Editorial
Special Article Collection on Antennas and Propagation for Space Applications

I. Introduction

FROM humble beginnings, marked with the launch of the first artificial Earth satellite, Sputnik 1, in 1957, having very basic functionalities, space systems have become omnipresent in today's societies, to the extent that some users are not even aware that the services they benefit from are enabled or complemented by satellites. Some good examples of these include weather forecast services, which rely on all the data collected by Earth observation (EO) satellites orbiting our planet, precise positioning and navigation services, supported by a number of Global Navigation Satellite Systems (GNSSs) in medium-Earth orbit, and long-distance communications to remote locations inaccessible to terrestrial networks thanks to advanced multiorbit satellite systems. Space also provides an environment for innovation and exploration, fostering international cooperation with remarkable initiatives such as the International Space Station (ISS), the Hubble Space Telescope (HST), and the James Webb Space Telescope (JWST).

It is noteworthy that the development of space systems is tightly linked to the progress in antenna and wireless technologies, as a critical means to establish effective links with orbiting objects. Radio waves are also very useful in mapping the Earth, benefiting from specific signatures at certain frequencies in combination with the unique vantage point provided by orbiting EO satellites. The IEEE Antennas and Propagation Society was in fact created just a few years before the dawn of the space age and followed closely its development with key technological advances being reported in its journals. Some examples of seminal contributions published in the IEEE Transactions on Antennas and Propagation include the corrugated horn [1], widely used in the geostationary Earth orbit (GEO) broadcasting satellites in the C- and Ku-bands developed around the turn of the century, and the stepped-septum polarizer [2], an essential component in circularly polarized communication and radar systems in waveguide technology still in use today. More recent examples include the smooth-wall horn antenna [3], suitable for multiple-beam broadband antenna systems onboard high throughput GEO satellites, the deployable mesh reflector antenna system developed for NASA's RainCube mission [4], successfully launched and deployed in orbit in 2018, and innovative ideas such as the proposal to use quasi-instantaneous meteorological information to reduce time variant atmospheric attenuation effects in K-band broadband satellite downlinks [5], and the premise of embarking multiple-beam antenna systems in C-band in replacement of the legacy broadcasting GEO satellite antenna farms producing contoured beams [6].

Space systems are now reaching maturity, with recent commercially-driven initiatives being often referred to as NewSpace, in an effort to differentiate them from more traditional institutionally-driven developments, or Space 4.0, following an analogy with the industrial revolutions. Low Earth orbit (LEO) constellations, such as OneWeb and Starlink, represent a new paradigm, bringing new challenges to both the space and ground segments, introducing new concepts and techniques linked to "mass production" and requiring careful considerations in industrializing key equipments, like antennas and radio frequency (RF) repeaters. Innovation is essential in this field of research, as demonstrated by the number of recent publications on the topic. New manufacturing techniques as well as automation techniques inspired by established industries, such as the automotive industry, are contributing to an accelerated maturation of the field, where research remains essential to bring forward disruptive concepts.

Selecting a limited number of contributions for this special article collection was a difficult task in view of the amount of highly relevant work related to space applications published in this journal. A total of 17 articles [A1], [A2], [A3], [A4], [A5], [A6], [A7], [A8], [A9], [A10], [A11], [A12], [A13], [A14], [A15], [A16], [A17] are listed covering 1) ground segment antennas, 2) space segment antennas, and 3) propagation in satellite links. These articles provide a good overview of on-going research and relevant fields of interest for the community.

