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Phased Array Antennas to Address the Growing Need of LEO Space to Ground Links

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Abstract

Unlike many other areas of satellite communication, ground station antennas have not seen substantial technological advancements since parabolic dishes were first introduced in the 1930s. The increasing need of ground station capacity to deal with the proliferation of satellite constellations, multiple orbital planes and unique cluster flying configurations, as well as the pressure to reduce costs for ground station services defines the demand to come up with a modernized approach for satellite communications access. Phased Array Antenna architecture provides the opportunity to deliver more reliable connectivity in a smaller footprint, with lower total cost of ownership. This paper investigates finding a commercially viable phased array antenna solution that brings significant benefits over legacy gimbaled tracking antennas. We investigate possible technological approaches and conclude with a suggestion for a phased array antenna ground terminal architecture.

Keywords: phased array antenna, PAA, ground terminal, beamforming

1. Introduction

This section introduces the context and motivation for exploring phased array antenna (PAA) technology as a modern solution for satellite ground terminals. It outlines the key advantages of PAA systems, discusses the challenges in achieving a commercially viable design, and highlights the potential applications and benefits of PAA technology in addressing the growing demands of Low Earth Orbit (LEO) satellite constellations.

New antenna technology, such as phased array, has been successfully applied in other communication domains and warrants thorough investigation for space-to-ground applications. PAA architecture provides an opportunity to deliver more reliable connectivity by reducing the physical size of installations, which in turn minimizes real estate requirements and infrastructure costs. Additionally, PAAs eliminate the need for complex mechanical tracking components, leading to lower maintenance expenses and faster deployment times. This architecture also optimizes cost efficiency through multi-beaming capabilities, enabling a single terminal to communicate with multiple satellites simultaneously further optimizing system usage time. To find better ways to address high-density constellations, phased array technology is emerging as an obvious choice for exploration.

At its basic form, a PAA system is composed of multiple antenna elements which can operate independently or in concert. The aggregation of elements provides nearly unlimited on-demand reconfigurability of beam count (satellite contact), beam position, polarization, and performance [1]. For instance, in high-density LEO satellite constellations, this reconfigurability enables seamless tracking of multiple satellites in different orbital planes. Since each individual element is already a high-performance antenna, they can be used for multi-beaming, enabling simultaneous downlinks with multiple satellites or working in concert forming a high gain beam. Additionally, PAAs offer advantages such as electronic beam steering, which eliminates the need for mechanical tracking and allows for faster link acquisition (no pre-pass times) and more precise satellite tracking due to adaptive beamforming.

Finding a commercially viable solution that outperforms legacy antennas has been challenging, but emerging technology shows promise for the Earth Observation (EO) industry and other downlink focused LEO services.

When considering the future of antenna technology, the primary problem statement is that a novel ground terminal solution must address LEO-to-ground key requirements set by commercial and agency customers. In the EO market, the priority requirement is sensor-to-customer data latency, which is driven by the availability of ground terminals. The possibility of fast deployment of PAA antennas can quickly improve availability in currently uncovered geographic areas. Furthermore, the usable antenna time of a PAA installation is improved compared to traditional tracking antennas since PAA terminals do not need pre- or post-pass times (quasi zero satellite to satellite switching time) for repositioning the reflector. This capability allows for rapid switching between satellites and enables contact durations based on current downlink demand to be determined in near real time.

Additionally, reducing downlink costs is of major importance. PAA technology promises increased ground terminal efficiency through higher aperture density and ease of maintenance and installation. The increased aperture density comes from the ability to support multiple beams (satellite contacts) per ground terminal installation. This, for example, reduces infrastructure costs such as hosting fees, real estate, civil engineering, and pad foundation efforts, as well as power equipment installation costs for breakout boxes, cables, and conduits. PAA technology is also expected to lower maintenance requirements, as many implementations reduce or eliminate the need for mechanical components. The smaller and modular components of PAAs make them simple to ship, fast to deploy, and easy to install. Moreover, the flexibility in switching between satellites increases ground terminal utilization, further driving down costs.

