Revisiting the Spaceborne Illuminators of Opportunity for Airborne Object Tracking

John Robie, **Alireza Famili**, and **Angelos Stavrou**, Virginia Tech

This article reviews existing research for cooperative passive coherent location and tracking employing spaceborne opportunistic illuminators, highlighting the need for novel cooperative real-time object detection and tracking approaches and discussing the lack of multistatic experimental data for future research.

As of August 2021, the U.S. Federal Aviation Administration receives more than 100 reports per month of near misses between manned aircraft and unmanned aerial systems (UASs).[1] Incidents such as these pose serious threats to the safety of pilots, passengers, people, and properties in the vicinity of a potential impact. Currently, we do not have the technical means to detect and track UASs in restricted airspaces prior to a near miss. Consequently, any measures to counter the multiobject real-time tracking of flying objects are primarily reactive. Moreover, the challenges of detecting small or low observable (LO) UASs affect the safety and operations of a wide range of national defense, civilian, and industrial sites. In dynamic environments that involve multiple targets of opportunity, radar has traditionally been the most robust approach for detection. While dedicated ground-based radar systems have provided detection in restricted airspaces, improvements can be made on the detection and tracking of multiple low-radar-cross-section (RCS) targets. One promising approach is the use of cooperative spaceborne illuminators acting as a multistatic radar to achieve passive coherent location (PCL) and tracking.

Digital Object Identifier 10.1109/MC.2022.3196190
Date of current version: 9 January 2023

Indeed, there is a growing volume of research regarding multistatic radar detection of aerial systems using spaceborne illuminators of opportunity (IoO). This literature has mostly examined the use of existing medium-Earth orbit (MEO)[2] and geostationary orbit (GEO)[3] constellations. These studies have shown promising results for flying object detection. Unfortunately, they do not provide sufficient spatial coverage and rely on the availability of one or more transmitters. This presents a challenge for radar systems that require flexibility in their area of operation. For example, many digital television satellites are geostationary, with orbits designed to service populous areas. Thus, they do not offer coverage over oceans and large swaths of less-developed regions.

Recently, there has been a rapid deployment of low-Earth orbit (LEO) constellations, such as SpaceX's Starlink. Their dense coverage and higher frequency of operation enable the detection of objects across the globe. Moreover, an operator can deploy multiple and relatively low-cost receivers in geographically diverse areas. This allows for detecting and tracking objects in real time, passively and without exposure. As illustrated in Figure 1, an extension of McDowell's work,[4] the population of actively transmitting LEO objects has increased sharply since 2015, particularly since the creation of the Starlink constellation.

In this article, we posit that spaceborne transmitters for bistatic and multistatic radar present a new opportunity for detection and tracking. This can be done by employing forward scattering signals for detection with ground-based receivers. Forward scattering signals occur when the bistatic angle of a radar system, defined from the transmitter to the target to the receiver, is approximately 180°. The forward scattering RCS of a target flying object can be significant when compared to backscattering RCS. This is especially true when the wavelength of the radar signal is small relative to the cross-sectional area of the target. Since many near-future satellites are equipped with centimeter and even millimeter wavelengths, they may be ideal for forward scattering detection of traditionally LO aerial systems, such as small commercial drones. Additionally, the edge diffraction models used to calculate forward scattering RCS values idealize targets as blackbodies rather than reflectors. The same target will create an extremely clear shadowing effect in a forward scattering geometry. This is contrary to backscattering, where a highly radio frequency (RF)-absorptive target results in less power at the receiver. Furthermore, we review recent research in passive bistatic and multistatic radar implementations using spaceborne IoO. We focus on both forward scattering and backscattering approaches for detecting and tracking aerial targets. Moreover, we present the tradeoffs among monostatic, bistatic, and multistatic radar configurations and different illuminators.

Our findings indicate that there is limited value in the use of multistatic forward scattering radar for aerial surveillance using MEO and GEO constellations. However, there is a clear opportunity and interesting research challenges in using LEOs to achieve cooperative PCL and tracking. What is missing in the literature is multistatic experimental data, which we propose is crucial to demonstrating the benefit of forward scattering with high-frequency signals. Also, investigating the computational

