Satellite Antenna Pointing Procedure Driven by the Ground Service Quality*

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Abstract
A satellite antenna alignment technique is proposed to ensure terrestrial service quality for users. The antenna bore sight orientation is calculated directly from measured data acquired from general ground receivers, which intercept the communication radio waves from any position on the earth’s surface. The method coordinates the satellite pointing parameters with signal strength at the receivers while considering location-specific geographical and antenna radiation characteristics and control accuracy. The theoretical development and its validity are examined in the course of equation derivation. Actual measured data of an existing satellite at the maneuver was applied to the method, and the capability was demonstrated and verified. With the wide diversity of satellite usage, such as for mobile communications, temporary network deployment or post-launch positioning accommodations, the proposed method provides a direct evaluation of satellite communication performance at the service level, in conjunction with using high frequency spot beam antennas, which are highly susceptible to pointing gain. This can facilitate swift and flexible satellite service planning and deployment for operators.

Key words: Satellite Communication, Satellite System, Antenna Pattern, Antenna Pointing, Parameter Extraction

1. Introduction

High radio frequencies and large antennas are now, more than ever, common considerations for communication satellite design. These provide sharp antenna gain slopes, and, as a consequence, communication performance becomes highly sensitive to pointing errors. Meanwhile, to utilize satellites capability as the maximum, users desire to recognize coverage areas available for their specific services. In addition, satellite antenna post-launch alignment is an attractive option for mobile applications, temporary network or utilization changes in terms of requesting signal strength on demand and dependent on locations.

Generally, satellite antenna systems are designed by taking into account nominal coverage and margin. The pointing accuracy and size of the margin is determined by a number of factors, including fabrication error, thermal distortion and attitude error. For communication satellites, link design must guarantee to meet the performance demands of users, which are defined by geographical points. In other words, no matter how the satellite is designed, deployed and controlled, users require stable signal.
strength at ground locations from where services are requested. Several pointing performance analysis and improvement techniques were developed in Refs.(4)-(6). The coverage of normal satellite systems is defined by the normalized radiated power E.I.R.P.(Equivalent Isotropically Radiated Power) and the antenna gain ratio G/T(Gain to System Noise Temperature) with a certain margin to compensate for several error sources, which are estimated by analysis and are partially confirmed through ground or in-orbit antenna testing with a limited number of data points. This coverage estimation provides the most conservative boundary from the combination of each worst-case prediction, but generally a number of error sources, including pointing error, thermal distortion or fabrication misalignment, are independent probable events(7). It is realistic to evaluate overall performance at the service level rather than to evaluate item-by-item, and satellite antenna positioning is adjustable, directly managing overall performance.

Firstly, the relationship between the antenna pointing angles and the receiving signal strength at ground level was analyzed. The algorithm development is aiming to provide an effective tool, formulated by using receiving signal strength at specific geographical locations at ground-based coordinates. There is difficulty in predicting the satellite pointing angle directly from receiver strength due to several error sources and non-homogeneous effects coming from geometrical and physical differences of the two parameters. The nonlinear characteristic was examined and formulated by linear approximations with an error boundary. If searching the most probable pointing angles conforming to a number of requirements, the method can be extended to the optimization of the least-squares prediction.

Next, several error sources, caused by antenna alignment, were examined in terms of signal strength sensitivity. Probability analysis was employed on the two components to evaluate directional gain characteristics of the satellite antenna, especially significant for recently common sharp saturated spot beams.

The derived method was tested through actual satellite position maneuvering and its capability and resilience to measurement errors were investigated. This procedure is not only utilized for the satellite antenna alignment control, but also for service augmentation, planning or post-launch service change analyses. It is obvious that the gain requirements at multiple points can not be achieved solely by adjusting the antenna direction. Also, since the method focuses on the pointing bias error, the contour collapse caused by beam forming error or array antenna grading lobe can not be handled in a direct manner. However, it is important to understand the maximum performance achievable from performing a positioning adjustment to meet the performance requirements on the ground. Also, it is effective in cases of temporal usage or common mobile applications which require location orientation. Evaluating antenna pointing capabilities by using ground signal strength will provide direct insight for service feasibility or adjustability studies, which, from the customer’s point of view, is necessary for effective satellite utilization and service planning.

