RESEARCH ARTICLE

Design and Analysis of a GEO-to-GEO Microwave Inter-Satellite Link (ISL) for the Next-Generation Data Relay Satellite Constellation (NG-DRSC)

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Abstract

In this paper, the design and analysis of a GEO-to-GEO microwave inter-satellite link (ISL) for the next-generation data relay satellite constellation (NG-DRSC) are described. Closed-form relations are derived to determine the satellite antenna tilt and the spacecraft coordinate system for the ISL. A 300 mm diameter offset reflector antenna (antenna-2) on GEO satellite-2 (at 242.5°E) transmits at Ka-band, and the signal is received by an identical 300 mm diameter offset reflector antenna (antenna-1) on GEO satellite-1 (at 42.5°E). In this way, satellite-2 sends data over the ISL to satellite-1, which relays it to the hub station. A new method is used to compute the power received by antenna-1 on satellite-1 due to transmitting antenna-2 on satellite-2. The received power is better than -110 dBm within an angular beam cone of approximately $\pm 1.5°$. It is shown that the ISL is almost insensitive to satellite platform instability.

Keywords: GEO-to-GEO communication link, inter-satellite link, data relay satellite, ISL reflector antenna, antenna coupling.

1 Introduction

GEO-to-GEO inter-satellite links (ISLs) are a complement to terrestrial ground stations and play a pivotal role in realizing the next-generation data relay satellite constellation (NG-DRSC). A GEO-to-GEO ISL provides a direct communication link between two GEO satellites, enabling data relay, network connectivity and traffic routing without relying solely on ground stations. Since both GEO satellites remain in the same (equatorial) orbital plane, they are stationary with respect to each other. Hence, steering and tracking of the antennas are not required, and line-of-sight communication suffices for the link between the two GEO satellites.

Satellite link fundamentals and orbital geometry are covered in standard texts [1, 2]. Various kinds of inter-satellite links have been applied by system designers and researchers to GEO, MEO and LEO constellations. Ji et al. [3] reviewed ISL technologies and their applications in LEO satellite networks,

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and Furqan et al. [4] characterized the geometry of LEO-GEO ISLs for bidirectional communication. An ISL between two collocated geostationary satellites was optimized in [5], while the principal technical challenges of inter-satellite communication were reviewed in [6]. Operational GEO data relay, as exemplified by NASA's Tracking and Data Relay Satellite System (TDRSS), was summarized in [7]. Ka-band ISL hardware has also been demonstrated on small platforms: a Ka-band receiver front-end with a noise-injection calibration circuit for CubeSat ISLs was reported in [8], showing that compact Ka-band ISL terminals are feasible. The preferred frequency bands for data relay satellite inter-orbit links, including the 25.25-27.5 GHz band in which the 26 GHz ISL of this work operates, are specified in ITU-R Recommendation SA.1019 [9].

This article focuses on the design and analysis of a GEO-to-GEO microwave ISL for the NG-DRSC. Mathematical relations are derived to determine the satellite antenna tilt and the spacecraft coordinate systems for the ISL. A 300 mm diameter offset reflector antenna (antenna-2) on GEO satellite-2, located at 242.5°E, transmits at Ka-band; the signal is received by an identical antenna (antenna-1) on GEO satellite-1, located at 42.5°E, which forwards the data to the hub station. The link considered here is therefore unidirectional (satellite-2 to satellite-1). The received power at antenna-1 is computed using a new antenna-coupling-based method, and the link is shown to be almost insensitive to the platform instability of both satellites.

2 Design and Analysis of the GEO-to-GEO Microwave ISL

Figure 1 shows the schematic model of the GEO-to-GEO microwave ISL for the NG-DRSC. Each ISL antenna has its own antenna coordinate system (ACS) and is mounted on the Earth-viewing (EV) deck of the spacecraft, defined with respect to the spacecraft coordinate system (SCS).