As with all technology, there are trade-offs to consider. All these advantages come with a drawback. Achieving high antenna directivity or gain with PAA ground terminals is more challenging compared to traditional parabolic reflectors. For PAAs high directivity requires large structures, as only the effective antenna area facing the LEO satellite contributes to the gain. Mechanical antennas can physically point the reflector, ensuring the entire area is effectively utilized, while static installations like phased array structures face inherent limitations in this regard. For applications where high directivity is of utmost priority, such as Lunar-to-ground and very distant communications, PAA technology cannot outperform traditional parabolic reflectors. Nonetheless, for LEO applications, the benefits of PAA ground terminals significantly outweigh their limitations, making them a compelling choice for next-generation ground terminals.

2. PAA ground terminal concept

The proposed implementation concept combines large-aperture antenna elements with phase-aligned signal combination. Given the availability and maturity of the technology, KSAT (Kongsberg Satellite Services) focuses in this study on Ka-band frequency solutions. A PAA ground terminal architecture will be discussed in the following sections.

For large-aperture antennas, the aperture size plays a crucial role in determining beamforming characteristics. Larger apertures enable more directional beams; however, the spacing between antennas must be carefully controlled to maintain phase coherence. When the spacing d is large relative to the wavelength λ ($d \gg \lambda$, where λ is approximately 11 mm in the Ka-band), multiple beams may be generated, causing the antennas to behave more like independent elements rather than forming a single coherent beam. Coherent Phase Control (CPC), implemented through a Beam Forming Device (BFD), ensures constructive interference, enabling the antennas to work together and direct energy efficiently. This phase-aligned signal combination enhances the overall array gain and results in a highly directional beam.

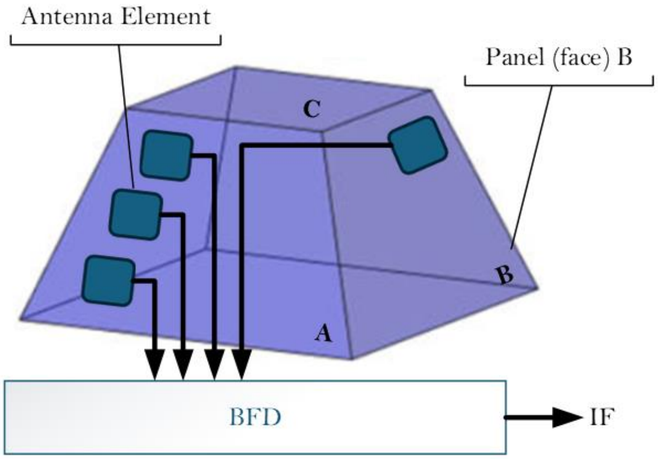

Fig. 1. PAA ground terminal principal design for a receive only system

As illustrated in Fig. 1, the PAA terminal consists of multiple panels, referred to as faces, each hosting several antenna elements. These panels are typically arranged in a frustum-shaped configuration, which increases the number of antenna elements oriented toward low elevation angles. This design enhances gain performance at low elevation angles, where the slant range to a LEO satellite is at its maximum. This configuration is essential because an antenna element's gain is always maximized along its boresight, making proper orientation critical for maintaining signal strength at low elevation angles.

The signals from individual antenna elements are combined within the BFD. Different signal combination techniques can be employed, including equal-gain combining (diversity combiner) and maximal-ratio combining. However, only phased signal combination results in beamforming, allowing for a coherent, directional radiation pattern.

The following chapters provide a more detailed investigation into the subsystem components.

3. Design considerations and technology selection

This chapter examines design considerations while also proposing a PAA ground terminal concept.

3.1 Antenna element placing

A flat-panel PAA element typically scans up to ±60° from boresight before gain degradation starts to accelerate. This limitation means that a Zenith facing flat-panel PAA would not be effective for supporting satellite links at elevations below approximately 30° elevation. As the scan angle (i.e., the angle between the boresight and the direction of the beam) increases, the effective projected aperture area of the PAA decreases, resulting in scan loss, which refers to the reduction in gain as the beam steers away from boresight. The scan loss in PAAs is often characterized by a cosine roll-off function, where the gain gradually decreases as the scan angle increases. For LEO to ground links, the link range is heavily dependent on the elevation angle. The longest communication ranges are observed at low elevation angles. In traditional antenna design, the required antenna gain is determined by the range at the minimum elevation angle (e.g., 5°). It is clear that for low elevation angles, the maximum antenna gain is essential. However, a flat-panel PAA, which is optimized for zenith-facing coverage, is not ideal for providing high gain at low elevation angles. To address this, multiple antenna elements should be arranged on tilted or curved surfaces (e.g., in a frustum shape or a truncated geodesic dome), which optimizes the gain at various elevation angles. This design ensures that a large effective aperture area is directed toward a satellite under low elevation angles, enhancing performance where it is most needed.