2. Formulation of geographical parameters

The relationship between geostationary satellite orbital location and ground receiver geographical location is defined. The relation with respect to latitude is presented in Fig.1(a). The latitude of the ground location and antenna bore sight elevation angle $\gamma$ are formulated in Eq.(1).

$$\gamma = \tan^{-1}\left(\frac{R \sin \theta}{P - R \cos \theta}\right) = f_{\gamma}(\theta)$$
Here, $\theta$ is the degree in latitude of the ground receiver that intercepts the signal. Once latitude is given, the relationship between bore sight azimuth angle $\eta$ and longitude can be derived easily by the same manner as the projection from the pole, as shown in Fig.1(b). 

$$\eta = \tan^{-1}\left\{ \frac{R \cos \theta \sin \phi}{P - R \cos \theta \cos \phi} \right\} = f_\eta(\theta, \phi) \quad (2)$$

Here, $\phi$ is the longitude difference between the sub-satellite point and the ground receiver. The antenna bore sight projection to the ground surface from the satellite is shown in Fig 3. The illustration is the view from the satellite, which shows that the ground receiver is located with the bore sight angle vector $\mathbf{a}$ (in degrees) from the sub-satellite point. The receiver is located with the angle $\alpha$ from the equator on the projected ground plane. Equations (3) and (4) show the relationship between the azimuth and elevation bore sight angle and the vector indication on the projected plane in Fig.1(c).

$$\gamma = a \sin \alpha \quad (3)$$

$$\eta = a \cos \alpha \quad (4)$$

Although the satellite roll and pitch angle rotations are directly transferred to these bore sight azimuth and elevation angles, yaw angle is dealt with as the contribution to the azimuth and elevation angle changes. The azimuth and elevation contributions of the change in yaw angle are derived relative to the distance from the satellite sub-satellite point shown in Fig1(c). Eqs.(5) and (6) show the bore sight elevation and azimuth angle projections of yaw angle contribution on the ground surface.

$$\Delta_{El} = a \cos \alpha \cdot \sin \Delta_{yaw} \quad (5)$$

$$\Delta_{Az} = a \sin \alpha \cdot \sin \Delta_{yaw} \quad (6)$$
$\Delta \text{yaw}$ is the yaw angle change.

Assuming the rotational changes are small, the approximation of $\theta \approx \sin \theta$ in radian representation can be applied. For example, the Azimuth of Eq.(6) becomes,

$$\Delta_{Az} = a \sin \alpha \cdot 2\pi / 360 \cdot \Delta_{yaw}$$  \hspace{1cm} (7)

It should be noted that the unit of Eq.(7) is degrees. As the maximum sight angle of the earth, the value of $a$ becomes 8.7 degrees maximum. We can see that by this approximation, even when the change in yaw is quite a large number, for example 30 degrees, it only contributes a maximum 0.007 degrees of error to $Az$ at the earth’s peripheral edge. Less yaw change yields further negligible error. Some different representations but the identical equation of Eq.(7) appear in literatures for example Ref.(8). If the antenna center of alignment is not the sub-satellite point, the vector $a$ will be the distance from the center of alignment, which can also be obtained using Eq.(1). With Eqs. (1) and (3), Eq.(7) becomes,

$$\Delta_{Az} = f_{\gamma}(\theta) \cdot 2\pi / 360 \cdot \Delta_{yaw}$$  \hspace{1cm} (8)

The total azimuth change, with pitch and yaw contributions combined, is

$$\Delta_{Az} = \Delta_{Pitch} + f_{\gamma}(\theta) \cdot 2\pi / 360 \cdot \Delta_{yaw}$$ \hspace{1cm} (9)

It is noted that the directions of rotation are based on Fig.1(c). In the same manner, the elevation change will also be formulated with Eq. (2) and (4) for $\eta$. The parameters of geographical location-based alignment are formulated.