In the Earth-centered, Earth-fixed (ECEF) coordinate convention, the origin is at the center of the Earth. The x-axis passes through the Earth-surface point at 0° longitude and 0° latitude, the y-axis passes through the point at 90°E longitude and 0° latitude, and the z-axis passes through the North Pole. Thus, positive longitude is towards the East and positive latitude is towards the North.

The satellite coordinate system (x_1, y_1, z_1) of GEO

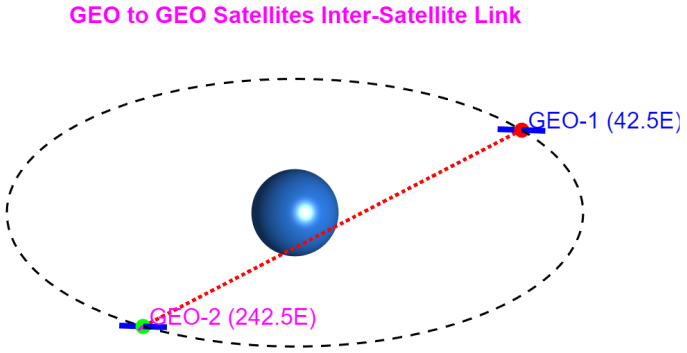


Figure 1. GEO-to-GEO microwave inter-satellite link (ISL) for the next-generation data relay satellite constellation (NG-DRSC).

satellite-1 is defined relative to the Earth coordinate system, with its origin at the position of satellite-1. Satellite-1 has orbital height h_1 (orbital radius r_1) and sub-satellite longitude Long_1 and latitude Lat_1. The satellite orbital radii are [1]

$$r_1 = R_E + h_1, \tag{1}$$
$$r_2 = R_E + h_2, \tag{2}$$

where R_E is the equatorial radius of the Earth. The position of GEO satellite-1, $\mathrm{Origin}_1(x_1, y_1, z_1)$, in ECEF is [1]

$$\mathbf{R}_{\mathrm{ECEF1}} = r_1 \begin{bmatrix} \cos(\mathrm{Long}_1)\cos(\mathrm{Lat}_1) \\ \sin(\mathrm{Long}_1)\cos(\mathrm{Lat}_1) \\ \sin(\mathrm{Lat}_1) \end{bmatrix}. \tag{3}$$

Similarly, the satellite coordinate system (x_2, y_2, z_2) of GEO satellite-2 is defined relative to the Earth coordinate system, with its origin at the position of satellite-2, orbital height h_2 (radius r_2), and sub-satellite longitude Long_2 and latitude Lat_2. The position of GEO satellite-2, $\mathrm{Origin}_2(x_2, y_2, z_2)$, in ECEF is

$$\mathbf{R}_{\mathrm{ECEF2}} = r_2 \begin{bmatrix} \cos(\mathrm{Long}_2)\cos(\mathrm{Lat}_2) \\ \sin(\mathrm{Long}_2)\cos(\mathrm{Lat}_2) \\ \sin(\mathrm{Lat}_2) \end{bmatrix}. \tag{4}$$

For the spacecraft, the West-North-Down (WND) coordinate convention is used: the z_1-axis points towards the sub-satellite point, the x_1-axis points to the West, and the y_1-axis lies in the plane containing the satellite position and the Earth's axis. In TICRA Tools, such a coordinate system is defined relative to its base (ECEF) coordinate system by its origin and the direction cosines of its axes [10]. For the WND convention, the direction cosine matrix (DCM) $\mathbf{M}_1$ of

GEO satellite-1 is

$$\begin{bmatrix}\hat{x}_1\\ \hat{y}_1\\ \hat{z}_1\end{bmatrix} = \mathbf{M}_1 = \begin{bmatrix}\sin(\text{Long}_1) & -\cos(\text{Long}_1) & 0\\ -\cos(\text{Long}_1)\sin(\text{Lat}_1) & -\sin(\text{Long}_1)\sin(\text{Lat}_1) & \cos(\text{Lat}_1)\\ -\cos(\text{Long}_1)\cos(\text{Lat}_1) & -\sin(\text{Long}_1)\cos(\text{Lat}_1) & -\sin(\text{Lat}_1)\end{bmatrix}. \tag{5}$$

