SCIENCE CHINA
Information Sciences

• LETTER •

August 2026, Vol. 69, Iss. 8, 189304:1–189304:2
https://doi.org/10.1007/s11432-025-4860-6

Low-complexity beamforming method for digital beam-scanning in low earth orbit satellites

Yutong TIAN[1], Haining YANG[1,2*], Shijia YI[1], Na LI[1] & Yujian CHENG[1]

[1] *School of Electronic Science and Engineering, University of Electronic Science and Technology of China, Chengdu 611731, China*
[2] *Tianfu Wireless Intelligence Research Institute, Chengdu 611731, China*

Received 11 Jun 2025/Revised 26 November 2025/Accepted 11 March 2026/Published online 8 July 2026

Citation Tian Y T, Yang H N, Yi S J, et al. Low-complexity beamforming method for digital beam-scanning in low earth orbit satellites. Sci China Inf Sci, 2026, 69(8): 189304, https://doi.org/10.1007/s11432-025-4860-6

Benefiting from the characteristics of low orbit, path loss, and transmission delay, low earth orbit (LEO) satellites and their constellations are widely applied for communication [1], remote sensing [2], and navigation [3]. The phased array antenna is the standard configuration of LEO satellites, enabling the simultaneous realization of multiple, independent high-gain beams for achieving wide area coverage, broadband transmission, multi-point sensing, and other urgent needs.

However, the dynamic nature of the orbits of LEO satellites poses unique challenges because the high velocity of LEO satellites makes it difficult to achieve target tracking. Rapid beam-scanning in LEO satellites is urgently needed to enable the satellites to track high-speed targets [4,5]. To achieve such rapid motion, user terminals on the ground must constantly accommodate changing satellite positions. To maintain continuous communication, efficient beam-scanning techniques are essential. With the proliferation of user terminals, from smartphones to Internet-of-Things devices, the demand for satellite systems that can quickly and accurately direct beams toward numerous users has emerged. Hence, a fast beam-scanning method is needed.

In this study, a low-complexity digital beamforming method is proposed for beam-scanning in LEO satellites. As shown in Figure 1, to track ground targets with a rapidly changing instantaneous angular velocity, beam-scanning should be faster than the rate of change of the angular velocity per updating angle. The various pattern requirements would result in a hard and complicated synthesis task. Hence, the proposed method is designed to transform an initial pattern with a shift of the given angle to the desired one. The proposed method comprises two phases. First, the initial pattern-related beamforming weight is determined through a convex optimization process. Subsequently, the scanning pattern-related beamforming vector is determined through a low-complexity beamforming method, which exploits the initial beamforming weight. The low-complexity beamforming process is designed to be an orthogonal Procrustes problem, which guarantees the scanning pattern power and consistency between the initial and scanning patterns. The scanning beamforming weight has a closed-form solution without a complex operator, enabling low-complexity computation.

Although the initial task in the proposed framework is a convex optimization for computing the initial high-performance beam pattern, this step is required only once. In many satellite applications, the initial beam pattern remains unchanged for long periods, while the beam needs to be scanned across a large angular region with very low latency. The proposed method addresses this need by enabling optimization-free steering after initialization, achieving real-time performance with negligible computational cost. Unlike the conventional phase-shift method, the proposed method offers a superior trade-off between performance and complexity while affording the superior ability to maintain the shape of the pattern during scanning as well as the computational speed.

Methods. The proposed method is implemented in two stages: initial pattern generation and low-complexity beamforming. First, the expected pattern is obtained by generating the initial pattern. Considering a uniform plane array (UPA) with M_x and M_y elements in the direction of the x- and y-axis directions, where the steering vector is $\mathbf{a}(\theta,\phi)$, the basic model of the beamforming involves weighted summation of the steering vectors. Considering the weight vector $\mathbf{w}\in\mathbb{C}^N$, the field pattern $F(\theta)$ in the direction of θ is formulated as $F(\theta)=\mathbf{w}^{\mathrm{H}}\mathbf{a}(\theta)$. For detection, a high concentration of radiation energy is required, and the directivity D of the array is formulated as follows:

$$D=\frac{4\pi|F(\theta_0)|^2}{\int_{-\pi/2}^{\pi/2}|F(\theta)|^2d\theta}, \tag{1}$$

where θ_0 denotes the direction of the mainlobe.