For legacy gimbaled tracking antennas, the gain remains constant across all elevation angles. However, if the satellite does not utilize adaptive coding and modulation schemes, this results in unused link margin. Fig. 2 illustrates how the ground terminal G/T (Gain-to-Temperature) requirement decreases as the elevation angle increases for a LEO-to-ground link. This insight can be leveraged to shape the gain profile of a PAA ground terminal, thereby reducing the number of antenna elements required, i.e. less elements are required facing high elevation angles.

3.2 Antenna element technology

This chapter examines different key considerations for evaluating antenna element technology and proposes an implementation approach based on these findings.

3.2.1 Instantaneous bandwidth

Current PAA technology has been primarily designed to support narrowband carriers, such as those used in cellular tower deployments or for accessing NGSO/GEO (Non-Geostationary Satellite Orbit / Geostationary Orbit) communication satellites. In these applications, the available frequency spectrum is typically divided into multiple channels (see Fig. 3), each with an instantaneous bandwidth of approximately <100 MHz. This subdivision enables support for multiple users but inherently limits the data throughput of each individual channel. In contrast, classical EO services rely on a single wideband (WB) channel to maximize data transmission capacity. Supporting wideband signals (>500 MHz up to 1500 MHz as available in the EO Ka-band) is therefore a critical requirement when selecting antenna element technology for such applications.

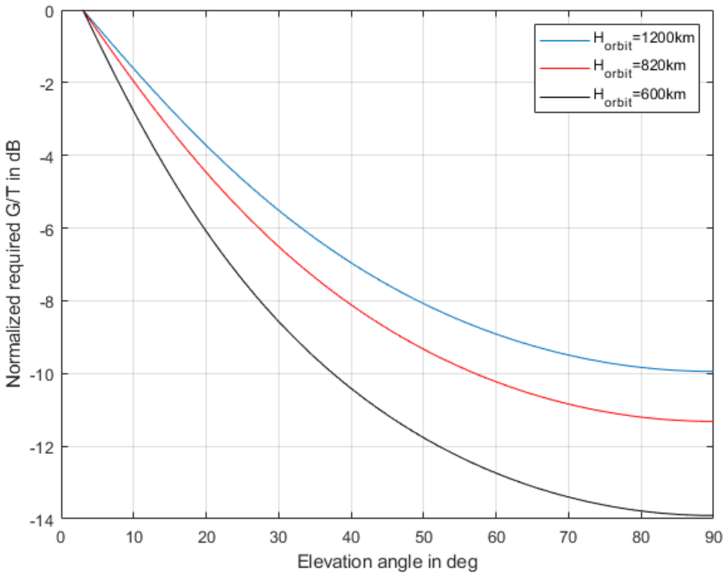

Fig. 2. The plot shows the reduction of the (normalized) required ground terminal G/T vs elevation angle for three different LEO satellite orbit heights. Calculated for 26.5 GHz.
Details on the calculation are provided in appendix A.

3.2.2 Technology availability

While PAA technology is currently available for terrestrial applications (e.g., cellular towers) and for satellite communications (SatCom) in the Ka-band (e.g., in-flight connectivity, consumer broadband), adapting this technology for EO applications in the Ka-band requires further optimization. Additionally, as PAA technology is in principle a narrowband technology operation in lower frequency bands, such as the X-band, necessitates a scaled or new design to ensure compatibility and performance. Commercial Off-The-Shelf (COTS) PAA products are primarily designed for SatCom in the Ku-band and Ka-band, supporting downlink frequencies from 17.7 to 21.2 GHz and uplink frequencies from 27.5 to 31 GHz. In contrast, EO applications in the Ka-band utilize a downlink frequency range of 25.5 to 27 GHz. Although these bands are adjacent, design optimizations are required to ensure efficient operation across these different frequency ranges. Therefore, in principle, PAA technology can also be extended to S-band and X-band applications. While preliminary designs and prototypes exist for these additional frequency bands, implementation and performance validation have not yet been conducted due to the lack of established use cases.