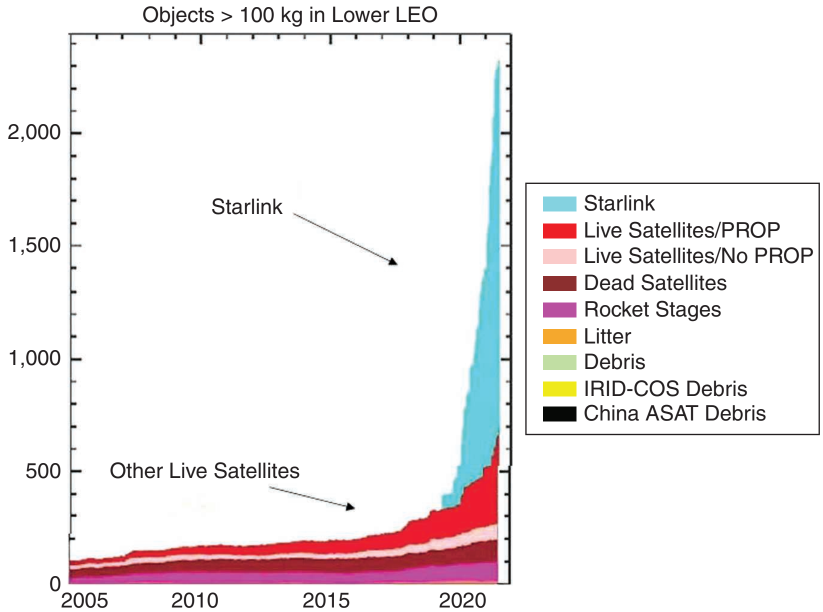

FIGURE 1. The LEO population. (Source: unpublished; reproduced based on McDowell,[4] with author permission.) ASAT: anti-satellite; IRID-COS: iridium-cosmos; PROP: propellant.

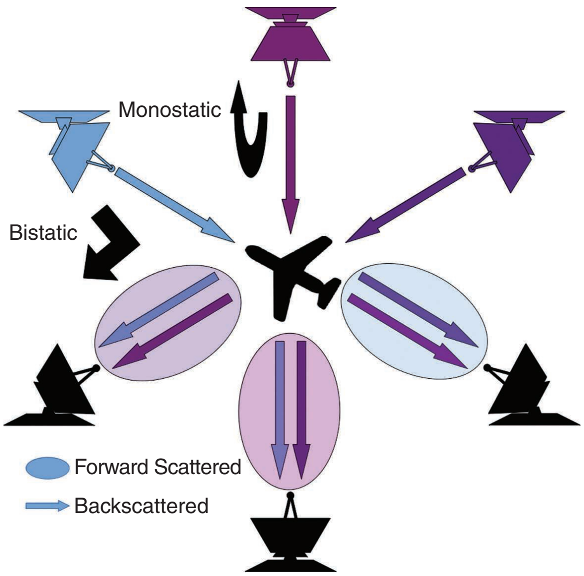

FIGURE 2. The monostatic, bistatic, and multistatic radar configurations.

requirements of multistatic systems for real-time multiple-object tracking needs more consideration.[5, 6]

RADAR SYSTEM CONFIGURATIONS

This section briefly describes various radar system configurations, namely, monostatic, bistatic, and multistatic (see Figure 2 and Table 1). We give a cursory overview of the familiar concept of monostatic radar. However, primarily in this review, we are interested in configurations with passive receivers, which, by definition, would be bistatic or multistatic.

Monostatic radar

A monostatic radar is one where the transmitter and receiver are colocated.

TABLE 1. The advantages and disadvantages of each radar configuration.

Configuration	Advantages	Disadvantages	Current implementation
Monostatic backscattering	Almost a century of research, development, and practice Many advantages in countless scenarios	Susceptible to well-established detection countermeasures Typically limited coverage area	Most existing radars
Monostatic forward scattering	Not physically possible	Not physically possible	Transmitter and receiver cannot be colocated for forward scattering
Bistatic backscattering	Can perform detection without revealing receiver location May find more reflective portions of the target	Difficult to separate bistatic signal from direct path signal and interference	Limited implementation, typically military
Bistatic forward scattering	Can result in extremely large RCSs	Occurs only for brief time windows when target or radar are moving	Used by the earliest radars before antennas could handle both transmitting and receiving
Multistatic backscattering	Can defeat some traditional radar countermeasures	Synthesis of receiver measurements Shared timing	Not commonly used; can be seen in some aerial defense radar networks, such as Australia's Jindalee Operational Radar Network
Multistatic forward scattering	Defeats traditional radar countermeasures	Relies on large-scale deployment by radar operators or uncertainty in using noncooperative illuminators Requires precise shared timing	None identified outside of the literature

The transmitter sends an RF signal into the environment; the signal reflects off of a target and is received back. Typical monostatic radars use a single antenna that switches between transmit and receive modes. The characteristics of the transmitted signal are used to perform target detection, localization, tracking, and imaging. The basic operation of this configuration is governed by the monostatic version of the well-known radar range equation.[3] The range equation calculates the amount of the transmitted signal that is returned to the receiver from backscattering off of the target. This received signal can see gains from factors such as the antenna gain, multipulse integration, and large target RCS values. Losses come from sources such as the propagation distance to the target, antenna inefficiencies, and small RCS values. Monostatic radars face many challenges, such as the discrimination of target signals from thermal noise and clutter, detection of LO objects, and operation in adversarial environments. Monostatic radars are, by definition, active and do not use IoOs as primary signal sources.

