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Multibeam Lens Antenna Application for Global Navigation Satellite System Anti-Jam and Anti-Spoof Capability

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This report researches the application of a multibeam Luneburg lens antenna to provide an anti-jam and anti-spoofing solution for Global Navigation Satellite System signals in a single aperture. In addition, the antenna can provide a direction-finding capability when paired with traditional radar techniques, such as monopulse tracking, that utilize multiple simultaneous beams to compare signal amplitudes or phases.

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Abstract

This report researches the application of a multibeam Luneburg lens antenna to provide an anti-jam and anti-spoofing solution for Global Navigation Satellite System signals in a single aperture. In addition, the antenna can provide a direction-finding capability when paired with traditional radar techniques, such as monopulse tracking, that utilize multiple simultaneous beams to compare signal amplitudes or phases.

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1.0 TI Request

1.1 Inquiry

What technologies exist that could protect commercial aircraft against jamming and spoofing?

1.2 Description

This report investigates the feasibility and expected performance of applying anti-jam (AJ)/anti-spoofing (AS) Global Positioning System (GPS)/Global Navigation Satellite System (GNSS) technology for use in civilian aircraft.

2.0 TI Response

2.1 Background

In some instances, enemy drone systems employ software-defined radios to mimic GNSS satellite signals with erroneous location data in attempts to confuse receivers and misrepresent true position [1–3]. Most methods for averting spoofing attacks are signal-processing based. Controlled reception pattern antennas (CRPA) technology is essentially adaptive null steering and is effectively used to avert jamming but may not be fully optimized to handle spoofing [4]. Additionally, CRPAs do not track the location of interferers.

An alternative or complimentary technique for improving GNSS reception resiliency in applications that can tolerate large-size antennas is to employ multibeam, narrow-beamwidth directional antennas. An ideal solution to this problem is a multibeam spherical Luneburg lens. Theoretically, if the beams are narrow enough, jammers and spoofers are effectively mitigated by keeping them outside the main beam. Additionally, monopulse tracking [5] can be envisioned using four selected feeds in a lens system. When employing monopulse techniques, it may be acceptable to utilize the broader beams of modest-size lenses.

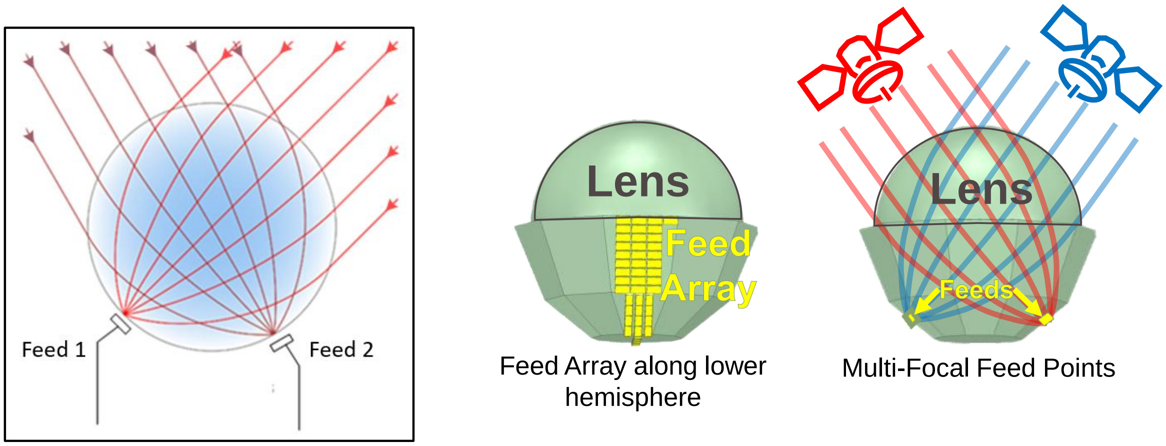
This study looks at the trade space for a Luneburg lens antenna design with respect to lens size, beamwidth, and view angle vs. GNSS satellite coverage of various GNSS constellations. Further study will need to be done to develop a monopulse tracking algorithm to be able to direction find a spoofer using a multibeam Luneburg lens antenna. This is outside the scope of this study.