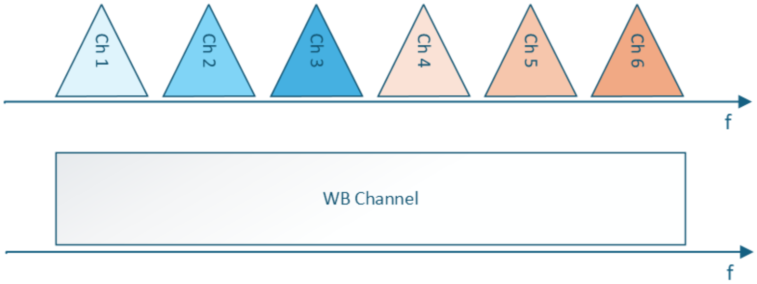

Fig. 3. Comparison between NGSO/GEO (top) vs Earth Observation (bottom) channelization

It is important to note that a single PAA element can only support a specific frequency band. Consequently, when designing and deploying PAA terminals, careful consideration must be given to the type and quantity of antenna elements required. For instance, a multi-band PAA must incorporate multiple dedicated elements, each optimized for its respective frequency band. An alternative approach to achieving multi-band capability is to deploy separate, colocated PAA terminals dedicated to distinct frequency bands, such as S-, X-, and Ka-band, rather than integrating multiple frequency-specific elements within a single, more complex system.

3.2.3 Proposed antenna element technology

KSAT proposes utilizing ThinKom's antenna element technology (ThinKom Solutions, Inc., CA, USA) for PAA ground terminals. There are two available technologies: Variable Inclination Continuous Transverse Stub (VICTS) [2], and Ultra-Wideband [3].

VICTS technology employs a two-dimensional scanning mechanism that consists of three coplanar rotating layers, enabling polarization control and beam steering in both elevation and azimuth. VICTS technology offers several advantages over alternative phased array solutions. It is a mature and operationally proven technology with a Technology Readiness Level (TRL) of 9, having been widely deployed in aeronautical applications for over two decades. Additionally, it features low power consumption, minimizing heat dissipation challenges—an essential factor in ground terminal design. Due to the high gain per antenna element, fewer elements are required, simplifying signal combination and reducing overall system complexity. However, this approach comes at the cost of reduced beamforming flexibility compared to electronically steered array (ESA) implementations. Nevertheless, VICTS technology remains a practical and efficient solution.

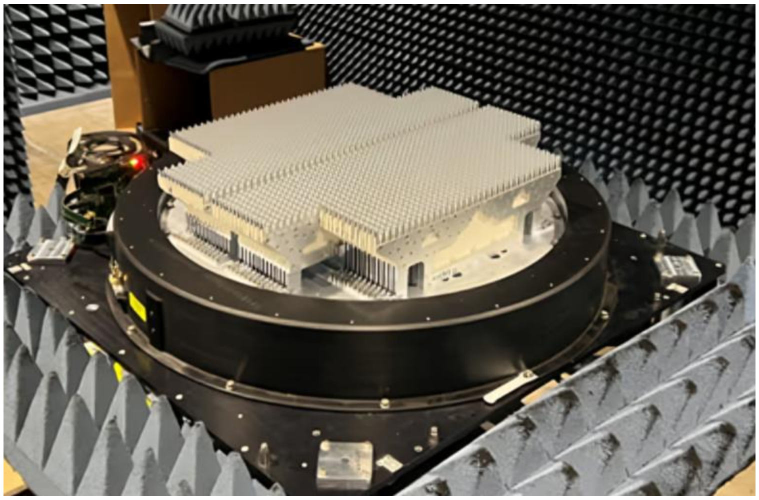

Fig. 3. ThinKom's Ultra-Wideband antenna element technology [3]: rotating layers in the black circular housing with flared notch radiators on top.