According to related research on beamforming, the directivity of the array is convex, with the following equivalent transformation:

$$\max_{\mathbf{w}} D \Leftrightarrow \min_{\mathbf{w}} \int_{-\pi/2}^{\pi/2}|F(\theta)|^2d\theta=\mathbf{w}^{\mathrm{H}}\mathbf{a}(\theta)\mathbf{a}^{\mathrm{H}}(\theta)\mathbf{w}. \tag{2}$$

Readers can refer to Appendix A for more information.

Similarly, assuming a given value η, the sidelobe level of the field pattern is formulated as follows:

$$|F(\theta_{side})|=|\mathbf{w}^{\mathrm{H}}\cdot\mathbf{a}(\theta_{side})|<\eta,\theta_{side}\in\mathcal{R}_{side}, \tag{3}$$

* Corresponding author (email: hnyang@uestc.edu.cn)

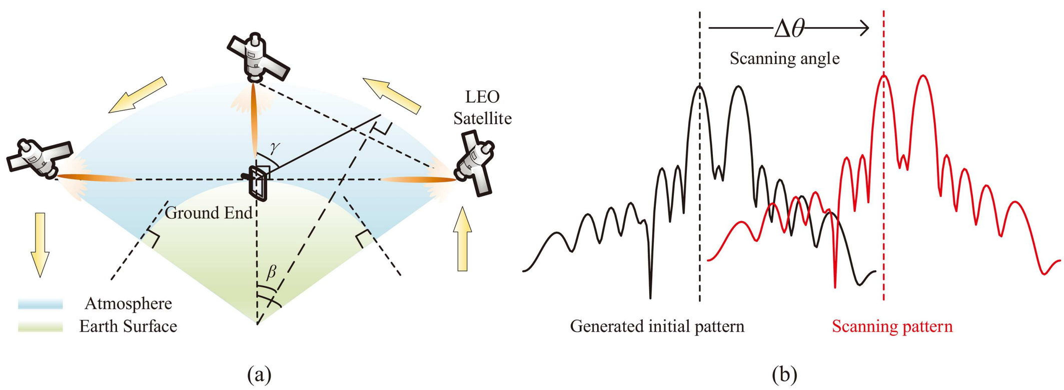

Figure 1 (Color online) (a) Schematic of LEO satellite communicating with/detecting the ground end. β denotes the angle with respect to the satellite and the Earth's core. γ denotes the angle with respect to the satellite and ground end. (b) Low-complexity beamforming process for beam-scanning for achieving fast and low-degradation beam pattern scanning.

where $\mathcal{R}_{side}$ denotes the set of sidelobe regions. Finally, to implement the multi-beams, the mainlobe and other beams are constrained as $\mathbf{w}^{\mathrm{H}}\mathbf{a}(\theta_0,\phi_0)=1$.

Comprehensively, the optimization problem is as follows:

$$\begin{aligned} &\min_{\mathbf{w}} \mathbf{w}^{\mathrm{H}}\mathbf{a}(\theta,\phi)\mathbf{a}^{\mathrm{H}}(\theta,\phi)\mathbf{w} \\ &\text{s.t. } |\mathbf{w}^{\mathrm{H}}\mathbf{a}(\theta_{side},\phi_{side})| < \eta, \{\theta_{side},\phi_{side}\}\in\mathcal{R}_{side}, \\ &\qquad \mathbf{w}^{\mathrm{H}}\mathbf{a}(\theta_0,\phi_0)=1. \end{aligned} \tag{4}$$

This is a convex problem and the determined $\mathbf{w}$ is recognized to be the weight vector of the initial pattern.

