# NUFORC Skywitness

## An Invitation to Support Civic UFO Disclosure

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## Summary

NUFORC Skywitness is a three-part system combining a civilian passive radar network, a mobile app capable of triangulation with video, and a reporting center that together will prove the existence of unidentified flying objects (UFOs). The Skywitness radar is a nationwide network of inexpensive citizen-owned radar receivers that work together to map the paths of unnaturally fast or agile objects in the air. The Skywitness mobile app provides video recording and triangulation to obtain independent multisensor data from objects picked up on radar. These calibrated measurements combine with eyewitness reports submitted to the National UFO Reporting Center to create unprecedented documentation of anomalous events. Skywitness makes it possible for ordinary people to own and deploy sensor technology, working with others across the country to make citizen-driven multi-sensor UFO disclosure happen.

The project team is led by Mitch Randall, an engineer who developed radar hardware and software technologies that are used internationally by organizations like the National Center for Atmospheric Research (NCAR), NASA, and the National Oceanic and Atmospheric Administration (NOAA). Skywitness implements an inexpensive, compact form of radar that is receive-only, piggybacking off the transmissions from FM radio towers that already exist.

With philanthropic support of $3.5M, Randall and his team will develop a plug-and-play consumer Skywitness radar receiver, the video recording and triangulation mobile app, and the processing center that provides a birds-eye view of anomalous objects in the sky wherever Skywitness receivers are located. As well, significant upgrades and restructuring are planned for NUFORC to make it an even more powerful resource in concert with these new Skywitness technologies.

Skywitness will capture precise, objective information from anomalous aircraft suitable for scientific research. It will bring people together to answer a clearly defined and crucial question that has transformative implications for society. It will

destigmatize the UFO topic. **Skywitness represents an unprecedented effort to bring scientific rigor, public engagement, and innovative technology to the study of UFOs.**

# Overview

## A Nationwide Passive Radar Network

Skywitness radar receivers listen for signals that are first broadcast from normal FM radio stations and then reflected from objects that accelerate quickly or that make science-defying turns in flight. By connecting these receivers so they can combine their data, the speed and direction of unordinary objects in the air can be drawn on a map that's shared by everyone who participates. Skywitness removes normal airplane traffic from the map when it analyzes data — what's left are flying machines that are of unknown origin.

Radar systems usually determine the distance and velocity of an object in the sky by sending out electromagnetic waves to bounce off of it, then measuring how long that signal takes to return to the radar receiver. Military and airport radar systems usually create, broadcast and receive their own radio signal.

Skywitness works differently. Using technology that was first demonstrated in the 1940s, the Skywitness radar receivers don't send a radio signal outward. Instead, they passively receive signals from normal radio stations. Those radio station signals fill the sky across the country every day. A Skywitness receiver compares a signal that arrives directly from a radio station with a signal from the same radio station that has bounced from an object in the sky. When the data from four or more regional Skywitness radar receivers are merged, a complete picture of the location, path and speed of an object in the air can be mapped.


*Map of U.S. FM radio service contours by Erin Davis, [erdavis.com](erdavis.com).*

Skywitness consists of multiple passive radar detectors that collect data about a flying object's location in three-dimensional (3D) space, its velocity, and acceleration over time. Skywitness processes this data to monitor and report the kinematics — the geometry of the motion — of objects in flight. Kinematic data tells us if an object is demonstrating instantaneous acceleration or change of direction, one of the five flight characteristics that identify UFOs:

1. Sudden and instantaneous acceleration
2. Hypersonic velocities without signatures
3. Low observability
4. Trans-medium travel
5. Positive lift without the normally associated aerodynamic means for lift and thrust

Data can be gathered from objects up to 80 kilometers in altitude, horizontal distances up to 150 kilometers, and speeds of up to six times the speed of sound. An object's velocity and position can be measured up to fifteen times per second. By measuring both the velocity and position of an object, Skywitness can mathematically infer its acceleration, which is key to determining if its characteristics are normal for known propulsion technologies. With enough data, an object's radar cross section can also be measured, providing an approximation of its size. Skywitness, made from many passive radar receivers that share their data over a network, can be called a 'decentralized passive multistatic radar mesh network.' 'Multistatic' means there is more than one radar and receiver in the network. Object tracks can be resolved with as few as four receivers within 50 kilometers of an object, and Skywitness could automatically guide optical instruments like cameras and telescopes to direct themselves at a detected object.

Key elements of a passive multistatic radar network include the ability to listen to an FM radio signal source and to the echoes of those transmissions that are reflected from objects. The Doppler shift of echoes bounced back from an object are measured to reveal its velocity, and the object is located in space through trigonometry that solves the triangles composed by the object and four or more radars. Accurate timekeeping contributes to generating kinematic data, and this data processing is centralized. Failsafes are built into Skywitness, like the ability to compare reflection data from a receiver that has a record of the original radio signal with that of data collected by a completely separate radar receiver on the Skywitness network. That kind of adaptation will happen automatically to make best use of available reflected radio signals, wherever a Skywitness receiver is located.