The z_2-, x_2- and y_2-axes of GEO satellite-2 are defined in the same way, and its DCM $\mathbf{M}_2$ is

$$\begin{bmatrix}\hat{x}_2\\ \hat{y}_2\\ \hat{z}_2\end{bmatrix} = \mathbf{M}_2 = \begin{bmatrix}\sin(\text{Long}_2) & -\cos(\text{Long}_2) & 0\\ -\cos(\text{Long}_2)\sin(\text{Lat}_2) & -\sin(\text{Long}_2)\sin(\text{Lat}_2) & \cos(\text{Lat}_2)\\ -\cos(\text{Long}_2)\cos(\text{Lat}_2) & -\sin(\text{Long}_2)\cos(\text{Lat}_2) & -\sin(\text{Lat}_2)\end{bmatrix}. \tag{6}$$

The line-of-sight (LoS) vector between the two satellites of the ISL is

$$\mathbf{P}_S = \mathbf{R}_{\text{ECEF2}} - \mathbf{R}_{\text{ECEF1}}, \tag{7}$$

and its components in the coordinate system of satellite-1 are

$$\begin{bmatrix}P_{S1}\\ P_{S2}\\ P_{S3}\end{bmatrix} = \mathbf{M}_1\left(\mathbf{R}_{\text{ECEF2}} - \mathbf{R}_{\text{ECEF1}}\right). \tag{8}$$

Transforming the LoS vector into the satellite-1 coordinate system and simplifying gives

$$P_{S1} = -r_2\cos(\text{Lat}_2)\sin(\Delta\text{Long}), \tag{9}$$

$$P_{S2} = r_2\big[-\cos(\text{Lat}_2)\cos(\Delta\text{Long})\sin(\text{Lat}_1) + \sin(\text{Lat}_2)\cos(\text{Lat}_1)\big], \tag{10}$$

$$P_{S3} = r_1 - r_2\big[\cos(\text{Lat}_2)\cos(\Delta\text{Long})\cos(\text{Lat}_1) + \sin(\text{Lat}_2)\sin(\text{Lat}_1)\big]. \tag{11}$$

where

$$\Delta\text{Long} = \text{Long}_2 - \text{Long}_1. \tag{12}$$

The uv-coordinates of the antenna are obtained from Eqs. (9)-(11):

$$u = \frac{P_{S1}}{\sqrt{P_{S1}^2 + P_{S2}^2 + P_{S3}^2}}, \tag{13}$$

$$v = \frac{P_{S2}}{\sqrt{P_{S1}^2 + P_{S2}^2 + P_{S3}^2}}. \tag{14}$$

The azimuth and elevation angles of the antenna on satellite-1 in the elevation-over-azimuth convention are

$$EL = \sin^{-1}(v), \tag{15}$$

$$Az = -\sin^{-1}\left(\frac{u}{\cos(EL)}\right). \tag{16}$$

The azimuth and elevation angles of the antenna on satellite-2 are obtained from the same relations with the roles of the two satellites interchanged.

The LoS distance between the two GEO satellites, d_{ISL}, and the minimum height of the ISL path above the Earth's surface, h_{ISL}, follow from the chord geometry of the geostationary orbit ($r_1 = r_2$, $\text{Lat}_1 = \text{Lat}_2 = 0$):

$$d_{\text{ISL}} = 2r_1\sin\left(\frac{|\Delta\text{Long}|}{2}\right), \tag{17}$$

$$h_{\text{ISL}} = r_1\cos\left(\frac{|\Delta\text{Long}|}{2}\right) - R_E, \tag{18}$$

where $|\Delta\text{Long}|$ is taken as the principal value in $[0°, 180°]$. The link is not blocked by the Earth as long as $|\Delta\text{Long}| < 2\cos^{-1}(R_E/r_1) \approx 162.6°$.

Table 1 lists the technical requirements for the inter-GEO satellite link.

Table 1. Specifications of the ISL.