Bistatic and multistatic radar

Bistatic radar uses a single transmitter and a single receiver but does not colocate them. In this configuration, the receiver may be a passive element that can function without revealing its location and RF characteristics. Unlike a monostatic system, the paths from the transmitter to the target and the target to the receiver are not the same, breaking some of the assumptions made in the monostatic radar equation. There are new variables involved in bistatic radar operation, called the *bistatic range* and *bistatic angle*.[7] The bistatic range is simply the length of the path from the transmitter to the target to the receiver. The bistatic angle is the angle defined by this path. It is typical to measure both the delay time along the bistatic range and along the direct path from the transmitter to the receiver. The lag between these two signals corresponds to the difference in the signal path. When transmit and receive positions are known, it results in a determination of the bistatic range. This bistatic range gives a set of solutions for the target position. Thus, it is impossible to perform target localization in a passive bistatic configuration with a single transmit pulse. A bistatic system may result in a different RCS from a monostatic system, due to varying target geometry and material behaviors at different bistatic angles. Many intentionally low-RCS systems are designed to evade detection by monostatic systems, but these designs may not succeed across the spectrum of bistatic angles. In particular, the RCS for a bistatic angle of approximately 180° is governed by a different set of equations, due to the applicability of a new scattering mechanism, termed *forward scattering*, which is discussed in a later section.

In contrast, a multistatic radar system may have *n* transmitters and *m* receivers across diverse geographical positions, which, through sensor fusion, may provide far greater coverage and capability than any single bistatic pair. Unlike bistatic radar, multistatic configurations allow for multiple bistatic angles, angles of illumination, bistatic ranges, waveforms, and transmission modes.[7] The comparison of multiple bistatic pairs allows for methods such as interferometric imaging with incomplete sources from IoOs.[2] This requires significant computational optimization to perform in real time. Moreover, a multistatic configuration can perform time-independent localization of a target.[8]

RADAR SCATTERING

A modern summary of the physics of forward scattering is presented in Kulpa.[9] The reflection of a radar system is also referred to as *backscattering*.[10] The key components of the radar range equation are the transmit power, P_t; minimum detectable signal power, P_{min}; transmit wavelength, λ; transmitter and receiver antenna gains, G_T and G_R; and target RCS, σ. To determine the amount of power that will arrive at the receiver due to the backscattering of the target, the equation considers the amount of power that would exist at some range, assuming a perfect isotropic radiator. This power is defined as the transmitter power evenly distributed over the surface of a sphere with a radius equal to the range of the point in question. Next, to consider the focusing power of the antennas in the system, the power is multiplied by the receiver and transmitter's antenna gain. For a monostatic system, this value will be the same, but for a bistatic system, it may not be. Finally, to consider the amount of energy actually backscattered by the target, this power is multiplied by the target's RCS. A backscattering RCS is dependent on many properties, such as the target's cross-sectional area, RF reflectivity, surface roughness, and temperature. For many targets, the RCS is the primary concern in the radar equation, and consequently, small targets and targets with radar-absorbent materials present challenges for detection.

It should be noted that the RCS values for most radar targets are derived empirically and highly dependent on the aspect angle of the target. For example, a traditional aircraft tail typically acts as a corner reflector, which leads to a high RCS at aspect angles that illuminate the tail. Other parts of the same aircraft, though, may reflect very little energy back in the receiver's direction. It is beneficial to illuminate multiple aspect angles to maximize the probability of detection for any system. Consequently, it can be seen how multistatic radars can be beneficial for the reception of backscattered signals.

In addition to backscattering, forward scattering occurs when the bistatic angle, defined from the transmitter to the target to the receiver, is approximately 180°. The forward scattering RCS of a radar target is proportionate to the square of the target's cross-sectional area divided by the square of the transmitter wavelength. The forward scattering RCS is greatly enhanced over the backscattering RCS for small and RF-absorptive targets, given that the radar wavelength is small relative to the target. Radmard et al.[11] perform a simulation of the passive forward scattering detection of a Space Shuttle, using the Inmarsat GEO constellation. The simulation results imply a high probability of detection, even accounting for many real-world losses.

A drawback of the forward scattering radar is that the bistatic angle for any given set of transmitter, target, and receiver locations is unlikely to remain close to 180º for long periods of time. Bistatic forward scattering systems have been deployed for air surveillance somewhat sporadically over the past century.[12] These systems all deployed their own transmitters, leading to increased deployment costs while covering small areas. However, as we show next, multistatic forward scattering networks warrant new attention with spaceborne illuminators.

SPACEBORNE ILLUMINATORS

When searching for a transmitter position that provides coverage of the largest volume of airspace, one will rarely, if ever, do better than a position in orbit. The line of sight from a position in orbit to a point in the air will be impeded only by weather and the horizon, and positions in orbit provide for the farthest possible horizons. As such, spaceborne illuminators provide ideal coverage for wide-scale aerial surveillance systems. Additionally, aerodynamic designs tend to have the largest cross-sectional area roughly parallel to the surface of Earth. Consequently, the largest forward scattering RCS values will require either the transmitter or the receiver to be above the airborne system.