II. Overview of the Special Article Collection

A. Ground Segment Antennas

1) User Terminals (Papers [A1], [A2], [A3], [A4], [A5], [A6], [A7], [A8]): The first two contributions discuss array antenna solutions compatible with electronic steering for user terminals connecting with LEO satellites. The papers focus on the aperture design. In [A1], a circularly polarized element with out-of-band filtering is proposed. The operating band covers frequencies 28–33 GHz, while providing out-of-band suppression of at least 14 dB in a 2×2 array configuration with sequential rotation to enhance axial ratio performance. The spacing of the array is $0.7\lambda_0$. The filtering function is of interest for the uplink antenna, limiting the impact of unwanted harmonics generated by nonlinear components. In [A2], a dual-band aperture is discussed with a bandwidth of

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more than 2.5 GHz in both the transmit (Tx) and the receive (Rx) frequency bands allocated to broadband communications in the K-/Ka-band. The array design combines Tx-only and Tx/Rx elements in an interleaved rectangular grid, enabling an element-spacing of about half-a-wavelength in both bands, which is essential to prevent grating lobes over large scanning angles as required in LEO systems. A lens is integrated in the aperture of each element and acts as a quarter-wavelength impedance transformer.

Transmit arrays are also investigated as an alternative to phased arrays for user terminal applications. In [A3], a dual-band dual-polarized solution with shared aperture is proposed. It operates in the K-/Ka-band and produces circularly polarized signals. A hybrid phase delay and phase rotation technique is used at the unit cell level with a 2-bit phase compensation per frequency band. The K- and Ka-band elements of the transmitarray are interleaved, achieving an aperture efficiency of approximately 25% in the lower frequency band and 15% in the upper frequency band.

Mechanically-steered user terminal antennas are also the object of intensive investigations, particularly for applications that require low cost and low power consumption, two well-known limitations of current electronically-steered phased array solutions. Several works are reported on adaptations of the Risley prism concept to microwaves. Beam steering is achieved by mechanically rotating two deflecting surfaces, generally implemented using phase-shifting surfaces. With an independent control of each surface, 2-D steering is obtained. The deflecting surfaces require an impinging plane wave to operate as intended. In [A4], a radial line slot array antenna is used as a feeder. The deflecting surfaces are placed in the near-field region, achieving a total height of only $3\lambda_0$. The reported results demonstrate scanning up to 40° from the broadside direction with scan losses of about 5 dB.

In [A5], the feeder is a leaky wave antenna integrating the first deflecting surface functionality. Thus, only one deflecting surface is required above the feeder, simplifying the overall stack-up. The realized prototype, using a printed dielectric deflecting surface, demonstrates good scanning up to 50° with scan losses below 3 dB. The results are reported over a 2-GHz bandwidth centered at 20.2 GHz, showing a variation of the pointing direction with frequency due to the leaky wave feeder, remaining nevertheless compatible with instantaneous bandwidths in the order of 100 MHz.

The deflecting surfaces designed using a phase-shifting technique typically exhibit a macro-periodicity responsible for unwanted grating lobes. This limitation is solved in [A6] by introducing a generalized Risley prism formulation that breaks the invariance of the unit-cell patterns along the direction orthogonal to the deflecting plane. The concept is demonstrated by splitting the collimating functionality typically required from the feeding structure into the two deflecting surfaces. The prototype thus combines a horn antenna and two partially-collimating deflecting surfaces. The experimental results show an improvement in sidelobe level of at least 4 dB, also having a positive impact on the peak gain. The antenna scans up to 55° with scan losses of 3.6 dB.

Another interesting concept providing beam steering with mechanical rotation is the variable inclination continuous transverse stub antenna. When the transverse stubs are aligned with the planar wavefront of the impinging field propagating in the parallel plate waveguide feeder, the beam points in the broadside direction. A progressive inclination of the wavefront with reference to the transverse stubs introduces an increasing phase gradient along the stubs resulting in a beam deflection. Combining this relative rotation with the rotation of the complete structure, 2-D beam steering is achieved. In [A7], a dual-band combined-aperture design is proposed for K-/Ka-band user terminal applications. The main challenge for this concept is to achieve consistent beam pointing directions in Tx and Rx. This is demonstrated over a 2-GHz bandwidth in both the uplink and downlink, assuming respective frequencies are paired, i.e., the lowest frequency in the uplink is paired with the lowest frequency in the uplink band, and so on. Scanning is demonstrated up to about 65° from broadside direction with a gain drop below 3.5 dB.