Parameter	Value
GEO satellite-1 location	42.5°E
GEO satellite-2 location	242.5°E
Frequency, GEO satellite-1 (receive)	25.25-27.5 GHz
Frequency, GEO satellite-2 (transmit)	25.25-27.5 GHz
Polarization	Right-hand circular (RHCP)
Platform instability, GEO satellites 1 and 2	$\pm 0.15°$ in both azimuth and elevation
Transmit power, antenna-2 on satellite-2	10 W (40 dBm)
Received power, antenna-1 on satellite-1	-105 to -120 dBm

An offset reflector antenna has been designed, analyzed and optimized for the specifications in Table 1. Identical offset parabolic reflector antennas are selected for both satellites of the ISL. Figure 2 depicts the geometry of the Ka-band 300 mm offset reflector antenna. The reflector diameter was selected to provide the required peak gain over the frequency band.

Table 2 lists the optics of the offset reflector antenna. The reflector is illuminated by a Ka-band feed system comprising a radial corrugated horn and a septum polarizer. The horn has a variable-depth, variable-width mode converter and linearly profiled radial corrugations. The antenna uses a paraboloid

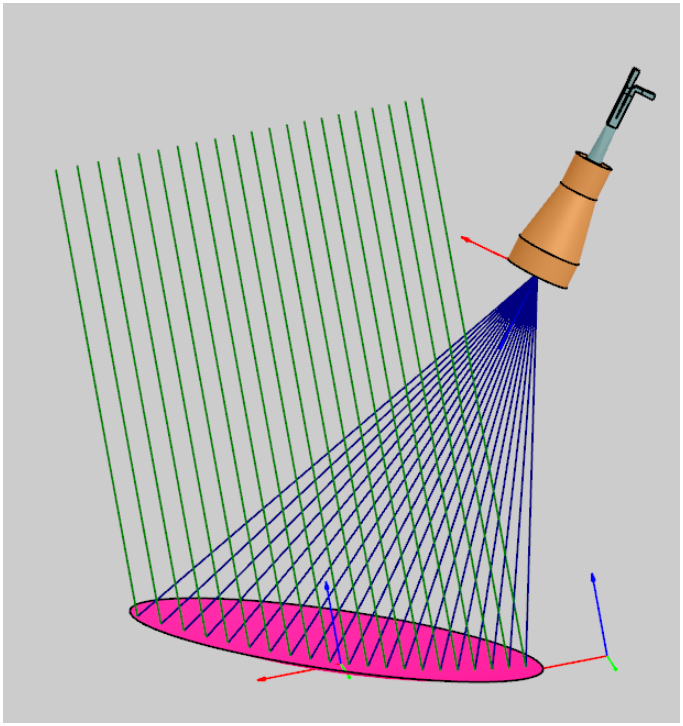


Figure 2. Ka-band 300 mm offset reflector antenna for the ISL.

with a suitable offset center distance to minimize feed blockage and scattering.

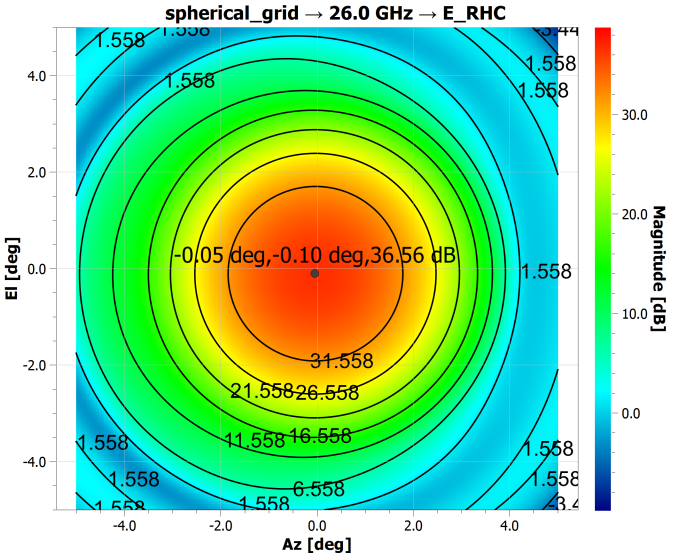
Table 2. Optics of the antenna.