2.2 Technical Analysis

This section provides an overview of the Luneburg lens, lens applications for AJ/AS, a lens trade study, and information on GNSS satellite systems.

2.2.1 Luneburg Lens Overview

A Luneburg lens is a spherically symmetric gradient-index lens, where each point on the surface of the lens is the focal point for a parallel radiation incident on the opposite side, as shown in Figure 1a [6]. An array of feeds can be populated around the lower hemisphere of the lens to produce multiple individual directional beams through the lens, allowing multiple targets to be simultaneously tracked in the sky, as depicted in Figure 1b. Tracking is achieved by feed hand-off along the array.



(a) **(b)**

Figure 1. Luneburg Lens Concept (a) [6] With Multifeed Design on Lower Hemisphere (b) *(Source: K. Quock).*

2.2.2 Lens Application for AJ/AS

GNSS or GPS antennas are traditionally omnidirectional, which means they can be susceptible to jamming and spoofing from almost any direction, with no easy ability to know the location of the source of interference. Directional antennas are much more effective, as they require the interferer to be within a narrower main beam. Using multiple beams to look at multiple GNSS signals increases resiliency to interference. Figure 2 shows a high-level view of the multibeam concept with a spoofer. Interferers are isolated to a single beam, while other beams operate unaffected to provide a good signal. Note that this directional multibeam approach is not limited to GNSS satellites but can be used with other communications satellites coupled with alternative position, navigation, and timing techniques.

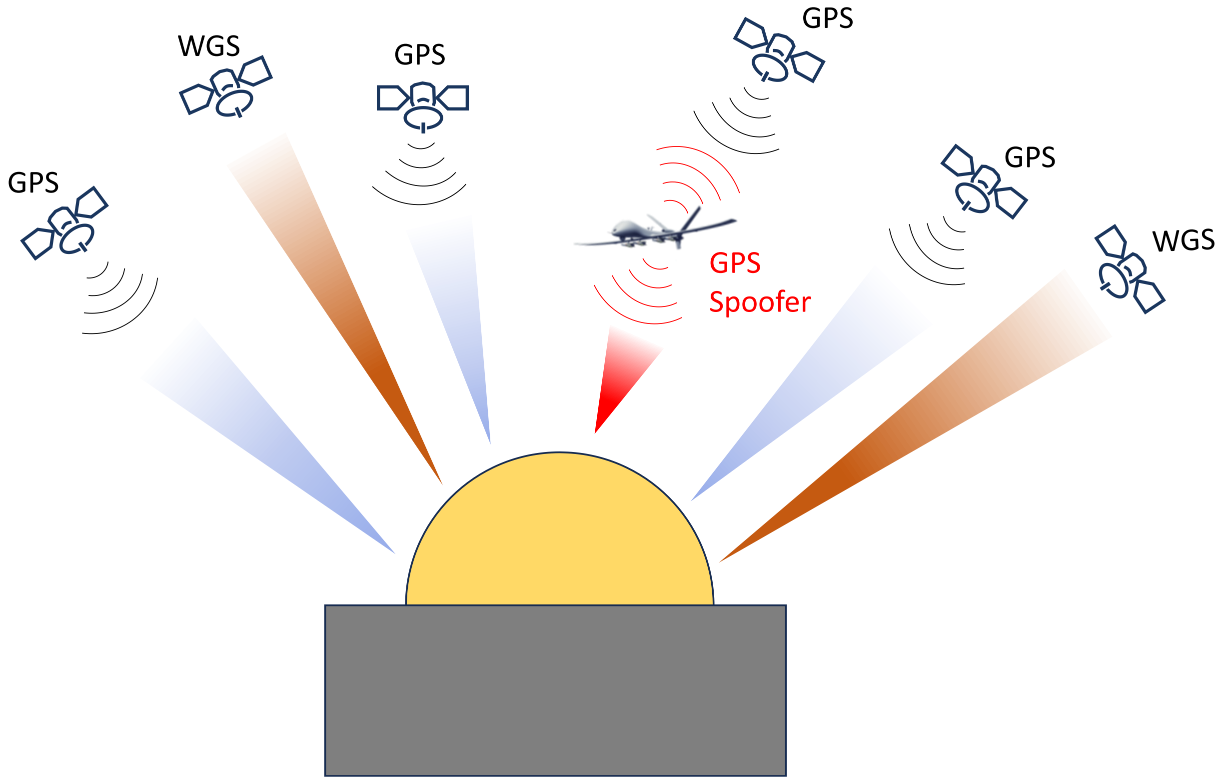


Figure 2. Resilient GPS Using a Directional Multibeam Lens Antenna *(Source: K. Quock)*.