While spaceborne systems are ideal from a coverage perspective, fielding a satellite constellation is extraordinarily complex and costly. It is much more ideal to make use of existing constellations if possible. As we have seen in the sections on bistatic and multistatic radar, there is no need to have ownership and control of the transmitters as long as the direct path signal to the receiver can be characterized. A diverse set of existing satellite constellations illuminate Earth's surface. Each constellation has different RF and orbital characteristics that may add to or detract from the viability of a passive radar design. A general overview of the needs and capabilities of spaceborne radar is given in Lacomme et al.[10] Table 2 displays some of the parameters of interest for the satellite constellations most frequently referenced in the passive multistatic literature.

As with all radar systems, the choice of system parameters, such as the transmit power, frequency, antenna gain, and so on, should be tailored to the application. Persico et al.[13] perform a radar design for small satellite platforms, illustrating the tradeoffs between different design choices. While a passive radar will not control the characteristics of the transmitter, it is still crucial to perform this analysis to understand the limitations of the system.

All reviewed publications use transmitters in the L and S-bands, which are typical choices of frequency ranges for long-range transmitters, due to their favorable atmospheric absorption rates. Additionally, reasonably stable L and S-band receiver hardware is available at low commercial costs. We see that the Starlink constellation operates at much higher frequencies, allowing for greater bandwidths but higher path losses. Altitude corresponds to the direct signal path length, assuming a surface-based receiver. In addition, many characteristics of a stable orbit may be derived from a measurement of altitude. Constellation altitudes are broken into three categories of orbit: LEO, MEO, and GEO (Figure 3). The constellation population, or number of active satellites in a constellation, provides a metric for the availability of a satellite for some point on the surface. Availability is also a function of speed relative to the surface and area of illumination. We see that of the presented constellations, there are lesser populations as altitude increases, with a huge disparity between Starlink and all other constellations. The following sections present the characteristics of each orbital category and discuss how they will impact system operation.

Geostationary constellations

GEO for Earth occurs at approximately 35,786 km. Satellites orbiting at this altitude have orbital periods equal to

Earth's rotational period and consequently remain motionless relative to the surface of Earth. By definition, satellites in this orbit illuminate a static area. At such high altitudes, the beam spot at the surface is quite large, and consequently, very few transmitters are required. Additionally, this orbit is at the highest altitude utilized by RF communication systems and is most affected by path loss. To provide adequate service at the surface with effective radiated powers constrained by the size, weight, power, and cost requirements of space travel, there is a limited range of feasible transmit frequencies.

Depending on the use case, the static illumination area may benefit a radar system. Whereas MEO and LEO coverage areas will change as the target moves, possibly reducing the illumination time, the illumination time from a GEO transmitter will depend entirely on target velocity. There will also be no Doppler shift in the received signal, due to the motion of the transmitter, which simplifies the signal processing challenges at the receiver and does not create any unnecessary Doppler ambiguity.

For a bistatic forward scattering radar, the receiving antenna would not have to change position over time. This is an improvement over a moving transmitter with a poorly characterized position but is poor for most applications. A bistatic system with motionless components has also been referred to as a *geofence*. Systems such as these have been employed to perform intrusion detection for small areas, as described by Falconi et al.,[14] but would require many receivers to cover an appreciable area. In addition, the area covered by a single GEO transmitter and many surface receivers would approximate a conical region and, for a system of only seven or 13 transmitters, would be incapable of covering much of the upper atmosphere.

MEO constellations

MEO is defined as the altitudes between 2,000 and 35,786 km. Within this range lies Earth's semisynchronous orbit, at approximately 20,200 km. At this altitude, most illuminators of interest, such as GPS, reside due to a stable rotational period of roughly 12 h. In terms of the transmitter position and velocity, MEO satellites offer a middle ground between GEO and LEO objects. While single MEO transmitters do not provide continuous coverage of a single portion of Earth's surface, it provides periodic coverage of a larger

TABLE 2. The data on relevant illuminators.