In [A8], the continuous transverse stubs are fed in parallel using a corporate network. This approach provides a wide-band response enabling the same aperture to operate from 17 to 31 GHz. The planar wavefront in the parallel plate waveguide feeder is produced using a pillbox beamformer. The variable inclination is obtained by mechanically displacing the H-plane horn illuminating the pillbox beamformer. The reported aperture efficiency of this solution is above 40% across all the operating bands. Scanning is demonstrated up to 42° from broadside direction. The thickness of the complete assembly is about $4\lambda_0$.

2) Ground Stations, Radio Telescopes, and Tracking Antennas (Papers [A9], [A10], [A11]): Ground stations are key components in satellite constellations as they enable connectivity with terrestrial networks and specifically, access to the Internet. While future LEO systems integrating intersatellite links may directly route the signal in orbit, existing systems require each satellite to be directly connected to the ground through a dense network of stations. Some of the technologies discussed above for user terminals may also be applied to ground station antennas. In [A9], a flat antenna solution combining a leaky wave feeder and a transmitarray is proposed. The specificity of this design is a true-time delay unit cell, providing wider instantaneous bandwidth, essential in feeder links aggregating the data of multiple user links. Two prototypes demonstrate the concept with a fixed-beam design. A reconfigurable design would require the integration of monolithic RF switches at the unit cell level. Scanning is demonstrated in simulation up to 60°, and a prototype with a pointing angle at 30° is validated in measurements.

Radio telescopes are also essential antennas on the ground, monitoring the sky in the microwave domain. With the multiplication of wireless applications and emitters, telescope antennas may become susceptible to interference arriving through their side lobes. In [A10], an innovative approach is proposed to produce radiation pattern nulls in order to mitigate the impact of these interfering signals. This is achieved by integrating a reconfigurable reflectarray rim at the edge of the large parabolic dish. This approach enables sidelobe nulling over all the azimuth angles. A 1-bit reconfigurable unit cell design with a pin diode switch is proposed to keep the complexity low. Nulling is demonstrated in simulation, with a minimal impact on the peak gain of the antenna.

Another critical component of the ground segment are tracking antennas. These are particularly important in moving platforms. In the case of GEO satellites, the elevation angle from a given geographical region is essentially fixed, and thus, efficient tracking may be achieved using an annular-shaped beam with an omnidirectional pattern in azimuth and a narrow beam in elevation. In [A11], closed-form expressions for the maximum achievable gain of such patterns are provided, as typical aperture efficiency formulas are only applicable to broadside pencil beams. The maximum gain formula is useful in estimating the figure of merit of an antenna and it is found that the maximum achievable value is proportional to the aperture radius, while in pencil beam antennas, it is proportional to the aperture area. This work provides an interesting first-order gain approximation for system-level analyses.

B. Space Segment Antennas (Papers [A12], [A13], [A14])

Space segment antennas are also critical in any satellite system. Their development is obviously less accessible to academia, hence, the lower number of scientific contributions in this journal. It is nevertheless an active field of research, with innovative ideas being reported by academics and space institutions focusing mostly on NewSpace applications. In [A12], a large deployable antenna is proposed with an aperture of 7×1.5 m. This rectangular high-aspect ratio form factor is particularly well adapted for future synthetic aperture radar missions, while facilitating its packaging on a small LEO satellite. A parabolic cylinder profile is retained as it simplifies the stowage and deployment cinematic. The mesh reflector is fed by a 1×32 element linear array operating in C-band. Various aspects of the development are reported in this work, including thermal analyses to demonstrate the stability of the proposed technical solution, and a deployment validation on the ground using a mechanical ground support equipment emulating in-orbit zero-g conditions.