3. Gain variation and pointing angle

Pointing angle and gain variation at geographical point

The pointing error observed from the signal strength change at the ground receiver includes any control errors, thermal distortion, alignment during fabrication, and measurement errors. In addition, locations on the ground affect differently the receiving gain change. For applications utilizing mobile terminals or temporal stations, it is convenient to use the location parameter expressed in latitude and longitude rather than the relative location from the satellite. A move of the same distance north/south and east/west shows significantly different gain changes, as illustrated in Fig.2. It is therefore important to evaluate pointing change effects to the signal strength by examining the terrestrial location coordinates of the receiver.

Using the original gain distribution, the signal strength derivatives can be obtained by linear approximation. They are denoted as follows:

$$\delta_{NS} = \Delta G / \Delta_{NS}$$
$$\delta_{EW} = \Delta G / \Delta_{EW}$$ \hspace{1cm} (10)

The initial gain distribution on the ground-based coordinate can be obtained by several methods: a) antenna pattern analysis and/or range test, b) in-orbit test data, c) actual measurements using mobile receivers or d) multiple point measurements of fixed ground receivers, which are linearly inter/extrapolated. Therefore, the north/south and east/west deviations can be obtained on latitudinal and longitudinal coordinates at the target point. In this framework, the signal strength gain change is represented by the linear sum of the two latitudinal and longitudinal location change components.

$$\Delta G = \Delta G_{NS} + \Delta G_{EW} = \delta_{NS} \Delta_{\theta} + \delta_{EW} \Delta_{\phi}$$ \hspace{1cm} (11)
This must be a linear extrapolation when applied to a large delta of more than the deviation which regulates the local gain derivative. Since signal strength gain pattern has a non-linear curved feature in general, shown in Fig.2, the iterative calculation to update the deviations will be required. In addition, the path loss and other local attributes should be taken into account when the angles change. The relationship of the latitudinal and longitudinal angles and bore sight angles in Eqs.(1) and (2), are obtained by numerical calculation and will be updated at the iteration since the target point is known beforehand. The relationships are represented as,

\[ \Delta_\phi = C_{\theta \theta} \Delta_E \]
\[ \Delta_\phi = C_{\phi \eta} \Delta_A \]  

Using Eq.(12), Eq.(11) becomes

\[ \Delta G = \left[ \delta_{NS} C_{\theta \theta}, \delta_{EW} C_{\phi \eta} \right] \begin{bmatrix} \Delta_E \\ \Delta_A \end{bmatrix} = C \begin{bmatrix} \Delta_E \\ \Delta_A \end{bmatrix} \]  

The linear combination is described by the matrix.

\[ \Delta G = C \begin{bmatrix} \Delta_E \\ \Delta_A \end{bmatrix} = C \begin{bmatrix} 1 & 0 & \beta_E \\ 0 & 1 & \beta_A \end{bmatrix} \begin{bmatrix} \Delta_{Roll} \\ \Delta_{Pitch} \\ \Delta_{Yaw} \end{bmatrix} \]  

The formulation for the relationship between signal strength and pointing angle change constituted by ground measurement data is obtained from the derivation of these equations.

**Least-squares approach for multiple requirements**

If it is intended to identify antenna alignment values for satisfying multiple requests, the least-squares approach can be applied even with the limited three parameters of freedom. To extract roll, pitch and yaw parameters simultaneously, the direct inversion of the Eq.(14) requires at least three ground receiver data points. This can be extended to the least-squares averaging technique. In this case, more than three ground data are taken into account and averaged, and the matrix becomes,
\[
\begin{bmatrix}
\Delta G_1 \\
\Delta G_2 \\
\vdots
\end{bmatrix} = \begin{bmatrix}
1 & 0 & \beta_{EI,1} \\
0 & 1 & \beta_{Ez,1} \\
0 & 1 & \beta_{Ez,2}
\end{bmatrix} \begin{bmatrix}
\Delta _{roll} \\
\Delta _{pitch} \\
\Delta _{yaw}
\end{bmatrix} = \begin{bmatrix}
\Delta _{roll} \\
\Delta _{pitch} \\
\Delta _{yaw}
\end{bmatrix}
\]

(15)

Suffixes 1 and 2 indicate different ground receivers.

\[
\begin{bmatrix}
\Delta _{roll} \\
\Delta _{pitch} \\
\Delta _{yaw}
\end{bmatrix} = (F^TWF)^{-1} F^T W \begin{bmatrix}
\Delta G_1 \\
\Delta G_2 \\
\vdots
\end{bmatrix}
\]