2.2.3 Lens Trade Study

When designing a Luneburg lens antenna, there are many design trades that can be made, depending on the application. Lens size and frequency may drive the lens material, and the design and field of view needed will drive the number of feeds necessary to populate on the lower hemisphere of the lens. This study provides details on practical numbers of feeds and beamwidths for various lens sizes and coverage cases in the L-band. Table 1 shows the beamwidth and number of feeds necessary to achieve near horizon-to-horizon coverage of +/–70° from zenith (and 360° in azimuth) for the example lens diameters within 12 to 48 in. Table 2 presents similar data for a +/–45° coverage cone.

Beamwidth is inversely proportional to the lens antenna diameter. A convenient equation for calculating the approximate beamwidth of a lens antenna is presented in Equation 1 as [7]:

$$Beamwidth\ (°) \approx \frac{180}{\pi}\left(\frac{\lambda}{D}\right), \tag{1}$$

where λ is the wavelength and D is the diameter of the lens.

Table 1. Number of Feeds for Various Lens Diameters for Coverage +/–70° in L-Band *(Source: S. Rogers)*

f (GHz)	Maximum Scan From Zenith (+/– This Number) (°)	Coverage Total (°)	Diameter (in)	Wavelength (in)	Beamwidth (°)	N Feeds
1.5	70	140	12	7.87	37.57	12
1.5	70	140	24	7.87	18.79	49
1.5	70	140	36	7.87	12.52	110
1.5	70	140	48	7.87	9.39	196

Table 2. Number of Feeds for Various Lens Diameters for Coverage +/–45° in L-Band *(Source: S. Rogers)*

f (GHz)	Maximum Scan From Zenith (+/– This Number) (°)	Coverage Total (°)	Diameter (in)	Wavelength (in)	Beamwidth (°)	N Feeds
1.5	45	90	12	7.87	37.57	5
1.5	45	90	24	7.87	18.79	22
1.5	45	90	36	7.87	12.52	490
1.5	45	90	48	7.87	9.39	87

Tables 1 and 2, created using an algorithm that places the feeds uniformly around the lower hemisphere of the spherical lens for a given frequency (f), desired maximum scan angle from zenith, and lens diameter, show the lens trade-study results for various lens diameters at an operating frequency of 1.5 GHz. In conjunction with Equation 1, a 12-in lens diameter has a beamwidth of 37.57° and a 48-in lens diameter results in a half-power beamwidth of 9.39°.

For more granularity in trade studies, Figure 3 displays a graph of beamwidth vs. lens diameter for diameters in the range of 10–100 in. The graph reveals that it would be impractical from a size perspective to achieve beamwidths of 1°. However, extremely narrow beamwidths may not be necessary for tracking drone spoofers, as monopulse techniques can be used to achieve very accurate angle-of-arrival information [8]. Tradeoffs in actual system implementations will require further study and depend upon other factors, such as received signal-to-noise ratios.

2.2.4 GNSS Satellite Systems

Table 3 presents the frequency information for the major GNSS systems from the United States (GPS), European Union (Galileo), Russian Federation (GLONASS), and China (BeiDou) [9]. Often, resilient systems compare location data from these multiple medium earth orbit (MEO) GNSS satellite systems for spoof proofing. However, spoofers may take this into account and become more sophisticated such that they disrupt all systems.