Parameter	Value
Main reflector	300 mm diameter parabolic reflector
Main-reflector offset (x_0)	200 mm
Focal length	300 mm
Ka-band feed system	Radial corrugated horn with septum polarizer
Feed edge taper	-12 dB at $\pm 25.5°$
Phase centre of feed	≈ 0 mm

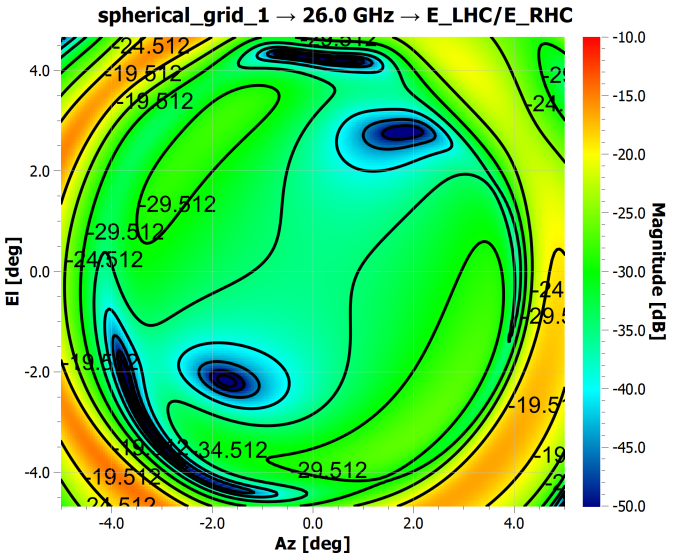
A MATLAB code was developed to obtain the spacecraft coordinate direction cosines using Eqs. (1)-(6) and the parameters in Table 3. The spacecraft antenna tilt was estimated using Eqs. (9)-(16), and the LoS distance d_{ISL} and minimum height h_{ISL} were computed using Eqs. (17)-(18). Table 3 lists the ISL parameters used in the MATLAB code.

The antenna tilts and other key ISL parameters are listed in Table 4.

Two spacecraft coordinate systems are defined by the direction cosines obtained from Eqs. (1)-(6). The



(a)



(b)

Figure 3. Pattern contours of the offset reflector antenna at 26 GHz: (a) co-polar contour; (b) XPD contour.

antenna tilts are implemented with respect to the respective SCS, and the two ISL antennas are aligned with respect to the tilted ACS. The coupling between the two antennas can be expressed by the scalar product of the directivity patterns of the transmit and receive antennas; it varies with the positions and orientations of both antennas. The coupling between the two antennas was computed with TICRA Tools 26.0 [10]. The power received by the antenna on satellite-1 is

$$P_{Rx}\,(\mathrm{dBm}) = P_{Tx}\,(\mathrm{dBm}) + C_{\mathrm{ISL}}\,(\mathrm{dB}), \qquad (19)$$

where P_{Tx} is the transmit power of the antenna on satellite-2 and C_{ISL} is the antenna coupling between the two ISL antennas, which includes the gains of both