Given the scanning angles, the low-complexity beamforming process starting from the initial pattern and moving to the desired scanning patterns is considered. First, the objective of the low-complexity beamforming is designed. Set the weight vector of the initial pattern as $\mathbf{w}_0$ and one of the scanning patterns as $\mathbf{w}_1$. The scanning angles of elevation and azimuth are then assigned as $\Delta\theta$, $\Delta\phi$. In this study, the initial and scanning field values are expected to be equal. It is proposed that $\mathbf{w}_1$ can be determined by the least squares method. To guarantee constant power of the system and prevent loss of generality, the constraint with the unit power is introduced. The ultimate optimization problem is formulated as follows:

$$\begin{aligned} &\min_{\mathbf{w}_1} \left\|\mathbf{w}_0^{\mathrm{H}}\mathbf{A}(0,0)-\mathbf{w}_1^{\mathrm{H}}\mathbf{A}(\Delta\theta,\Delta\phi)\right\|_F^2 \\ &\text{s.t. } \mathbf{w}_1\mathbf{w}_1^{\mathrm{H}}=\mathbf{I}_{M_xM_y}. \end{aligned} \tag{5}$$

This is an orthogonal Procrustes problem, which is non-convex. In this study, the problem is reformulated, and the closed-form solution of $\mathbf{w}_1$ is determined as follows:

$$\mathbf{w}_1=\mathbf{U}\mathbf{I}_{M_xM_y\times 1}v^*, \tag{6}$$

where $\mathbf{I}_{M_xM_y\times 1}$ denotes the identity matrix with a size of $M_xM_y\times 1$; $\mathbf{U}\in\mathbb{C}^{M_xM_y\times M_xM_y}$ and v denote the left singular matrix and right singular matrix of $\mathbf{A}(\Delta\theta,\Delta\phi)\mathbf{A}^{\mathrm{H}}(0,0)\mathbf{w}_0$ respectively. Readers can refer to Appendix B for concrete formulations.

Numerical simulations. In this section, the proposed method is verified by assessing two cases categorized by uniform linear array and UPA, and is further explored by comparison with different methods employing various parameters. The methods used for comparison are the improved genetic algorithm, mask-based convex optimization (Mask-CVX), and conventional phase-shift methods. The synthesized patterns, time cost, corresponding differences in the peak sidelobe level, and fidelity of the shape of the pattern are determined using the proposed method with different parameters. The simulation results are presented in Appendix C.

Conclusion. This study proposes a low-complexity digital beamforming method for addressing the fast beam-scanning requirement of LEO satellites with high angular velocity, which universally requires real-time tracking using a multi-functional pattern. First, the proposed method leverages a closed-form solution to the orthogonal Procrustes problem, which negates the need for computationally intensive operations. Second, the proposed method facilitates the rapid synthesis of complicated patterns with acceptable performance degradation compared to the initial pattern. Third, unlike universal beam-scanning methods, this study introduces a low-complexity digital beamforming method for beam-scanning, where the scanning time cost is as low as 0.01 ms. The method is particularly effective when a single high-quality pattern is reused for extended periods, enabling repeated fast scans without re-running costly optimization.

Acknowledgements This work was supported in part by National Natural Science Foundation of China (Grant No. 62471094), Natural Science Foundation of Chongqing (Grant No. CSTB2025NSCQ-XWYYZDX0004), and Natural Science Foundation of Sichuan Province (Grant No. 2026NSFSC0393).

Supporting information Appendixes A–C. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

References

1 Talgat A, Kishk M A, Alouini M S. Stochastic geometry-based analysis of LEO satellite communication systems. IEEE Commun Lett, 2021, 25: 2458–2462
2 Kim J B, Lee I H, Jung H. LEO satellite-aided over-the-air computation for unmanned aerial vehicle swarm sensing. IEEE Commun Lett, 2024, 28: 143–147
3 Reid T G R, Neish A M, Walter T, et al. Broadband LEO constellations for navigation. Navigation, 2018, 65: 205–220
4 Vásquez-Peralvo J A, Querol J, Ortíz F, et al. Flexible beamforming for direct radiating arrays in satellite communications. IEEE Access, 2023, 11: 79684–79696
5 Jiang H, Xu K, Zhang Q, et al. Backward-to-forward wide-angle fast beam-scanning leaky-wave antenna with consistent gain. IEEE Trans Antennas Propagat, 2021, 69: 2987–2992