Computation of Point-Ahead Angles Between Satellites for Laser Communication

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***Abstract*—This paper presents a detailed formula for calculating the Point-Ahead Angle (PAA) based on the relative geometric configuration of two satellites and analyzes PAA characteristics across various orbital operational scenarios (intra-plane and inter-plane) using Two-Line Element (TLE) data. In intra-plane satellite configurations, the total PAA is approximately 5 μrad, with some increases due to phase reversals in polar regions. Inter-plane configurations demand much larger corrections, particularly for satellites moving in the same direction, ranging from 11 to 17 μrad. The variation becomes up to 97 μrad in the case of satellites move in opposite directions.**

***Index Terms*—Inter-Satellite Laser Communication, Point-Ahead Angle**

I. Introduction

Inter-satellite laser communication (ISL) is emerging as a core enabler for next-generation space-based data transmission systems, primarily due to its superior performance compared to traditional microwave links [1]. ISL offers significantly higher transmission rates, broader bandwidth, and strong immunity to electromagnetic interference, making it highly suitable for large-scale satellite constellations and advanced communication architectures. Despite these advantages, ISL presents critical technical challenges, most notably the requirement for extremely accurate pointing precision. Because laser beams operate at much shorter wavelengths, their divergence is minimal, requiring the transmitting satellite to aim its beam with very high accuracy toward the receiving terminal.

To ensure reliable long-distance optical links, advanced Pointing, Acquisition, and Tracking (PAT) systems are necessary. These systems facilitate both the initial establishment of the communication link and its continuous maintenance throughout the transmission period. One key aspect of accurate pointing is the Point-Ahead Angle (PAA)—an angular correction that accounts for the relative motion between satellites during the finite time it takes for a laser beam to travel. The magnitude of this correction depends on both the relative velocity between satellites and the distance of the optical link. In practice, the PAA can range from tens to several hundred μrad.

This paper is structured as follows. Section 2 presents the detailed formulation for calculating the PAA based on the relative geometry between two satellites. Section 3 explores the characteristics of the PAA under various orbital operation scenarios using Two-Line Element (TLE) data and, based on these analyses, proposes appropriate PAA values. Section 4 concludes the paper with a summary.

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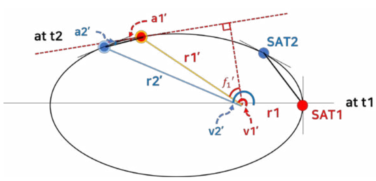

Fig. 1. Geometric structure and associated vectors in orbits of Satellite 1 (SAT1) and Satellite 2 (SAT2). It is assumed that the two satellites are aligned in same line of sight at t_1.

II. PAA Calculation

The PAA is primarily determined by the component of the relative velocity between the two satellites along the line-of-sight (LOS) direction. The PAA can be approximated by the following expression:

$$\theta_{\text{PAA}} = 2 * \frac{v_{\text{rel}}}{c} \tag{1}$$

where $v_{\text{rel, LOS}}$ is the projection of the relative velocity vector, and c is the speed of light.

The PAA also can be derived from the relative motion implied by orbital elements, particularly by evaluating the angular deviation between the instantaneous line-of-sight and the satellite's velocity vector. The PAA can be calculated as follows when $v < 180°$:

$$\frac{\sin(v+f)}{\sin(v-f)} = \frac{2a-r}{r}, \frac{r_2'}{r_1'} = \frac{\cos(f_1' + a_1')}{\cos(f_1' + a_1' + (v_2 - v_1))} \tag{2}$$

III. Orbital Senarios

We considered two operational scenarios: intra-plane and inter-plane configurations. In an intra-plane configuration, both satellites orbit within the same orbital plane. In contrast, an inter-plane configuration involves satellites located in different orbital planes, separated by an angular offset in inclination.

A. Using orbital elements in TLE

The PAAs for the duration of signal exchange between the two satellites pairs, which are presumed to be located within the same orbital plane, were calculated using the formulas 2. The TLE of ONEWEB satellites are used for the analysis.