Building on the mature VICTS technology, ThinKom developed the new Ultra-Wideband antenna technology [3] to support larger channel bandwidths while simultaneously reducing sidelobes and eliminating frequency-dependent beam-walk. The Ultra-Wideband antenna retains the three rotating layers of a VICTS antenna but introduces a modified composition in the lower two layers. For a receive antenna, the RF signal first passes through a meanderline polarizer layer, inducing switchable right-hand circular polarization (RHCP) or left-hand circular polarization (LHCP), similar to a standard VICTS antenna. Below the polarizer layer, the structure facing the Low-Noise Block Downconverter (LNB) incorporates a suspended air stripline feed network. Unlike VICTS designs, the differential angle between the lower two layers is used to set a tuneable time delay, rather than a simple phase shift. At the top of the structure, facing the satellite, flared notch radiators are positioned. The air stripline feed network acts as a power splitter, distributing signals to different radiators. Basically, the rotating air stripline feed network forms an adaptive wavefront which is coupled into the flared notch radiators. A representative fact sheet for such an Ultra-Wideband antenna element is provided in Table 1 below.

3.3 Beamforming device technology and functionality

This section describes Beam Forming Device (BFD) as implemented by ThinKom.

The analog intermediate frequency (IF) LNB output from each individual antenna element is fed into the BFD. The first stage involves analog signal conditioning, which includes 27 dB dynamic range Automatic Gain Control (AGC) amplification to bring the signal near the full scale of the Giga Samples Per Second (GSPS) Analog-to-Digital Converters (ADCs) with 86 dB dynamic range, as well as filtering. Anti-aliasing filters attenuate unwanted out-of-band noise to prevent aliasing, while reconstruction filters isolate signals within the target Nyquist zone. Additionally, power limiters are implemented to protect the ADC front end from excessive signal power.

Table 1. ThinKom Ultra-Wideband antenna element technology facts sheet

Active aperture diameter	28" (0.71m)
Frequency	EO Ka-band (25.5 – 27.0 GHz)
Instantaneous bandwidth	>1500MHz
Boresight G/T	>16dB/K with true cosine$^{1.0}$ scan loss
Scan loss	cosine$^{1.0}$ profile
Polarization	Switchable LHCP or RHCP
Beam pointing accuracy	<0.2°
Max. beam velocity	100°/s
Max. beam acceleration	100°/s^2
Technology	True Time Delay (TTD) design
Frequency dependency of pointing	No beam-walk over the full frequency range
Weight	60 lbs. (27 kg)
Average power consumption	55 W only
Signal output	IF-signal after LNB
MTTR (Mean Time to Recovery)	10 minutes (hot swappable)
MTBF (Mean Time Between Failures)	50.000+ hours (for ground terminal preliminary module)

A real-time True Time Delay (TTD) mechanism compensates for quasi-static positional differences among antenna elements. This principle is applicable particularly for large arrays with baselines extending up to tens of meters. An embedded optimization algorithm maintains performance by compensating for small variations such as temperature-induced drifts in cable length and element-to-element geometry shifts. This algorithm operates by measuring phase differences between input signals, effectively functioning as an auto-tracking mechanism that continuously optimizes signal coherence. In this case, the phase offsets primarily stem from quasi-static values that drift slightly over time.

A key function of the BFD is the coherent combination of signals from multiple antenna elements, requiring high-precision phase alignment ($\Delta\varphi$) to ensure proper synchronization. Digital phase shifters with up to 48-bit resolution enable fine-tuned phase adjustments to achieve optimal coherence. The beamforming approach is a hybrid method, primarily utilizing TTD for beam steering, supplemented by fine beam position adjustments via phase shifters. Additionally, the BFD unit controls the mechanical beam coarse pointing of individual antenna elements.

The BFD output is available in either the digital domain (DIFI [4] or VITA49.2 [5]) or at IF frequencies, depending on system requirements.

