.65	38.33
4/16/2015 16:03	-51	-10.78	-54.37	43.59
4/16/2015 18:30	-53	-23.27	-58.01	34.74
4/16/2015 20:21	-57	-10.56	-50.06	39.50

4/16/2015 22:12	-60	-10.86	-48.23	37.37
4/17/2015 00:15	-61	-12.08	-51.40	39.32
4/17/2015 02:12	-64	-13.60	-51.68	38.08

Furthermore the observation series of polarization angle is plotted in Figure 5 with solid point. From the figure, the observation series of polarization angle is very close to the simulation results. The maximum difference is about 2.5 degrees.

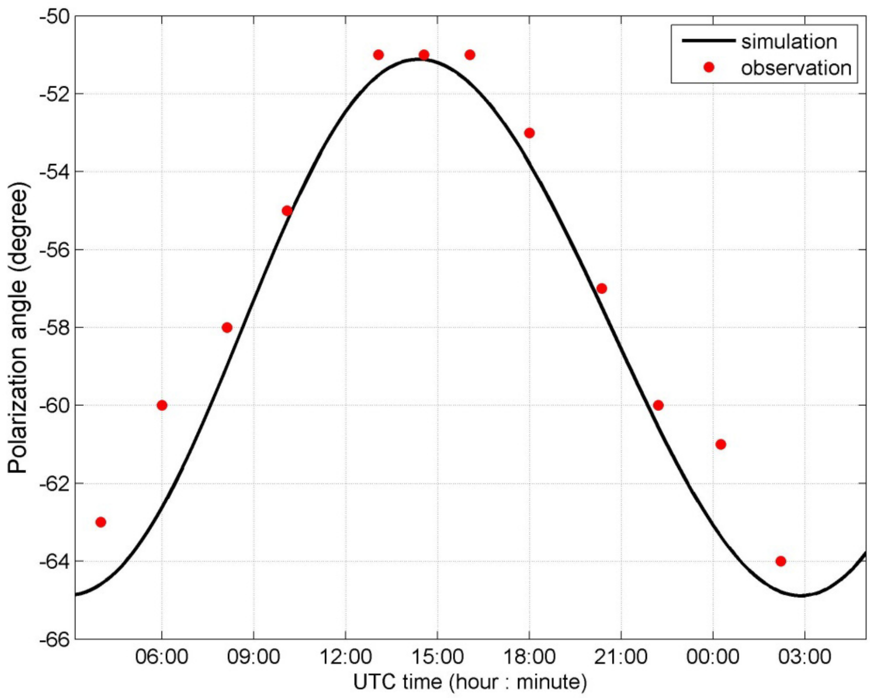

Figure 5. Observation series of the polarization angle

7. Conclusions

In this work, a study of polarization tracking of earth station is given. Furthermore, the MEASAT-2 satellite observations at earth station in Tianjin of China verify its accuracy. The little difference between simulation and observation series could result from satellite beam-center deviating sub-satellite projection point, Faraday effects, and so on. Actually, this tracking process can be used where satellite communications in MEO and LEO satellites downlink linear polarization signal. So, the method can be embeded into computer program of antenna adjustment in satellite communications earth station. Of course, the analysis only can be used to carry out polarization roughly tracking. To achieve optimum polarization matching, the earth station should finely adjust polarization according to the power density of radio signal.

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