Satellite Name	PAA (μrad)	Satellite Name	PAA (μrad/s)
ONEWEB0166	1.8	ONEWEB0166	5.0
ONEWEB0328	3.6	ONEWEB0151	7.2

TABLE I
PAA FOR ONEWEB SATELLITES USING ORBITAL ELEMENTS

B. Using coordinates in TLE

The PAA can also be derived from the positional and velocity information obtained through TLE-based coordinate data. We calculate PAA based on the Earth-Centered Inertial (ECI) frame using SGP4 library. ONEWEB0165 is designated as the reference satellite, and the relative azimuth and elevation were calculated with respect to other satellites. The top panel of Figure 2 illustrates the relative azimuth, elevation, and PAA of ONEWEB0445, which is assumed to be located within the same orbital plane (intra-plane) as ONEWEB0165 and separated by a distance of 800 km. The center part of Figure 2 presents the corresponding parameters for ONEWEB0617, which is presumed to reside in a different orbital plane (inter-plane) relative to ONEWEB0165 and the relative distance is around 2000 km. The satellites follow the same direction in their orbital paths. The bottom of Figure 2 refers the parameters of ONEWEB0252, an inter-plane satellite, which moves in opposite direction with reference satellite. The required PAA represents the total angular correction that must be applied by the Point-Ahead Mirror (PAM), as described in [2], to ensure accurate pointing between the satellites. We additionally compute the total PAA using Equation 1, referred to as the PAA tangential, and compare it with the PAM value. The two values are found to be identical and this agreement is also illustrated in the bottom-right panels of each satellites.

For intra-plane satellite configurations, the total PAA is approximately 5 μrad, with some higher values attributed to phase reversals occurring in polar regions. In contrast, inter-plane configurations require significantly larger PAM corrections, ranging from 11 to 17 μrad for satellites traveling in the same direction. This variation is especially elavated in configurations involving satellites moving in opposite directions, with values ranging from almost 11 to 97 μrad. The most rapid changes in PAA are observed when two satellites approach one another and then separate. These results highlight the importance of carefully designing the relative distance and orbital arrangement between inter-plane satellites to ensure that the PAA remains within the operational tracking range of the PAT system.

IV. SUMMARY

PAA values were computed for intra- and inter-plane cases using ONEWEB satellite data. Intra-plane angles were minimal, while inter-plane angles were notably larger. Proper orbital scenario is essential to keep PAA within PAT tracking limits.

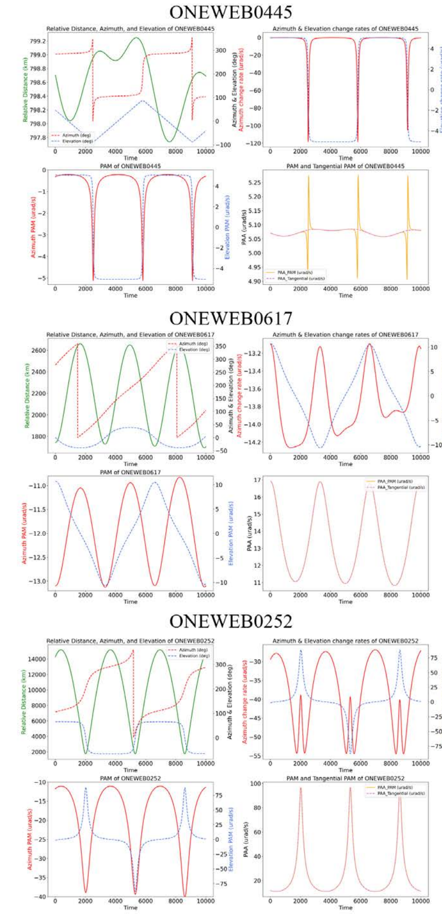

Fig. 2. Relative azimuth, elevation, PAA variation, and total PAM for ONEWEB satellites. Each 2x2 panels represents intra-plane, inter-plane in same direction, and inter-plane with opposite direction satellite from top to bottom.

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REFERENCES

[1] Z. Xinjun and Y. Ai, “Design and analysis of a kind of optical system for free space optical communication,” Proc. Semiconductor Optoelectronics, vol. 24, no. 3, 2003

[2] R. H. Ibrahim and A. H. Saleh, “Determination the optimum orbit for low Earth satellites by changing the eccentricity,” J. Phys.: Conf. Ser., vol. 1530, 2020, p. 012127