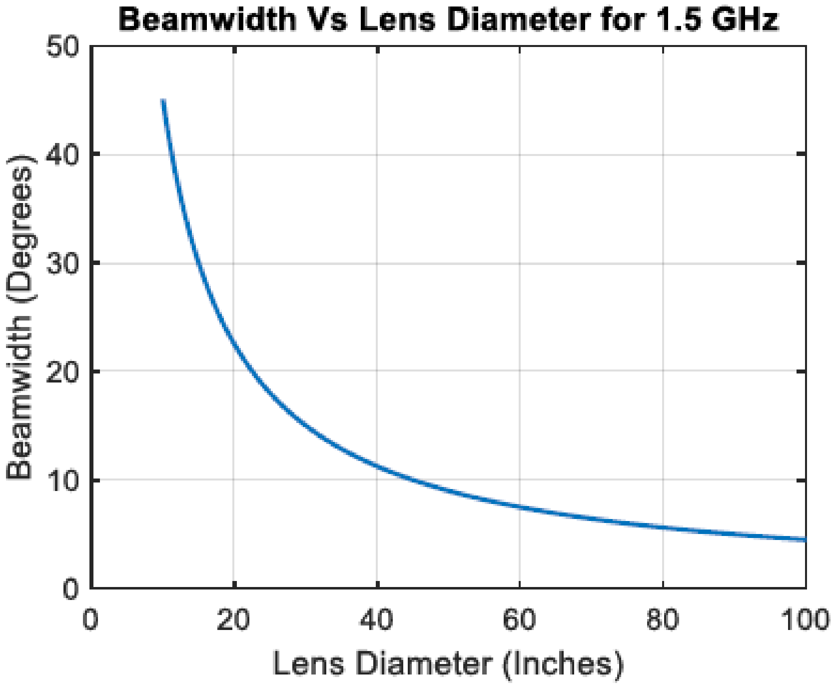


Figure 3. Beamwidth vs. Lens Diameter at 1.5 GHz [7].

Table 1. GNSS System Frequencies [9]

GNSS System	Band	Frequency (MHz)	Description
GPS	L1	1,575.42	Civilian Signal
	L2	1,227.60	Military and Some Civilian Users
	L5	1,176.45	Safety-of-Life Applications
GLONASS	L1	1,602.00	Frequency Division Multiple Access
	L2	1,246.00	Military and Civilian Uses
Galileo	E1	1,575.42	Open Service (Same as GPS L1)
	E5a	1,176.45	Safety-of-Life Applications
	E5b	1,207.14	Open Service
	E6	1,278.75	Commercial Service
BeiDou	B1	1,561.098	Open Service
	B2	1,207.14	Open Service (Same as Galileo E5b)
	B3	1,268.52	Military Uses

The open-source software Gpredict [10] was used to visualize the location and velocities of the GNSS satellites relative to the base location of ATG headquarters in Peachtree Corners, GA. Gpredict utilizes two-line element data of satellite locations published and updated by Celestrak. Figures 4 and 5 show the locations of the MEO GNSS satellites in one instant of time in an azimuth/elevation plot, where the outer circle represents the horizon and the origin of the plot represents zenith.