Skywitness is able to remove civilian and military aircraft from its data because these aircraft have a transponder. An aircraft's transponder sends out a radio signal with a unique four-digit code as it flies. This helps air traffic controllers recognize aircraft as they guide them through airspace. These transponder signals are how popular apps are able to show aircraft and their flight paths on a map on your phone or computer. Skywitness uses this transponder information to delete normal aircraft from the map that is its user interface. What remains on the map will be flying objects that are unidentifiable by air traffic controllers, visible in real time to all Skywitness network participants.

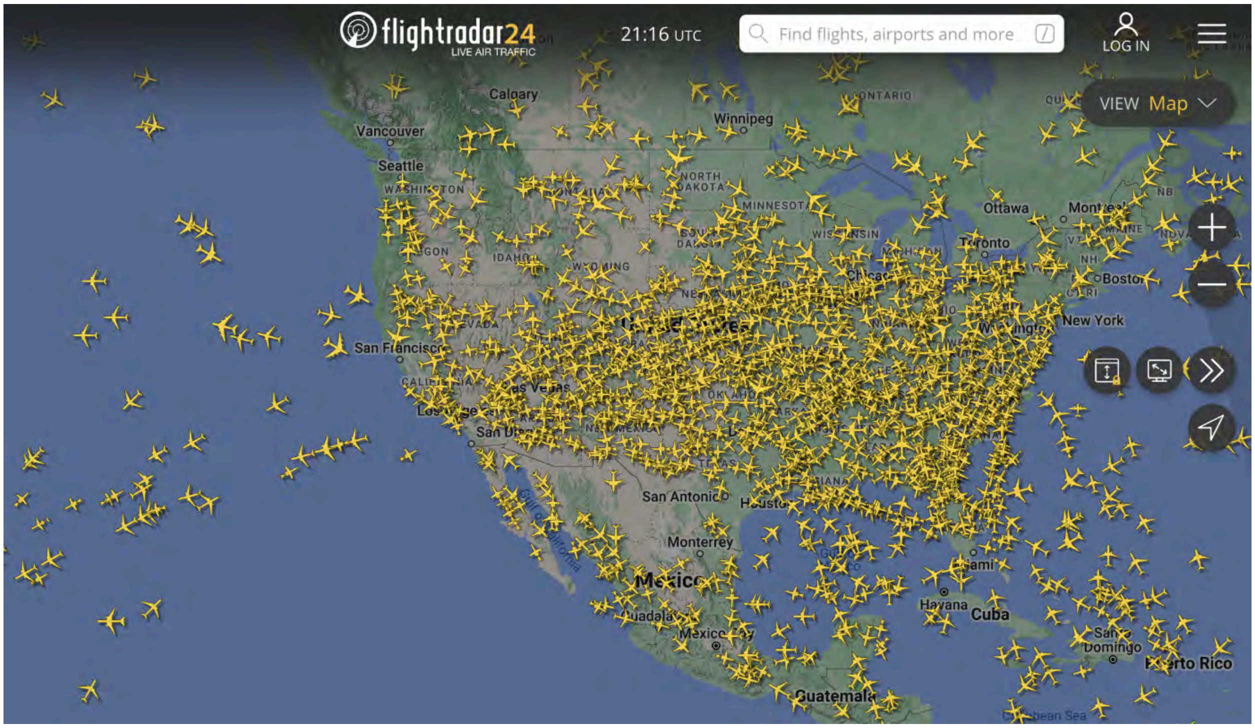



*Image of real-time U.S. air traffic generated by the [FlightRadar24.com](FlightRadar24.com) application.*

## A Video Triangulation App

Pew Research Center reports that 97% of Americans now own a cellphone of some kind, and nine in ten own a smartphone. The first iPhone was released in 1997; now more than 310 million Americans own a smartphone. This ubiquitous high technology infrastructure will be harnessed by Skywitness to power the most complete and inclusive civilian-deployed UFO identification, tracking and reporting system ever conceived.

The Skywitness app transforms a common cell phone into a calibrated scientific instrument. Within the Skywitness app, the phone's video camera will combine with the motion sensor information provided by the phone while each frame is captured. A phone’s accelerometer and gyroscope sensors fuse data to determine how a phone is being held toward the sky and a magnetometer determines the direction it’s pointed. With photos and data from more than one camera, optical triangulation will be possible, resulting in multi-sensor reporting from both Skywitness passive radar and the mobile devices of participants. Multi-sensor data is a high standard for corroboration of UFO sightings.