(16)

W is the weighting matrix defined in the least-squares method.

\[
W = \text{diag} \left[ \frac{1}{\epsilon_i^2} \right]
\]

(17)

\[
\epsilon_i^2 = \Delta G_i^2
\]

(18)

As gain change and associated error distribution become significantly different between north/south and east/west, as shown in Fig.2, we use Eq.(11) for separate weighting for the north/south and east/west factors.

\[
\Delta G = \begin{bmatrix}
\delta_{NS} C_{\theta y} & 0 \\
0 & \delta_{EW} C_{\varphi n}
\end{bmatrix} \begin{bmatrix}
\Delta E_y \\
\Delta E_n
\end{bmatrix}
\]

(19)

This separates weighting parameter as directional components that create the north/south and east/west independent weighting matrix. The weighting matrix will be,

\[
W = \begin{bmatrix}
W_{1NS} & W_{1EW} & 0 & 0 & \cdots & 0 \\
0 & 0 & W_{2NS} & W_{2EW} & \cdots & 0 \\
0 & 0 & \cdots & 0 & W_{nNS} & W_{nEW}
\end{bmatrix}
\]

(20)

4. Capability analysis and location sensitivity

If additional signal gains can promptly be provided upon request, the satellite system can become a more flexible communication medium. Although this may not be achieved solely by antenna alignment with only three degrees of freedom, if the requirement can be confined within a specific area or time, it may be adequate. The averaging approach shown in Eq.(16) will not always produce an optimum result, because the conflict of the requirements yields only compromise within the limited freedoms. Therefore, the gain sensitivity at each location from antenna alignment obtained by Eq.(15) should be examined to find an adjustment strategy or capability limitation before proceeding to calculate the pointing alignment. This provides direct insight of the antenna alignment attribute at the specific service locations concerned. In general, the sensitivity is high at the periphery due to the geographical shape of the earth and at the edge of the antenna contour due to the sharp drop in propagation power, and it should be noted that it is highly dependant on direction.

The algorithm based on the signal strength at the ground receivers should take the following factors into consideration.
Path loss effects

Because of the earth’s shape and satellite radio propagation geometries, an aligning antenna will not necessarily yield the same signal strength by simply parallel-shifting the projection data from the original pointing angle. Propagation loss changes due to the fact that the link path lengths are different at each location on the earth’s surface. The difference in link paths is obtained schematically by Fig. 1(a).

\[
L_0^2 = (P - R \cos \theta)^2 + (R \sin \theta)^2
\]

\[
= P^2 + R^2 - 2PR \cos \theta
\]

is given at each ground location. Since path loss is relative to the square of the magnitude of propagation length, the path loss difference for each location data will be,

\[
D_{\text{Loss}} = (4\pi/\lambda)^2 L_1^2 - (4\pi/\lambda)^2 L_0^2
\]

\[
= (4\pi/\lambda)^2 2PR \{\cos \theta - \cos(\theta + \Delta_\phi)\}
\]

\[
= (4\pi/\lambda)^2 4PR \sin(\theta + \Delta_\phi/2) \sin(\Delta_\phi/2)
\]

\[
\cong (4\pi/\lambda)^2 2PR \sin \frac{2\pi}{360} \Delta_\phi
\]

, where \( \lambda \) is the wavelength of the radio wave. Using the pointing angle shift on the ground coordinate of Eq.(12) and Eq.(22), the effect of elevation alignment is derived. In the same manner, the azimuth effect can be obtained by modifying Eq.(22) with Eq.(2). This factor should be applied for sensitivity and recursive analysis of the measured data and its applied location. It is noted that since this effect depends on earth location, the formulation herein, based on latitude and longitude, is effective and convenient, which is especially significant at high latitude locations.

Local effects

Atmospheric effects also contribute to signal strength gain. This may be a location-oriented or time-dependent factor. If specific degradation or improvement is expected at the location, loss/gain factors will be applied as a bias to the equation. When this effect shows a fluctuation of the gain change, the variance needs to be considered. If it is introduced to the least-squares approach in Eq.(16), the loss/gain effect and variance will be incorporated into the gain bias and weighting matrix, respectively. The ground receivers have their own characteristics. This is also dealt with as a local factor in the same manner as atmospheric effect.