In [A13], an innovative nonregular multiple-beam coverage antenna is reported. It relies on a reflector antenna fed by a focal array comprising overlapped feed clusters. The size of each cluster is tuned to match the nonregular multiple-beam coverage requirements. A critical aspect of this concept is the development of the beamforming networks, which may be specific to each cluster. The work leverages the benefits of additive manufacturing techniques for that purpose and a prototype of a complete subarray is reported, displaying RF performance aligned with the predictions.

Another important aspect in multiple-beam broadband antenna systems is the congruence of the coverage in Tx and Rx, with a frequency ratio of approximately 1.5:1. When merging the two bands on the same antenna aperture, innovative techniques are required to broaden the beamwidth in the upper frequency band so it matches that in the lower frequency band. This is achieved in [A14] by introducing a 180° phase shift to some unit cells on the edge of a reflectarray in the upper band only, thus preserving the gain in the lower band and corresponding to that of the full aperture. The introduced phase shift provides destructive interference, effectively canceling out the field reflected by the outer rim of the reflector. As a result, the effective aperture in the upper band is smaller and thus the beam widens, matching the beamwidth in the lower band with adequate optimization. Numerical results are reported to demonstrate the effectiveness of the proposed method.

C. Propagation (Papers [A15], [A16], [A17])

Last but not least, propagation is an essential aspect in any space-based system. With communication satellites going up in frequency due to spectrum congestion and the need for larger bandwidths, Q-/V-band links are now becoming a reality. First explored onboard the GEO satellite Alphasat, launched in 2013, Q-/V-band feeder links are now used onboard commercial satellites, like the recently launched Jupiter 3. This calls for improved channel models at those frequencies characterized by stronger fluctuations due to changing atmospheric conditions. In [A15], a data-driven Q-band satellite channel model is proposed using artificial neural networks. A least absolute shrinkage and selection operator (LASSO) algorithm is used to select seven predominant parameters out of 14 commonly used atmospheric parameters. This approach provides a more accurate and less complex channel model, with numerical results aligning well with the measured channel attenuation.

Q-band links are particularly impacted by rain, which is the main contributor to atmospheric attenuation. The effect of clouds is also important, but differentiating all the major contributors is a challenging task. An experimental evaluation of cloud attenuation in the Q-band is reported in [A16] based on data collected over five years. The obtained results are in good agreement with radiosounding models and indicate that the ITU-R P.840-8, an ITU recommendation providing methods to predict the attenuation due to clouds and fog on Earth-space paths, tend to overestimate the attenuation. These results are useful for improving cloud attenuation models.

Another region of the atmosphere having a particularly significant impact on radio wave propagation at high frequencies is the ionosphere, and specifically its uppermost layer, known as the F-region. Flute instability, which is a type of plasma instability, can impact trans-ionospheric propagation. In [A17], a phase cube geometry representation of a flute structure is proposed, which provides a 3-D interface to a propagator coupled with ray tracing. Horizontal and vertical polarization effects are also examined with respect to the flute structure geometry. Despite the approximations, the model provides qualitative insight into the temporal, spatial, and frequency characteristics of the forward-scattered field.

III. Conclusion and Acknowledgment

As demonstrated by this special article collection, antennas and propagation for space applications are a broad field of research. User terminals are clearly a key enabling technology for current LEO constellations under development, evidenced by the number of research articles on the topic. This specific field of research also benefits from synergies with other application domains, and in particular, millimeter-wave terrestrial communications, in which cost is also a key driver for market acceptance. This explains the strong interest of the community in innovative antenna solutions.

As new applications emerge, more advanced and integrated wireless systems are required. These will certainly benefit from co-engineering developments, involving a variety of other fields of expertise, covering electronics, mechanical and thermal engineering, materials and processes, and signal processing. In combination with model-based system engineering, wireless systems will remain a key sector of innovation for the betterment of the society.

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APPENDIX: RELATED ARTICLES

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