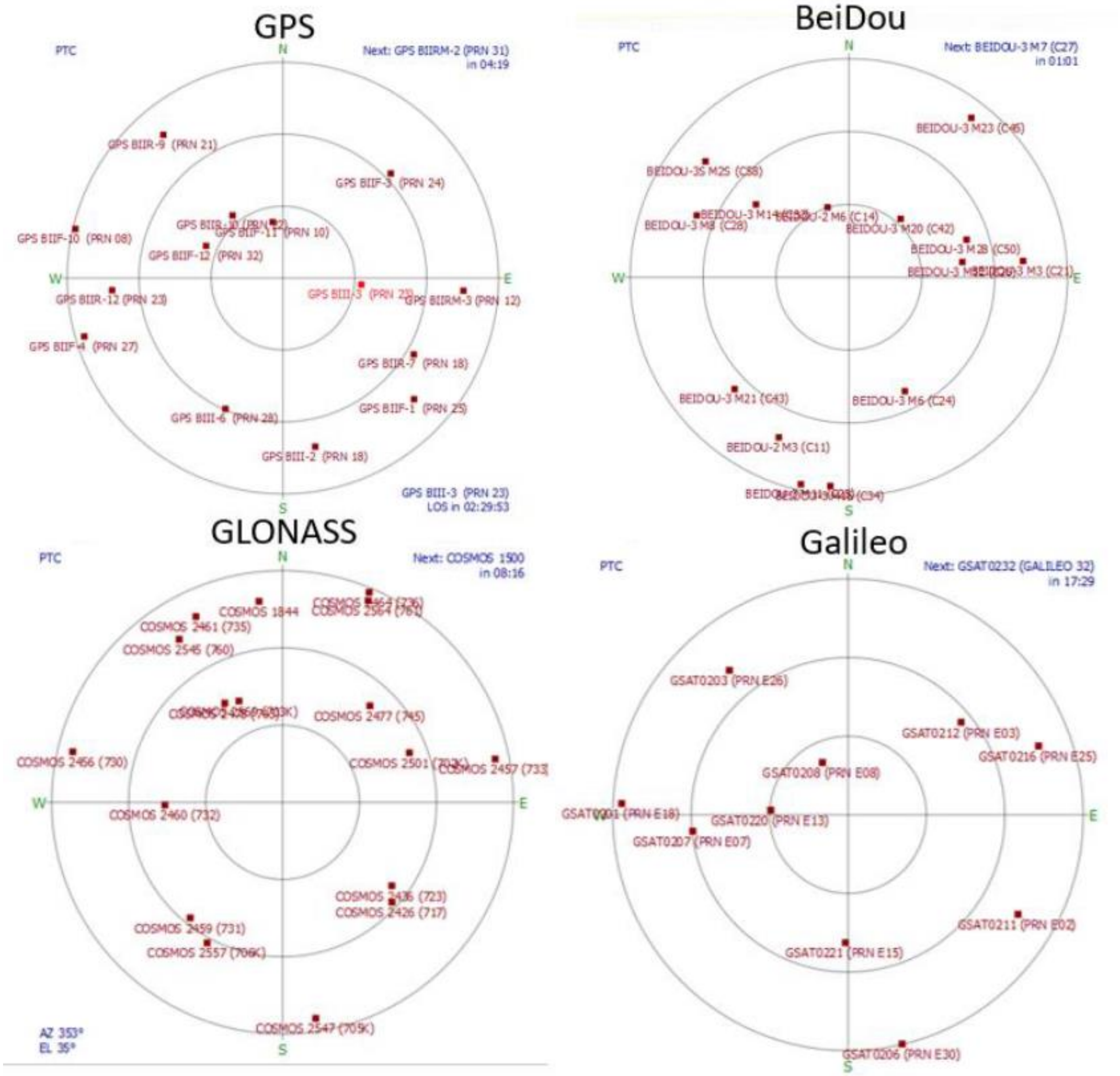


Figure 4. Example Snapshot GPS, GLONASS, BeiDou, and Galileo Satellite Locations Relative to Peachtree Corners, GA (Elevation Increments = 30°) *(Source: S. Rogers).*

These examples show that there are multiple satellites in each network within a 60° cone of zenith (middle circle). From observation of the positions of the MEO satellites in real time in the Gpredict application, it is seen that these move slowly, relative to the stationary reference location, especially when compared to low-earth-orbit satellites such as OneWeb and Starlink. This helps with tracking and minimizes the need to perform satellite switches.