5. Error probability of antenna pointing

The challenge of direct evaluation, as proposed here, is determining calculation accuracy when applied to actual environments. Since pointing orientation error is assessed by the deviation from the target point on the earth’s surface, a circular error probability scheme is used to characterize the error profile. However, the directional dependence of varying signal strengths is notable at each location and latitude/longitude. We intend to formulate the two component errors in order to understand the relationship between antenna orientation error and gain variations.

Gaussian error distribution is assumed to regulate the probability boundary using a specific standard deviation \( \sigma \) as the worst-case scenario. As mentioned previously, yaw error is dealt with as contributions to roll and pitch axes, which are summed up as independent factors. Therefore, the error function on each axis can be derived by the square root summation of each rotation and the contribution of yaw. Based on Eqs. (5) and (6), the error functions are,
\[ \Delta_{el} = \sqrt{\Delta_{roll}^2 + (a \cos \alpha \cdot \sin \Delta_{yaw})^2} \]  
\[ \Delta_{ae} = \sqrt{\Delta_{pitch}^2 + (a \sin \alpha \cdot \sin \Delta_{yaw})^2} \]

Although the alignment effect of each axis is independent and different, the error probability of a gain degradation is evaluated on the two dimensional plane. In other words, the probability projected on the plane is a single event of the two components. Therefore, the square root summation of Eqs. (23) and (24) is not adequate. We must review the probability functions of the two components in Ref. (10). The probability functions of each axis are,

\[ f(x) = \frac{1}{\sqrt{2\pi} \sigma_x} \exp \left\{ -\frac{(x - \mu_x)^2}{2\sigma_x^2} \right\} \]  
\[ g(y) = \frac{1}{\sqrt{2\pi} \sigma_y} \exp \left\{ -\frac{(y - \mu_y)^2}{2\sigma_y^2} \right\} \]

, where \( \sigma, \mu \) are the standard deviation and average of each axis. The above two events must be considered simultaneously. Therefore, Eqs. (26) and (27) are multiplied, and produce,

\[ f(x)g(y) = \frac{1}{2\pi\sigma_x\sigma_y} \exp \left\{ -\frac{(x - \mu_x)^2}{2\sigma_x^2} - \frac{(y - \mu_y)^2}{2\sigma_y^2} \right\} \]

The probability of two components \((x,y)\) is obtained. Direct integration requires some mathematical efforts in Ref. (11). Assessed in terms of the standard deviation, \((x,y)\) can be normalized with respect to each \(\sigma\).

\[ (x, y) \rightarrow (\bar{x}, \bar{y}) \]  

As Gaussian probability distribution is assumed, the average for each axis is zero. Cartesian to circular coordinate transformation is applied.

\[ \bar{r}^2 = \bar{x}^2 + \bar{y}^2 \]

The following integration provides the probability summation of two components distribution \((\bar{x}, \bar{y})\) up to the specific probability boundary.

\[ \int f(\bar{x})g(\bar{y})d\bar{x}d\bar{y} = \int h(\bar{r})r \, d\theta dr = \frac{1}{2\pi} \int \exp \left\{ -\frac{\bar{r}^2}{2} \right\} r \, d\theta dr \]

Numerical integration is performed. The calculation is equivalent to finding an elliptical plane in which two component errors lie within the boundary of constant probability density in the x-y plane. Here, we can obtain the probability of circular error for each axis projection, which can be applied to the developed latitude/longitude directional gain driven formulation. For example, if the probability of each single axis is assumed within 3 \(\sigma\) deviation respectively, the corresponding elliptical area of the two components distribution becomes 0.989 probability instead of 0.997 of 3 \(\sigma\) in a single component. When 0.997 probability is pursued, the integration must be extended from the 3 \(\sigma\) of the single component to obtain the same probability, in which the integration is extended up to 1.14 times. In other words, when the individual axes are normalized by their standard deviation, the two components of circular error are obtained by just extending the integration range, which coefficients given in numerical calculation. To
combine gain error factors described in the former section, these N/S and E/W directional error contributions will be applied as the product of the circular error probability. It is noted that this is the case for the $3\sigma$; the cases for $\sigma$ or $2\sigma$ takes different coefficients.