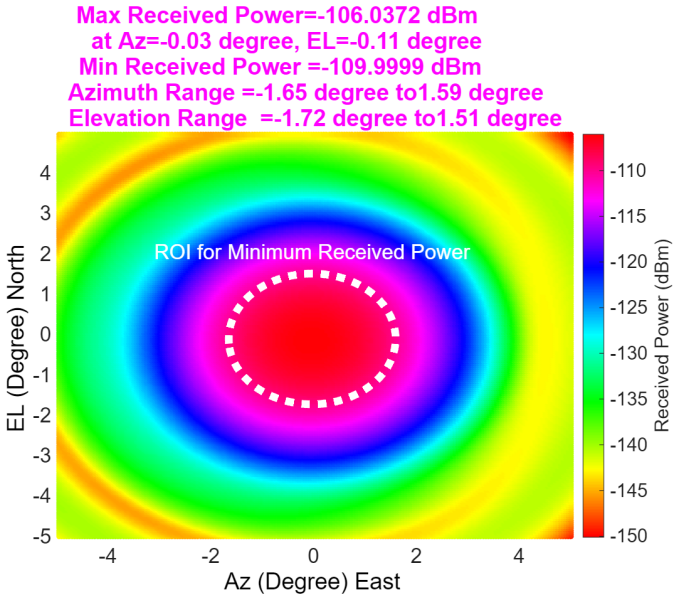


Figure 4. Received power at the antenna on satellite-1 due to the power transmitted by the antenna on satellite-2.

Table 3. ISL parameters used in the computation.

Parameter	Value
Equatorial radius of the Earth (R_E)	6378.137 km
Orbital height of GEO satellite-1 (h_1)	35786.03 km
Orbital height of GEO satellite-2 (h_2)	35786.03 km
Geostationary orbit radius of GEO-1 ($r_1 = R_E + h_1$)	42164.2 km
Geostationary orbit radius of GEO-2 ($r_2 = R_E + h_2$)	42164.2 km

antennas and the free-space propagation loss.

3 Results and Discussion

The offset reflector antenna with its feed system was analyzed using TICRA Tools 26.0 [10]. The physical optics/physical theory of diffraction (PO/PTD) method was used for the reflector, and the mode-matching and method of moments (MoM) techniques of TICRA CHAMP 3D were used for the integrated feed system [10]. Multiple reflections between the reflector and the feed system were included in the analysis.

Figure 3 depicts the co-polar and cross-polar discrimination (XPD) pattern contours of the offset reflector antenna at 26 GHz.

The reflector antenna has a peak gain of 36.56 dBi, with a slight beam squint due to the offset geometry and circular polarization. The complete antenna was also analyzed using full-wave MoM, which gives a peak gain of 36.43 dBi at 26 GHz. The close agreement (0.13 dB) between the two numerical methods cross-validates the PO/PTD analysis.

Table 4. Antenna tilts and ISL characteristics.

Parameter	Value
GEO satellite-1 antenna tilt	10° (towards West)
GEO satellite-2 antenna tilt	10° (towards East)
LoS distance between the two GEO satellites (d_{ISL})	83047 km
Minimum height of the ISL path above the Earth's surface (h_{ISL})	943.6 km

Figure 4 illustrates the received power at the antenna on satellite-1 due to 10 W transmitted from antenna-2 on satellite-2. The white dashed line in Figure 4 marks the region of interest (ROI) in which the received power is -110 dBm or better. The peak received power is -106.04 dBm, and the ROI spans $-1.65°$ to $+1.59°$ in azimuth and $-1.72°$ to $+1.51°$ in elevation, i.e., an angular beam cone of approximately $\pm 1.5°$.

Further, different cases of ISL antenna misalignment were considered to represent the platform instability of GEO satellites 1 and 2 ($\pm 0.15°$ in both azimuth and elevation). The received power at the antenna on satellite-1 was estimated for each misalignment case and is plotted as a radar graph in Figure 5. The received power varies only between -106.1 and -106.3 dBm over all cases, i.e., by at most 0.2 dB from the aligned case, showing that the ISL is almost insensitive to satellite platform instability.

4 Conclusion

A methodology for the design and analysis of a GEO-to-GEO microwave ISL has been described for the NG-DRSC. For satellites at 42.5°E and 242.5°E, a 10° antenna tilt, an LoS distance of 83047 km and a received power better than -110 dBm within approximately $\pm 1.5°$ were obtained, with a variation of at most about 0.2 dB under $\pm 0.15°$ platform instability. This technique may also find application in GEO-to-LEO or GEO-to-MEO ISL design.