Constellation	Frequency (MHz)	Altitude (km)	Population
LEO			
Globalstar	2,484	1,414	48
Iridium	1,621	780	75
Starlink	Ku, Ka, and V	550, 1,110, and 340	>1,600
MEO			
Constellation	**Frequency (MHz)**	**Altitude (km)**	**Population**
GPS	1,575, 1,227, and 1,176	20,200	24
Global navigation satellite system	1,602 and 1,246	19,100	24
Galileo	1,575	20,505	24
BeiDou	1,561, 1,207, and 1,268	21,528	24
GEO			
Constellation	**Frequency (MHz)**	**Altitude (km)**	**Population**
Navigation Indian Constellation	1,176 and 2,492	35,786	7
Inmarsat	1,626	35,405	13

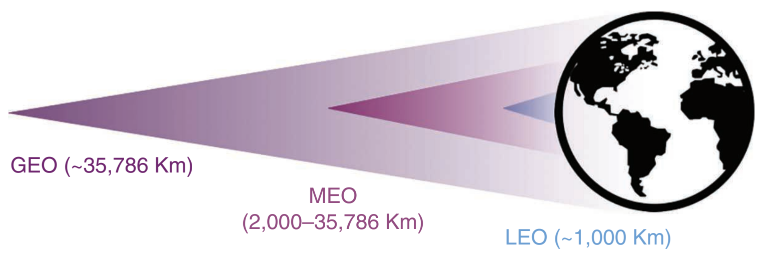

FIGURE 3. The GEO, MEO, and LEO orbitals.

area. MEO satellites have an orbital period ranging from around 2 to 24 h, meaning that an area is illuminated by a single transmitter between one and 12 times per day from multiple angles. A MEO transmitter will illuminate a point on the surface for on the order of 1 h per transit. The current literature has identified MEO transmitters as optimal for passive radar, though this was in contrast only to GEO.

LEO constellations

LEO is defined as orbits below 2,000 km. The cost of placing a system in LEO is considerably less than the higher orbits, which, combined with the advent of low-cost miniaturized satellites, has resulted in a rapid proliferation of LEO objects. Figure 1 illustrates this rapid increase in population, as recorded by McDowell.[4] It is anticipated that the population of the Starlink constellation could reach on the order of 10,000 in the coming years. Alongside the low cost of achieving LEO, transmissions from LEO travel the least distance of any orbit to the surface. Thus, operating frequencies are less constrained by atmospheric absorption, and more consideration may be given to optimizing frequencies for network bandwidth.

A drawback to LEO IoOs is their high velocity relative to Earth's surface. For example, given their altitude, the Starlink satellites orbit at approximately 7.5 km/s. For any one surface receiver and one LEO transmitter, a forward scattering geometry may exist only for tens to hundreds of microseconds. The life span of such a signal may be crucial when determining how many transmitters and receivers are necessary to make a forward scattering network viable. In addition, the high velocity of LEO objects introduces a significant Doppler shift in the received signal, which would not occur when using a signal from a GEO transmitter. Coupled with potentially inaccurate information on the position and velocity of the transmitter at the receiver side, extracting useful Doppler information about the target could prove challenging. While the transit times of existing LEO constellations, such as Globalstar and Iridium, may disqualify them as useful IoOs, the sheer projected volume of Starlink transmitters appears to promise many illuminators visible at once for any point on the surface.

CURRENT RESEARCH

Many recent publications have successfully used forward-scattered signals from airborne targets using spaceborne illuminators in bistatic radar configurations. Using primarily digital video broadcasting (DVB) satellite and GPS transmissions, initial results are promising. In addition, existing simulations for multistatic forward scattering detection have not been validated with experimental data, to the best of our knowledge.

Antoniou et al.[3] use global navigation satellite system transmissions to perform imaging in a passive bistatic backscattering configuration. They state the advantages of a large constellation for achieving multiple illumination angles at a time. They focus on large MEO constellations, positing that radar imagery is more valuable when multiple images taken over time can be used to study environmental changes. Thus, the transmitter must revisit the area of interest with reasonable frequency. For these purposes, a GEO or near-GEO constellation would be inappropriate.

Gronowski et al.[15] use GPS transmissions for passive bistatic detection of an airborne Boeing 737-45 D, using the forward scattering signal. The use of DVB transmissions provides high transmit powers but does not provide coverage of many regions. The GPS signals are analyzed by employing low-cost USRP N210 software-defined radios with flexible RF front ends. Single antenna reception is enabled by the good characterization of the GPS coarse/acquisition signal. In addition, remotely deployed receivers would be simple to update in response to changes in transmitter signal characteristics, the IoO selection, and improvements in signal processing techniques. Burov et al.[16] perform passive bistatic detection of a Boeing 737-524. They use the forward-scattered signal from an Intelsat GEO transmitter. Their work provides the most comprehensive RCS calculations for realistic targets in the reviewed literature. It also demonstrates the high variability of RCS values with respect to the aspect angle. The authors also describe the benefits of multiple illumination angles at a given time step. Abdullah et al.[17] perform passive bistatic detection of a DJI Phantom quadcopter by using the forward-scattered signal from a DVB satellite at 11.725 GHz. The authors were able to detect micro-Doppler effects in the received signal, due to the motion of the blades. Of the papers reviewed, their work receives the clearest signal of the smallest target.