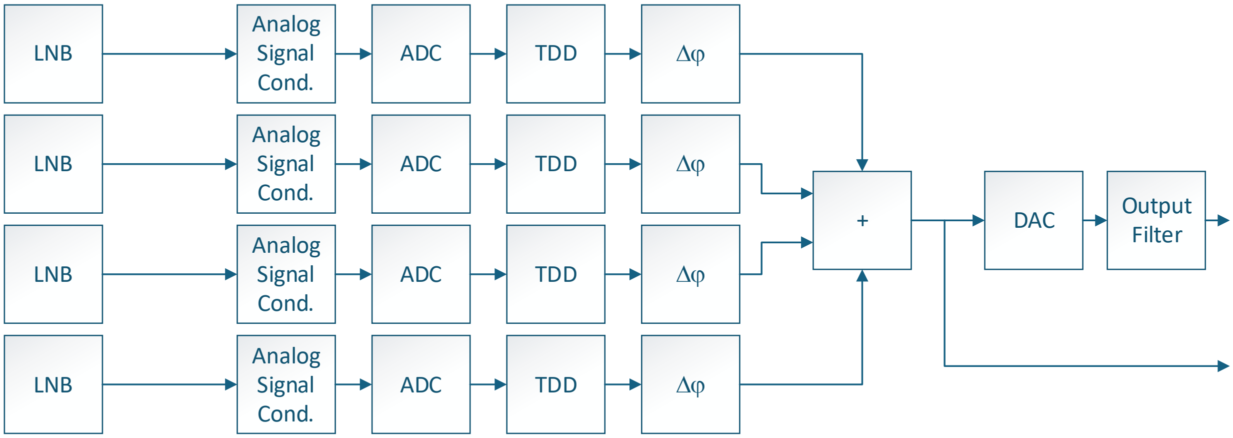

Fig. 4. Beamforming device block diagram exemplary for an array with 4 antenna elements.

4. PAA terminal deployment and maintenance

This section emphasizes the core benefits of the PAA terminal's architecture in terms of ease of installation, transportation, and maintenance.

For PAA terminals, particularly those provided by ThinKom, each modular component of the ground terminal system is designed for easy replacement in the field, requiring minimal tools, no extensive disassembly and no heavy machinery. This modular design enhances both maintenance efficiency and system reliability by enabling quick component swaps without specialized equipment. Furthermore, the modularity enables unlimited customizability for each specific site and application while also providing the option to reconfigure or expand the system in the future, thus allowing the ground terminal to adapt as requirements evolve over time.

The compact size and lightweight nature of the individual components facilitate easy and fast shipping and installation, especially when compared to traditional large, gimbaled antennas, which are sometimes not suitable for air cargo transport due to their size and weight. This advantage enables faster delivery of spare parts to site locations and simplified deployments in remote or polar areas, thereby reducing downtime and accelerating building out a ground terminal network.

5. Exemplary cost analysis of PAA terminals vs. traditional parabolic dishes

This section presents the findings of an internal study evaluating the commercial viability of replacing Ka-band parabolic tracking dishes with a PAA ground terminal based on ThinKom technology. The study estimates and compares the Total Cost of Ownership (TCO) for a Ka-band-only ground terminal. The analysis assumes that one PAA terminal can replace four traditional tracking dishes.

The Table 2 below presents a comparative assessment of CApital EXpenditures (CAPEX) and OPerational EXpenditures (OPEX) for a north polar location, with all values normalized to a hypothetical dish antenna cost of $1,000. CAPEX encompasses antenna hardware, infrastructure, installation, spare parts, shipping, and power equipment, while OPEX savings accounts for site hosting, electricity, on-site support, maintenance, and repairs. The analysis is based on constant energy costs at 2023 levels.

The results indicate that while initial investment costs for a PAA terminal are higher, the operational costs are significantly lower due to reduced space requirements, lower maintenance demands, and decreased energy consumption.

In summary, the study demonstrates that a PAA terminal can be a commercially viable alternative to traditional tracking dishes. However, specific cost savings and feasibility depend on individual deployment requirements, such as site conditions, system scale, and supported frequency bands. It should be noted that this represents an initial estimate. Ongoing advancements in PAA technology are already contributing to further cost reductions, suggesting that the commercial viability of the PAA solution is likely to improve over time.

6. Challenges and Limitations

While PAAs offer significant advantages, they also present several challenges and limitations that must be addressed.

One fundamental characteristic of PAA technology is its strong frequency dependence. Unlike parabolic dishes, which can relatively easily support multiple frequency bands using multi-band feeds, PAAs require dedicated antenna elements for each frequency band, making multi-band operation more complex and costly.

Additionally, compared to mechanically steered antennas, PAAs rely heavily on specialized integrated circuits, which introduces concerns about long-term availability and component obsolescence. Managing these risks requires careful supply chain oversight and proactive lifecycle planning.

Another challenge lies in frequency licensing. Current licensing regulations for earth station terminals are based on the well-defined antenna patterns of parabolic reflector dishes. However, the dynamic and variable radiation patterns of

PAA ground terminals introduce new regulatory complexities that must be addressed in collaboration with licensing authorities.