Notices from the Skywitness central hub are provided to each Skywitness participant who is in the path of an anomalous object, ensuring that the maximum number of witnesses and phones with a camera might view and record the anomaly.

## NUFORC UFO Reporting Center Upgrade

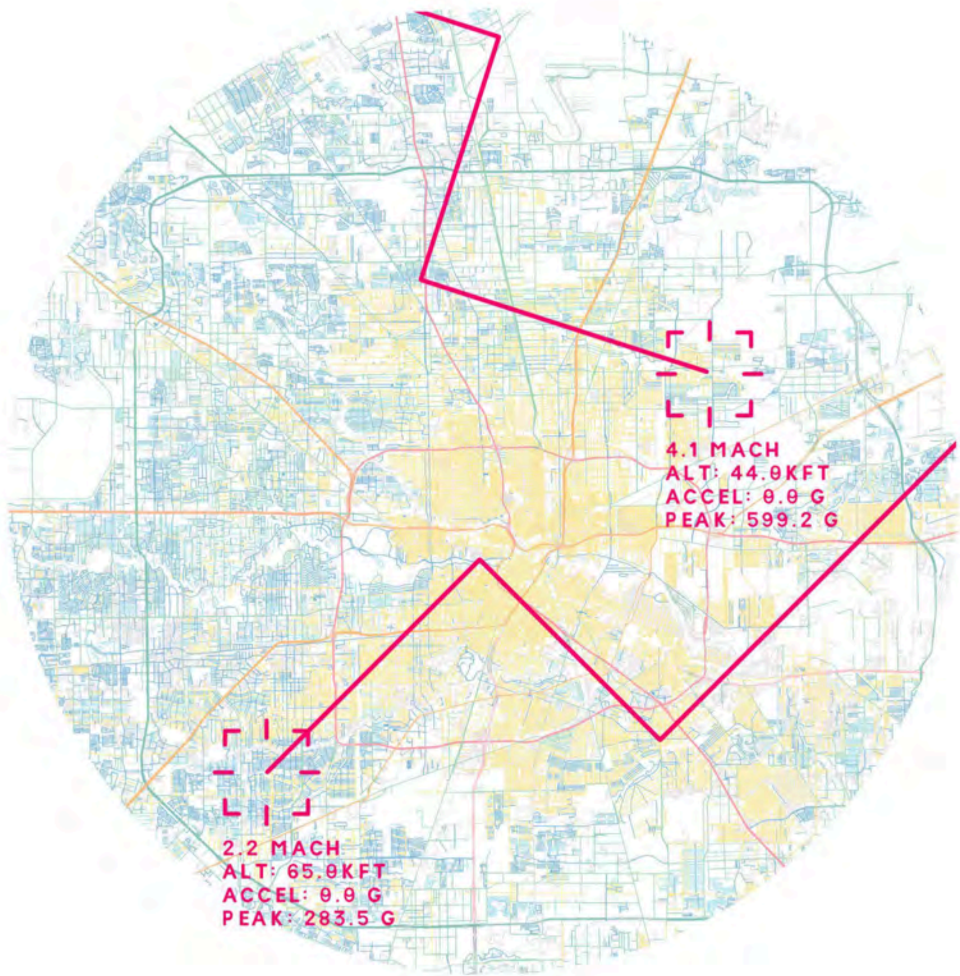
The National UFO Reporting Center will undergo a significant restructuring and modernization while maintaining the integrity that the field has come to expect. It will continue as a trusted centralized destination for the data gathered by the Skywitness network. NUFORC was established in 1974 and has operated a 24-hour UFO reporting hotline since then. Throughout five decades NUFORC has ensured the anonymity of UFO witnesses while gathering more than 170,000 reports of UFO sightings. The website and hotline are well known by law enforcement agencies, Federal Aviation Administration Air Route Traffic Control Centers and flight service stations, National Weather Service offices, military facilities, NASA, and 911 emergency dispatch centers across the United States and many parts of Canada. These agencies routinely direct calls they receive regarding possible UFO sightings to NUFORC.

Upgrades to NUFORC will include appending UFO records with AI-generated summaries that include metadata in a consistent, searchable format. Advanced search tools will be added to allow the records to be more easily accessed. NUFORC will be modified with an application programming interface (API) to accept UFO reports from the Skywitness app and others. The new API will help establish consistent data and location formats to aid in searchability, as well as helping users include more relevant data in their reports. NUFORC will be upgraded to include an extensive historical database of newspaper and magazine articles and associated search tools.

Modernization will generate policies and procedures for operations; establish the infrastructure to allow an expanded volunteer corps to intake UFO reports and organize an investigative branch of volunteers. Fundraising events will become formalized; a business model for sustained operations will emerge; and public and partner outreach will expand. Skywitness will become the nation’s pathway of choice for UFO reporting and civic disclosure.