As reference of the omni-directional representation for the $3\sigma$ case, the extended integration of two components are square-averaged.

$$\Delta_x = \frac{\sqrt{\left(\Delta_{\text{EI}}^2 + \Delta_{\text{El}}^2\right)^2 / 2}}{\sqrt{2}}$$

$$= \frac{\sqrt{(1.14\Delta_{0,\text{EI}})^2 + (1.14\Delta_{0,\text{El}})^2}}{\sqrt{2}}$$

$$= 0.81\sqrt{\Delta_{0,\text{EI}}^2 + \Delta_{0,\text{El}}^2}$$

where $\Delta_0$ are the original elevation or azimuth $3\sigma$ errors. This becomes the omni-directional circular $3\sigma$ error representation that is consistent to the half-cone criteria in Ref.(11).

**Two components error evaluation**

Considering that the gain variation is heavily dependent on location and direction, the factor of error must be considered for each local and directional gain variation. The schematic representation of this effect is shown in Fig.3 for comparing two component circular error and omni-directional averaged error. When the pointing error is evaluated using the probability function with standard deviation, it composes an elliptic area within a certain error boundary. The probability for each major axis is obtained with the directional standard deviations. When gain variation and geometrical factors are applied to evaluate in conjunction with the pointing error, the linear summation is adequate since they are entirely independent. Therefore, considering the standard deviation on the two component circular errors, the contribution on each axis is separately evaluated and then combined with other error factors, which retain the signal strength based circular error evaluation for antenna alignment. When it is applied to the least-squares approach, it will be dealt with as weighted parameters in Eq.(20).

![Fig. 3 Gain Sensitivity and Error Probability](image-url)
6. Pointing parameter extraction by measured data

To show the capability of this method, actual ground data obtained from satellite housekeeping maneuvers is applied and the parameters are extracted and evaluated. The antenna alignment maneuver used here was yaw control, and gain changes were,

\[ \Delta G_A = -1.9\, dB \]
\[ \Delta G_B = -0.3\, dB \] (32)

Earth Station A is located at North latitude 36°31'18" and East longitude 139°19'31" and Station B is North  36° 51' 47" and East 140°43'32". The bore sight angle to these earth stations are calculated as

\[
\begin{align*}
\gamma_A &= 5.85 \\
\eta_A &= 0.461 \\
\gamma_B &= 5.89 \\
\eta_B &= 0.643
\end{align*}
\] (33)

If conversion defined in Eq.(12) is applied numerically, we obtain

\[
\begin{bmatrix}
\Delta \theta_{A} \\
\Delta \varphi_{A} \\
\Delta \theta_{B} \\
\Delta \varphi_{B}
\end{bmatrix} =
\begin{bmatrix}
7.90 & 7.24 & 7.95 & 7.29 \\
\Delta E_{l,A} & \Delta E_{l,A} & \Delta E_{l,B} & \Delta E_{l,B}
\end{bmatrix}
\] (34)

![Fig. 4 Measured Gain Shifts](image)

Associated with the antenna gain deviation obtained in orbit or via ground testing, Eq.(15) is calculated and the gain distribution updated. This process is then iterated to converge the change. Since the example here is the model for two earth stations, two parameters can basically be identified. The objective of these tests is to examine the error resilience of the method, so the following three cases are presented: Case A - where roll and pitch are assumed to have the same error probability, Case B - where roll and yaw are identified with a fixed pitch error, and Case C - where the pitch and yaw are identified with a fixed roll error.

In addition to raw data calculations, two conditions are tested to examine error resilience. These are where an error of 10% is added/subtracted to the receiving level and the worst bias to the receiving level. This bias is assumed to have the maximum noise fluctuation measured by the receiver. The results are summarized in Table.1
Less accuracy in Case C is due to the difficulty in segregating the elements of yaw and pitch, since the two earth stations are almost at the same latitude.

More testing may be needed to quantify accuracy and feasibility. However, such objectives depend heavily on individual satellites and ground systems, as well as service scenarios. In terms of using actual satellite maneuvers, these results are a proper insight into the method’s capabilities and applications.