CHALLENGES FOR PASSIVE MULTISTATIC RADAR

One of the advantages of passive coherent detection is the ability to combine existing deployed infrastructure with ad hoc receivers. All available receivers can work together in tandem to carry out the detection and tracking tasks. While having multiple receivers offers many advantages, it also comes with some challenges. The most important computational challenge in passive detection using satellite illumination is the inherently large dimension of the problem when attempting to combine distributed readings. Transforming the scattered received data from different receivers to produce the final combined detection and localization result must also be done rapidly enough to produce fresh information in situations where an aerial target is moving rapidly. The problem of target detection can be modeled as a block sparse recovery problem.[18] Having multiple receivers and transmitters also helps when the object is small, the cross section is small, and there is inherent blocking of the radar signal off its surface.

Even for static targets, the raw information from the receivers produces a sensing matrix that has ultralarge dimension as a function of the number of receivers requiring novel parallel processing algorithms. From a computational standpoint, transferring the raw information into a powerful data center would make the most sense. However, the real-time signal information is generated by distributed receivers that might be operating in areas with limited network connectivity, making the transmission of high-fidelity signal information infeasible. Thus, to create a network of distributed receivers, we need to come up with novel distributed algorithms that operate partly at the edge and partly in a centralized location. The edge component of the algorithm will distill the signaling data by many orders of magnitude without significant loss of information, enabling the central location to combine readings from multiple radar locations into a single coherent view.[18]

Another challenge, especially for real-time object detection, is the need for continuous and precise time synchronization. Time synchronization can be achieved by both network synchronization and computational processing power to reduce any processing delays that can affect end-to-end processing latency. The number of receivers exacerbates the timing constraints, as we now have to compare readings from multiple receivers to create a meaningful understanding of the RF environment and interference. Thus, fusing all the data received from different sensors and making a meaningful decision need the use of powerful processors that can work together synchronized. The task requires high processing power because it requires collecting data from different sensors and device classifiers leveraging machine learning techniques.[19] Envisioning an example where Starlink satellites are employed as passive illuminators with multiple receivers deployed geographically close to cover a small region, it will require powerful edge computing capabilities[6] connected over high-bandwidth lines separate to the ones provided by the Starlink system.

While we have discussed, in this article, methods by which a forward scattering radar system may detect the presence of a target, we have not discussed how to learn anything else about it. Of interest to many operators is the question, What is the target? There is a tremendous amount of work leveraging machine learning to perform target classification in backscattering radar signals, but unfortunately these models will be useless for a forward-scattered signal of the same target.[20] Might a classification algorithm be able to learn details about how target geometries affect the rise time of our edge-diffracted signal? If we identify our target class, does the beamwidth of the signal reveal the target altitude? Might we even be able to infer some of the material properties of the target from the diffraction characteristics to help separate man-made systems from birds?

TO CREATE A NETWORK OF DISTRIBUTED RECEIVERS, WE NEED TO COME UP WITH NOVEL DISTRIBUTED ALGORITHMS THAT OPERATE PARTLY AT THE EDGE AND PARTLY IN A CENTRALIZED LOCATION.

WAY AHEAD

The literature on spaceborne passive radar identifies some key considerations for any implementation. As with any radar, there must be enough power from the target at the receiver to distinguish the signal from noise. This power depends on, among other things, the transmit power, which can be controlled only through the selection of the IoO. The required transmit power may be different depending on the choice of backscattering or forward scattering radar, primarily because the RCS of the target may vary considerably.

The frequency of the radar system is important not only due to path loss but also because of the consideration of the target RCS. In forward scattering, the transmit frequency is a clear factor in the RCS and may be crucial to the determination to use forward scattering. The relationship between the RCS and transmit frequency in backscattering is much more complicated but should be considered, as with any radar design.

Several of the publications reviewed here have detailed the desirability of multiple simultaneous angles of illumination. However, in practice, these publications have recorded only signals from a single transmitter. Particularly for forward scattering, the reception of multiple signals requires test setups at multiple points on the surface, which may be difficult to access. Additionally, the timing of these test events, for papers using MEO transmitters, corresponded with fortuitous positioning of the transmitter such that the forward scattering would occur for desired targets and be received at accessible locations. While this will be a consideration for any forward scattering system, the time between fortuitous alignments will decrease as the number of transmitters increases. For this reason, it is important to consider the availability of transmitters. The probability of two illuminators at once will be a function of the constellation population, signal beamwidth (at the transmitter for backscattering and at the target for forward scattering), and transmitter velocity.