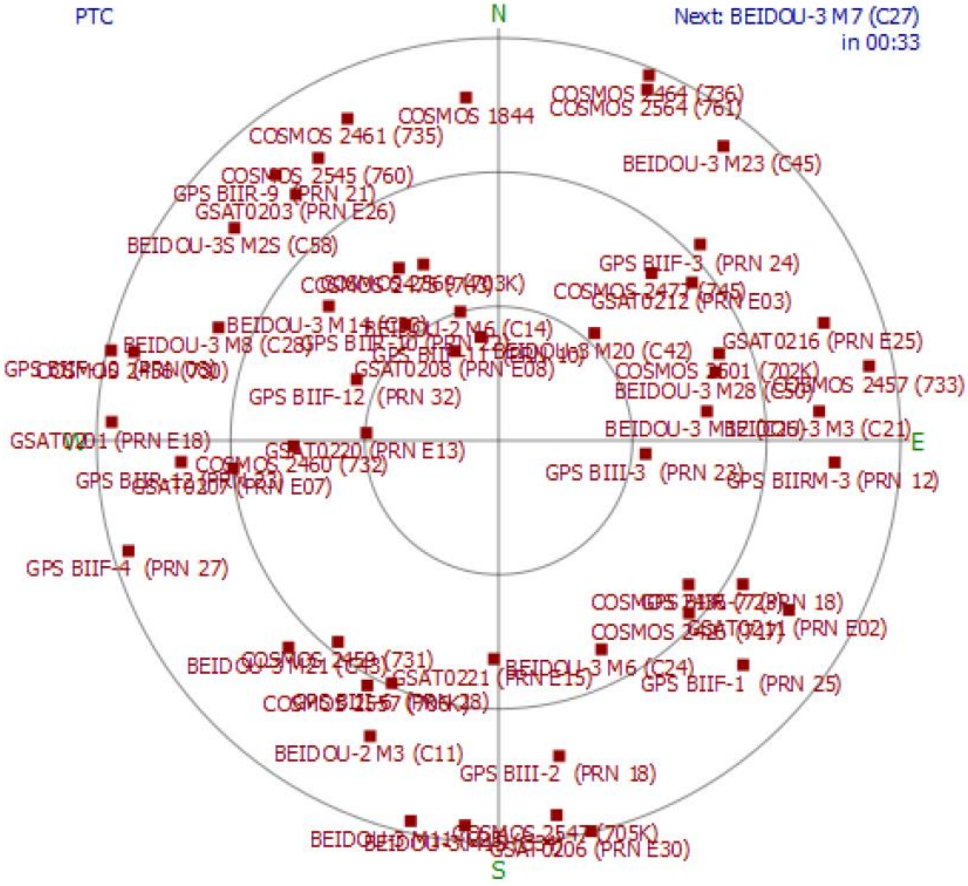


Figure 5. Snapshot of GNSS Satellite Networks of Figure 4 Included Together in One Plot *(Source: S. Rogers)*.

The takeaway from Figures 4 and 5 is that there are many GNSS satellites in view within a 60° cone (30° elevation from horizon), which means horizon-to-horizon coverage is not required to effectively achieve AJ/AS capability. Additional analysis is needed to determine the minimum required beamwidth necessary to design for monopulse tracking of the interferer.

2.3 Conclusions

A multibeam lens antenna is a promising technology for a positioning system that is AJ/AS and provides an added benefit of direction finding an interferer using traditional radar techniques, such as monopulse tracking. As a primary application, a lens antenna may not be ideal due to its size and complexity compared to GPS or CRPA antenna systems, but, as a value-added benefit for a satellite communications antenna, it provides significant value in combining capabilities into a single multiuse terminal system that can replace multiple systems on a platform.

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Biographies

Ken Quock has over 20 years of satellite communications experience specializing in the design and integration of tactical and strategic satellite communications systems for the U.S. Department of Defense. He is also a subject matter expert in mobile satellite communications and designing antennas for aeronautical platforms. Mr. Quock has a B.S. in electrical engineering.

Francis Forest has over 28 years of industry experience in radio-frequency (RF) transceiver design and product commercialization, including 14 years using micro-electromechanical inertial sensors and 5 years in the design of commercial air-to-ground antenna steering systems. At ATG Solutions, Dr. Forest is responsible for microwave RF and digital systems designs and antenna subsystems integration of multibeam lens-based antennas.

Shawn Rogers has 23 years of experience in industry working on advanced product development of numerous antennas, including phased arrays, lenses, radar systems, and satellite communications terminals, after receiving a Ph.D. in electrical engineering and specializing in computational electromagnetics. He has 14 patents and 25 publications and is the first author on a paper accepted for presentation at the 2023 Institute of Electrical and Electronics Engineers International Symposium on Antennas and Propagation. Dr. Rogers is also a co-inventor on one particular U.S. patent, as well as a U.S. patent application , which are both applicable to lens-based antenna designs.