Table 2. Cost analysis of PAA terminals vs. traditional parabolic dishes

CAPEX

Item	Dish Cost	4x Dish Cost	PAA Cost	Total Savings	Savings per Dish	% Savings
CAPEX Total	$ 1000	$ 4000	$ 6539	$ -2539	$ -635	-63%

Annual OPEX

Item	Dish Cost	4x Dish Cost	PAA Cost	Total Savings	Savings per Dish	% Savings
Annual Total	$ 131	$ 526	$ 157	$ 368	$ 92	70 %
OPEX 10 yr	$ 1314	$ 5255	$ 1571	$ 3685	$921	70 %
OPEX 15 yr	$ 1971	$ 7883	$ 2356	$ 5527	$ 1382	70 %

TCO

Timeline	Dish Cost	4x Dish Cost	PAA Cost	Total Savings	Savings per Dish	% Savings
10 years	$ 2314	$ 9255	$ 8109	$ 1146	$ 287	12 %
15 years	$ 2971	$ 11883	$ 8895	$ 2989	$ 747	25 %

Antenna gain performance is another key consideration. Parabolic dishes provide a consistent gain across all pointing angles, whereas PAAs often exhibit gain variations depending on the pointing angle. This variability can be problematic for communication links that rely on elevation-dependent pre-planned variable modulation and coding schemes. However, adaptive modulation and coding, which adjusts dynamically based on real-time link quality, offers a potential strategy for PAAs.

PAAs also introduce new complexities in resource management. While a tracking dish inherently supports only one satellite at a time, the number of simultaneous satellite connections a PAA terminal can support depends on the number of active antenna elements available at any given time. Effective resource allocation strategies are essential to maximize the utilization of a PAA-based ground terminal.

The proposed approach of implementing a PAA ground terminal using large-aperture antennas is a logical step toward practical deployment. However, compared to fully Electronically Steered Arrays (ESAs), large-aperture element PAAs offer less flexibility in shaping antenna patterns, which for example reduces their ability to mitigate Radio Frequency Interference (RFI).

Finally, PAA ground terminals represent a relatively new technology in the satellite ground terminal industry. Demonstrating their maturity and operational readiness requires real-world testing and validation. To address this, ThinKom and KSAT will conduct technology evaluations by developing and operationally testing a PAA ground terminal for EO Ka-band downlinks. The demonstrator is expected to be operational by 2026.

7. Conclusions

This paper demonstrates that large-element phased array ground terminals provide a scalable, energy-efficient, and operationally mature solution for LEO satellite communications. The combination of antenna array with hybrid beamforming makes this approach particularly well-suited for emerging multi-orbit satellite networks. Although fully digital arrays offer greater beamforming flexibility, the proposed solution achieves a favorable trade-off between complexity, performance, and deployment feasibility for next-generation ground terminals. While PAAs present technical and regulatory challenges, they hold significant potential for scalable and efficient LEO ground terminal deployments. Ongoing research, testing, and industry collaboration will be essential to further optimize performance, reduce costs, and ensure seamless integration into future satellite communication infrastructures.

Acknowledgements

The authors would like to express their sincere gratitude to ThinKom for its very valuable support in analyzing and identifying an effective approach for implementing a phased array antenna ground terminal. ThinKom' s expertise in antenna technology, combined with its collaborative efforts in exploring system design considerations, has been instrumental in shaping the direction of this work. The insights and technical contributions provided by ThinKom have significantly enhanced the understanding of key challenges and potential solutions for phased array ground terminals in LEO space-to-ground communication.

Appendix A (Elevation dependent range loss)

This section gives the calculation for an LEO-to-ground link range-loss *L* depending on the elevation angle ε [°] as given in [6].