MEO and GEO applications of both forward- and backscattering target detection have shown promising initial results in bistatic systems. To the best of our knowledge, no experimental setup has performed passive multistatic detection and localization, which would be a logical extension of the bistatic experiments and multistatic simulation publications. Additionally, to the best of our knowledge, there have been no studies on mitigating low illumination time with a high number of transmitters for passive radar. However, to detect and track a target in real time, we need considerable computational resources using imperfect information. Thus, understanding the computational requirements for distributed multireceiver multistatic systems is important. This is exacerbated by the need for real-time multiple object tracking, too.[5, 6]

The rapidly increasing deployment of spaceborne transmitters, particularly in LEO, presents a realistic opportunity for cooperative PCL due to dense coverage across the globe. In addition, the benefits of radar detection via forward scattering for either small or RF-absorptive targets warrant renewed consideration, given this denser coverage. The tradeoff between frequency and angular beamwidth for forward scattering signals is identified as optimal in the ultrahigh-frequency band for single bistatic pairs.[12] However, the increased frequency may outweigh the reduced angular beamwidth in large multistatic networks, given the benefit of such greatly enhanced RCS values. Additionally, the high velocity of LEO transmitters results in less time on target per orbit. As shown in Figure 4, the forward scattering RCS for an object the size of a small manned aircraft at Starlink frequencies is on the order of 70 dBm^2, which is considerably larger than the backscattering RCS of a cargo ship.

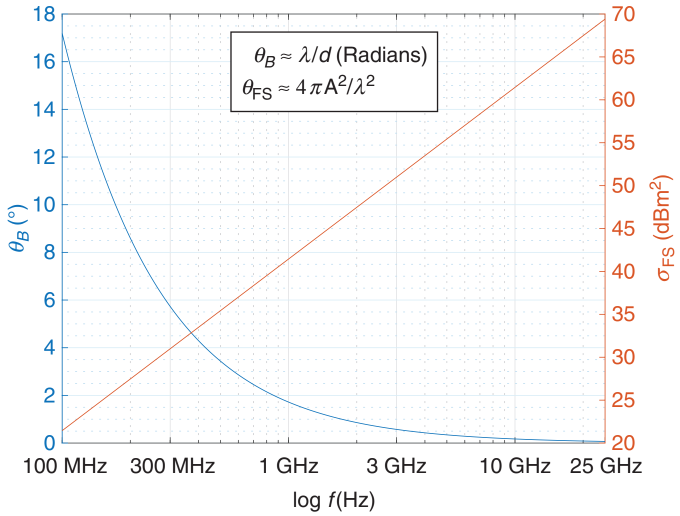

FIGURE 4. The forward scattering system trade space: the forward scatter RCS (σ_{FS}) and angular width of scatter (θ_B) for an idealized medium-sized airborne target with A = 10 m^2 and d = 10 m, where A is the cross-sectional area of the target and d is the greatest linear distance to the target.

Multistatic forward scattering experiments with MEO transmitters should be performed to validate the simulations and bistatic measurements made in recent literature. An examination of the Starlink constellation would enable researchers to identify the trade space between the illumination time and number of transmitters. If this proves promising, the potential for such greatly enhanced forward scattering RCS values for otherwise LO targets warrants considerable attention.

ABOUT THE AUTHORS

JOHN ROBIE is pursuing his M.S. in electrical engineering at Virginia Tech, Blacksburg, VA 24061 USA. His research interests include spectrum awareness in large wireless networks as well as advanced computational methods for radio-frequency modeling and simulation. Robie received a B.S. in physics from the University of Mary Washington in 2016. Contact him at jrobie@vt.edu.

ALIREZA FAMILI is pursuing his Ph.D. in electrical engineering in the Bradley Department of Electrical and Computer Engineering, Virginia Tech, Blacksburg, VA 24061 USA. His research interests include indoor positioning and wireless communications/networking. Famili received an M.S. in electrical engineering from Lehigh University in 2018. Contact him at afamili@vt.edu.

ANGELOS STAVROU is a professor in the Bradley Department of Electrical and Computer Engineering, Virginia Tech, Blacksburg, VA 24061 USA. His research interests include security and reliability for distributed systems, security principles for virtualization, and anonymity, with a focus on building and deploying large-scale systems. Stavrou received a Ph.D. (with distinction) in computer science from Columbia University. He is a Senior Member of IEEE. Contact him at angelos@vt.edu.