Data Availability Statement

The data and simulation scripts used to support

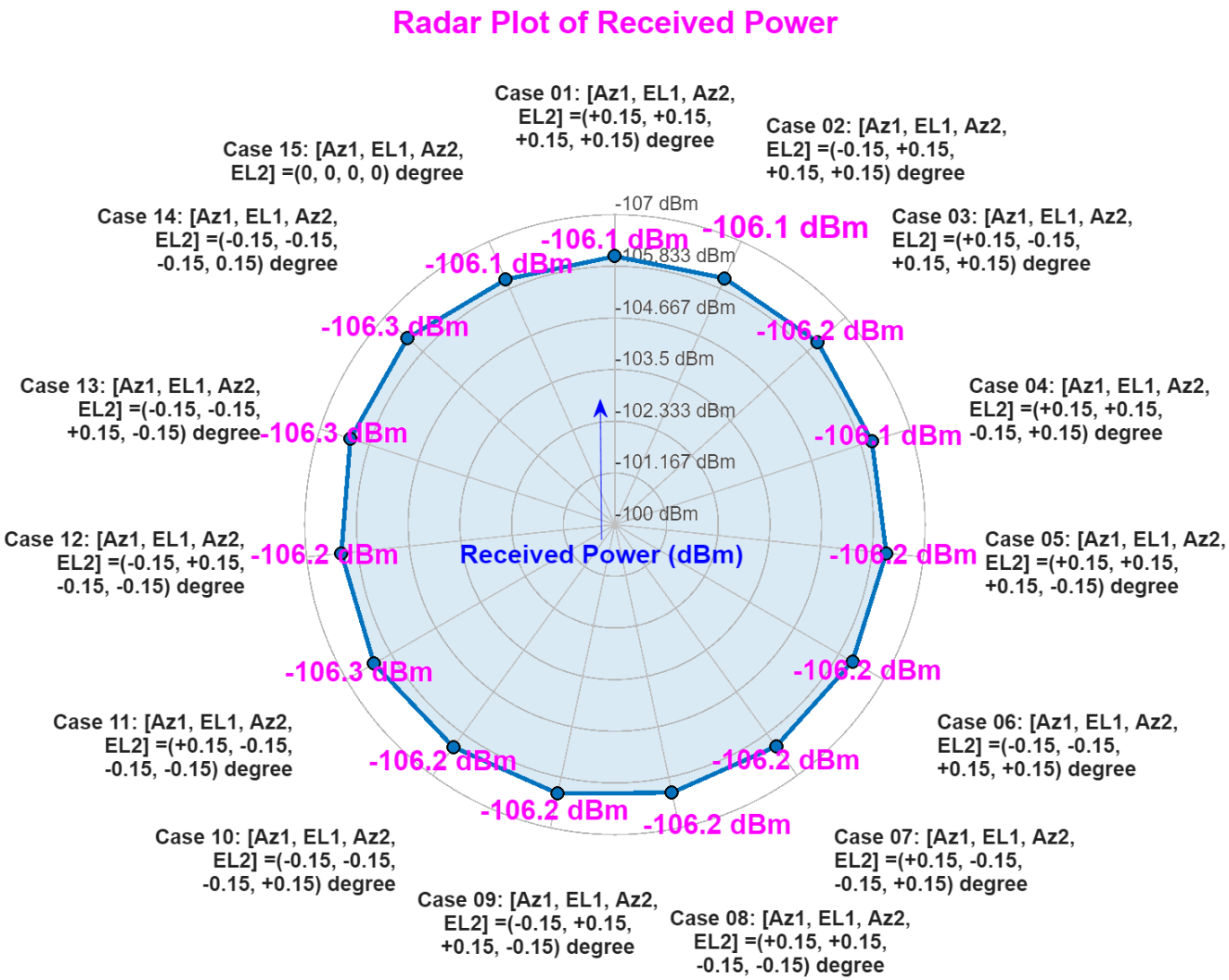


Figure 5. Received power for different cases of ISL antenna misalignment.

the findings of this study are available from the corresponding author upon reasonable request.

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Conflicts of Interest

The authors declare no conflicts of interest.

AI Use Statement

The authors declare that no generative AI was used in the preparation of this manuscript.

Ethical Approval and Consent to Participate

Not applicable. This study does not involve human participants or animals.

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