First the range *R [km]* needs to be calculated based on the mean Earth radius $R_e = 6371\ km$ and the satellite orbit-height above mean Earth radius *H [km]*.

$$\rho = \sin^{-1}\left(\frac{R_e}{H + R_e}\right)\frac{180°}{\pi}$$

$$\eta = \sin^{-1}\left[\cos\left(\epsilon\frac{\pi}{180°}\right)\sin\left(\rho\frac{\pi}{180°}\right)\right]\frac{180°}{\pi}$$

$$\lambda = 90° - \varepsilon - \gamma$$

$$R = R_e\left[\mathit{sin}\left(\lambda\frac{\pi}{180°}\right)\Big/\mathit{sin}\left(\eta\frac{\pi}{180°}\right)\right]$$

With the link range *R [km]* the range-loss *L [dB]* can be calculated depending on the carrier frequency *f [GHz]*.

$$L = 20\log_{10}\left(R\ \ {}^{1000}\!/_{km}\right) + 20\log_{10}\left(f\ \ {}^{10^9}\!/_{GHz}\right) - 147.55dB$$

The maximum G/T_{start} is required for the lowest operational elevation angle ε_{start}, e.g. 5°. The required ground terminal *G/T(ε)* decreases with increasing elevation angle ε, primarily due to the reduction in the elevation dependent range-loss *L(ε)* as the satellite gets closer to the ground station.

$$\frac{G}{T}(\varepsilon) = \frac{G}{T_{start}} - \left[L(\varepsilon_{start}) - L(\varepsilon)\right]$$

Appendix B (PAA ground terminal requirements matrix)

This section presents a representative requirements matrix for a PAA ground terminal. The provided gain values are at the lower end of what is typically acceptable for risk taking low margin NewSpace applications. However, gain scales well with the number of antenna elements, allowing to increase gain if needed.

#	Parameter	System	Type	Value (From)	Value (To)	Unit	Comment
1	Mechanical foundation interface	Environment	General				Bolted on a concrete foundation pad and elevated to avoid collecting drifting snow.
2	Operational environmental temperature	Environment	General	-20	45	°C	Lower minimum temperature is preferred, especially when located in polar region.
3	Operational humidity (non-condensing)	Environment	General	0	100	%	
4	Rain/snow up to	Environment	General		250	mm/h	The snow clearing concept needs to be investigated.
5	Wind capacity operational up to	Environment	General		180	km/h	
6	Antenna controller interface	M&C	per beam	REST API			one interface per beam (satellite support)
7	Inter satellite pass positioning time	M&C	per beam		1	sec	pre-pass time
8	Orbit-data format	M&C	per beam	OEM	TLE		both shall be supported
9	Antenna pattern Rx max. side-lobe peaks	RF	per beam	10		dB	compliant with ITU-R S.465-5
10	Axial ratio max (on axis)	RF	per beam		1	dB	Maximum value. A maximum axial ratio <3.5dB is acceptable. This will lead to a SNR degradation of approximately 1dB.
11	Directivity (3dB HPBW) - beamwidth of the combined beam	RF	per beam	0.3		°	min. value needs to be large enough so that the program track (open loop) pointing hits the satellite. It depends on orbit data accuracy.
12	System Gain Flatness Rx over any 40 MHz in Rx band (worst case)	RF	per beam		2	dB pk-pk	

13	System Gain Flatness Rx over any 500 MHz in Rx band (worst case)	RF	per beam		4	dB pk-pk	
14	G/T @clear sky, 26.5 GHz, 5deg elevation	RF	per beam	28		dB/K	20 dB/K is acceptable for some cases.
15	Polarization modes Rx	RF	per beam	Switch-able	LHCP, RHCP		single polarization. Dual polarization is preferred.
16	Absolute min. Rx instantaneous bandwidth (IBW)	RF	per beam	500	1500	MHz	1500 MHz preferred.
17	Rx frequency range	RF	per beam	25.5	27	GHz	
18	Rx IF frequency	RF	per beam	950	1450	MHz	modem interface Rx: L-band 50 Ohm or Digital IF
19	Modem input AGC range	RF	per beam	-50	-10	dBm	at IF, modem 50 Ohm interface Rx (in case of L-band IF interface), AGC time constant: 1ms
20	Azimuth (Az) scan range	Tracking	per beam	0	360	°	continuous signal required
21	Elevation (El) scan range	Tracking	per beam	5	90	°	continuous signal required. A minimum elevation of 10° is acceptable for some cases.
22	Minimum satellite orbit height	Tracking	per beam	350		km	
23	Number of beams	Tracking	General	2			It depends on orbit dynamics.
24	Tracking mode	Tracking	per beam		program		
25	CE certification	General	General				System CE certification is needed to be able to use the system in most places around the world.
26	Seamless continuous Rx signal	RF	per beam				Seamless continuous signal even when handing over the signal from panel to panel needs to be guaranteed.

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