Table 1 Analysis Results

<table>
<thead>
<tr>
<th>Axis</th>
<th>Actual value</th>
<th>Case A</th>
<th>Case B</th>
<th>Case C</th>
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<tbody>
<tr>
<td>Roll</td>
<td>0.0</td>
<td>-0.0000</td>
<td>-0.0037</td>
<td>0.0</td>
</tr>
<tr>
<td>Pitch</td>
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<td>-0.0000</td>
<td>0.0</td>
<td>-0.0049</td>
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<tr>
<td>Yaw</td>
<td>2.58</td>
<td>2.54</td>
<td>2.54</td>
<td>2.59</td>
</tr>
</tbody>
</table>

With constant ratio error inclusion (+/-10%)

<table>
<thead>
<tr>
<th>Axis</th>
<th>Actual value</th>
<th>Case A</th>
<th>Case B</th>
<th>Case C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roll</td>
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<td>-0.003/-0.003</td>
<td>-0.003/-0.000</td>
<td>0.0/0.0</td>
</tr>
<tr>
<td>Pitch</td>
<td>0.0</td>
<td>-0.003/-0.003</td>
<td>0.0/0.0</td>
<td>-0.004/-0.005</td>
</tr>
<tr>
<td>Yaw</td>
<td>2.58</td>
<td>2.29/2.80</td>
<td>2.28/2.79</td>
<td>2.33/2.85</td>
</tr>
</tbody>
</table>

With constant bias error inclusion (+/-Max measure noise)

<table>
<thead>
<tr>
<th>Axis</th>
<th>Actual value</th>
<th>Case A</th>
<th>Case B</th>
<th>Case C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roll</td>
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<td>-0.002/-0.017</td>
<td>0.0/0.0</td>
</tr>
<tr>
<td>Pitch</td>
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<td>-0.007/-0.014</td>
<td>0.0/0.0</td>
<td>-0.245/0.0235</td>
</tr>
<tr>
<td>Yaw</td>
<td>2.58</td>
<td>2.71/2.38</td>
<td>2.54/2.54</td>
<td>4.88/0.194</td>
</tr>
</tbody>
</table>

7. Applications and benefits

This method provides antenna alignment control or planning based on actual service requirements driven by ground-based parameters, i.e. latitudinal and longitudinal locations and signal strength. Besides antenna alignment control and planning, evaluating direct antenna orientation has several applications and benefits. The pointing error caused by daily or annual thermal distortion is not tangible from the satellite on-board sensors, which is important for a large antenna application. Although thermal deformation of the antenna, including the supporting satellite structure, causes complex deflection, generally this can be dealt with as a pointing error of specific diurnal characteristic, which has seasonal dependency. It is therefore theoretically possible to compensate these errors by controlling antenna orientation with bias targeting using ground data.

Conventional antenna pointing or alignment systems, in general, employ pilot signals from the ground station and accomplish control by analyzing the deviation from steady state. Since the proposed method segregates each pointing parameter from the actual receiving signals from the ground receivers, it provides direct feedback for pointing control to sustain the required gain, which is crucial for mobile communication or other location-sensitive systems. The signal strength obtained at the ground receiver can be used to update antenna gain distribution recursively, which contributes to a robust antenna pointing management system that can comply with service requirements.
8. Conclusion

Described here was a satellite antenna alignment technique ensuring service quality that translates the ground signal strength requirement to the overall pointing shift. It was examined in terms of error source and its propagating effects. In this paper, we formulated the antenna alignment based on ground signal strength from latitudinal and longitudinal terrestrial coordinates and examined the error sources and their effects in applying to signal strength-based formulation. Further, we tested the method associated with error assessments using actual data from existing satellites. The test results show the effectiveness of our proposed method. Although satellite design generally requires margins for each design value to obtain worst-case boundaries by considering overall uncertainties, numerous independent error sources allow margins to accumulate. Direct ground-based signal strength performance evaluation presented here is expected to receive strong demand for maximizing service coverage and to enhance usage flexibility with the recent steep beam antennas that employ higher frequencies and large apertures.

References