REFERENCES

1. "UAS sightings report," Federal Aviation Administration, Washington, DC, USA , 2021. Accessed: Aug. 7, 2021. [Online]. Available: https://www.faa.gov/uas/resources/public_records/uas_sightings_report/
2. B. Yonel, I.-Y. Son, and B. Yazici, "Exact multistatic interferometric imaging via generalized Wirtinger flow," *IEEE Trans. Comput. Imag.*, vol. 6, pp. 711–726, Jan. 2020, doi: 10.1109/TCI.2020.2967151.
3. M. Antoniou, Z. Zeng, L. Feifeng, and M. Cherniakov, "Experimental demonstration of passive BSAR imaging using navigation satellites and a fixed receiver," *IEEE Geosci. Remote Sens. Lett.*, vol. 9, no. 3, pp. 477–481, May 2012, doi: 10.1109/LGRS.2011.2172571.
4. J. C. McDowell, "The low earth orbit satellite population and impacts of the SpaceX Starlink constellation," *Astrophys. J.*, vol. 892, no. 2, p. L36, Apr. 2020, doi: 10.3847/2041-8213/ab8016.
5. C. Aume, K. Andrews, S. Pal, A. James, A. Seth, and S. Mukhopadhyay, "TrackInk: An IoT-enabled real-time object tracking system in space," *Sensors*, vol. 22, no. 2, p. 608, 2022. [Online]. Available: https://www.mdpi.com/1424-8220/22/2/608, doi: 10.3390/s22020608.
6. Z. Hu et al., "Cloud–edge cooperation for meteorological radar big data: A review of data quality control," *Complex Intell. Syst.*, pp. 1–15, Nov. 2021, doi: 10.1007/s40747-021-00581-w.
7. K. Kulpa and M. Malanowski, "From Klein Heidelberg to modern multistatic passive radar," in *Proc. 20th Int. Radar Symp. (IRS)*, Jun. 2019, pp. 1–9, doi: 10.23919/IRS.2019.8768176.
8. M. Malanowski and K. Kulpa, "Two methods for target localization in multistatic passive radar," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 48, no. 1, pp. 572–580, 2012, doi: 10.1109/TAES.2012.6129656.
9. K. Kulpa, "Forward scattering effect exploitation in passive radars," Air Force Research Laboratory (AFRL), Wright-Patterson Air Force Base, OH, USA, Tech. Rep. AD1096422,. Sep. 2019.
10. P. Lacomme, J.-P. Hardange, J.-C. Marchais, and E. Normant, "Air and spaceborne radar systems," in *Air and Spaceborne Radar Systems*, P. Lacomme, Ed. Norwich, NY, USA: William Andrew Publishing, 2007, pp. 1–504. [Online]. Available: https://www.sciencedirect.com/science/article/pii/B9781891121135500334
11. M. Radmard, S. Bayat, A. Farina, S. Hajsadeghian, and M. M. Nayebi, "Satellite-based forward scatter passive radar," in *Proc. 2016 17th Int. Radar Symp. (IRS)*, pp. 1–4, doi: 10.1109/IRS.2016.7497275.
12. C. Baker, "PCL waveforms," North Atlantic Treaty Organization (NATO), Brussels, Belgium, Tech. Rep. EN-SET-243-02, 2017.

13. A. R. Persico, P. Kirkland, C. Clemente, J. J. Soraghan, and M. Vasile, “Cubesat-based passive bistatic radar for space situational awareness: A feasibility study,” *IEEE Trans. Aerosp. Electron. Syst.* (1965–present), vol. 55, no. 1, pp. 476–485, 2019, doi: 10.1109/TAES.2018.2848340.
14. M. T. Falconi, D. Comite, A. Galli, D. Pastina, P. Lombardo, and F. Marzano, “Forward scatter radar for air surveillance: Characterizing the target-receiver transition from far-field to near-field regions,” *Remote Sens.*, vol. 9, no. 1, p. 50, 2017, doi: 10.3390/rs9010050.
15. K. Gronowski, P. Samczyński, K. Stasiak, and K. Kulpa, “First results of air target detection using single channel passive radar utilizing GPS illumination,” in *Proc. 2019 IEEE Radar Conf. (RadarConf)*, pp. 1–6, doi: 10.1109/RADAR.2019.8835655.
16. V. Burov, A. Myakinkov, A. Ryndyk, R. Fadeev, D. Balashova, and A. Blyakhman, “Multi-static forward scatter radar with illumination from telecommunication satellites for detection of airborne targets,” in *Proc. 2018 19th Int. Radar Symp. (IRS)*, pp. 1–10, doi: 10.23919/IRS.2018.8448101.
17. R. S. A. Raja Abdullah, S. Alhaji Musa, N. E. Abdul Rashid, A. Sali, A. A. Salah, and A. Ismail, “Passive forward-scattering radar using digital video broadcasting satellite signal for drone detection,” *Remote Sens.*, vol. 12, no. 18, p. 3075, 2020, doi: 10.3390/rs12183075.
18. H. Nikaein, A. Sheikhi, and S. Gazor, “Multitarget detection in passive MIMO radar using block sparse recovery,” *IEEE Access*, vol. 9, pp. 121,206–121,216, Aug. 2021, doi: 10.1109/ACCESS.2021.3108195.
19. D. Qi, F. Boyu, W. Feng, Z. Zhang, X. He, and C. Shang, “Digital tv signal based airborne passive radar clutter suppression via a parameter-searched algorithm,” *Wireless Personal Commun.*, vol. 120, no. 4, pp. 1–28, Oct. 2021, doi: 10.1007/s11277-021-08607-9.
20. I. Jouny, “Radar target classification using fusion of compressively sensed backscatter,” in *Proc. 31st Automatic Target Recognit.*, International Society for Optics and Photonics, 2021, vol. 11729, p. 117290T, doi: 10.1117/12.2587049.