An outcome of this work will be a Skywitness network that not only detects anomalous aircraft automatically and with data of scientific quality, but also provides modern tools for UFO reporting and analysis. By integrating and upgrading NUFORC, Skywitness will provide an effective national-scale, public-driven and modern platform for UFO disclosure.

The Skywitness interface on the NUFORC website will display a map that shows the motion of an anomalous object: Its velocity, altitude, range and kinematics.




*Mock active Skywitness sensor map.*
*Modified base map of Houston by Erin Davis, erdavis.com.*

Globally, Skywitness participants will be able to access this map and its real-time animations of anomalous objects, sharing the experience of collaborative civic disclosure and strengthening the community of civilian researchers and witnesses.

Skywitness will continue the legacy of NUFORC as a UFO reporting center while improving the quality of machine-captured sighting data and the manual reporting gateway. Data captured by Skywitness radar and photos taken with the app will automatically enter the NUFORC reporting archive, while first-hand reports will be submitted via the mobile app. The virtual NUFORC reporting path will be simple to navigate.

| Skywitness Passive Radar | Skywitness Mobile App | NUFORC Database |
|---|---|---|
| Kinematic Tracks | Kinematic Tracks | Integration |
| +/- Mach 6 Velocities | Optical Triangulation | Major Upgrades: |
| +/- 2700 G's Acceleration | Citizen Deployed | • Search Tools |
| Citizen Network | Cryptographic Authentication | • Standardization |
| 30 km Mesh Spacing | Multi-Sensor Corroboration | • Historical Database |
| 10,000 Sites | Automatic Report Vetting | • AI Summary |
| Nationwide Coverage | NUFORC Report Gateway | • AI Automation |
| Plug-n-Play | | Sustainable Operation |
| Real-time Display | | Volunteer Pool |
| Server Network | | Investigation Arm |

*An overview of Skywitness.*

The simple and inexpensive Skywitness passive radar receivers will enable a dense network across a larger geographic area and empower public engagement. Complex, observatory-grade receivers would not be affordable or widely adopted. Cell phones are a ubiquitous high technology resource for UFO reporting and data collection with the Skywitness app. Skywitness is the ideal model for an accessible, economical nationwide UFO disclosure network.

Skywitness gives everyone a way to be a part of the adventure. As a resource that examines the skies from many locations, it demonstrates the exponential power of crowdsourcing. In the NASA Unidentified Anomalous Phenomena Independent Study Team report released in September 2023, one conclusion was the recommendation "that NASA explore the viability of developing or acquiring a crowdsourcing system, such as open-source smartphone-based apps, to gather imaging data and other smartphone sensor data from multiple citizen observers as part of a wider effort to more systematically gather public UAP reports." Even NASA recognizes how powerful this kind of information-gathering can be.

The foundation of Skywitness is radar technology that has existed for decades. Other existing technologies bring Skywitness to life, too, but require professional designing that's specific to Skywitness. These include the physical engineering of the radar receivers and their electronic beam-steering antenna; an algorithm for signal filtering and processing of large amounts of data; and creating a user interface — the animated map that displays information about objects that Skywitness finds. An associated mobile app will leverage Skywitness data to give Skywitness participants a heads-up so they can be ready to capture video of approaching anomalous objects - the coveted 'multi-sensor data' that scientists seek.

These next steps involve technologies that are already established, but require the labor of specialized technicians like mechanical and software engineers. Philanthropic or grant support is needed to make Skywitness complete, with inexpensive radar receivers, centralized data processing, and a strategy for sustaining the network of privately-owned Skywitness receivers. **If you have capacity to support this important project, please contact Mitch Randall at mitchrandall@ascendantai.com.**

See a video about the capabilities of Skywitness at https://youtu.be/fb2i9wfc4RM. For a technical description of Skywitness, see the paper Skywatch: A Passive Multistatic Radar Network for the Measurement of Object Position and Velocity,' below. (Note: Skywitness was previously known as 'Skywatch.')

# Who Skywitness Serves

For many decades, evidence has been surfacing that we are not alone on this planet. Throughout modern times, flying craft have been witnessed defying the laws of nature. They don't have obvious engines or even wings; they hover, accelerate or change direction instantly and fly at speeds that are faster than any airplanes ever made. Whatever these flying objects might be, they're up there. Skywitness serves anyone curious about the mystery of what these are, where they came from, and why they're here.

These unidentified flying objects have flown fast and surprisingly close to military planes and appeared in so many numbers they've made the skies unsafe for pilots. The community of responsible, experienced aviators is now seeking the same answers about what these 'unidentified anomalous phenomena' are. Skywitness will help make America's skies safer.

Skywitness identifies fast-moving objects in the air, including falling objects like meteors. Astronomers and other scientists can follow the speed and direction of meteors more easily than ever before, giving them an even better chance of recovering rocks from space that hit the ground. Data about meteors that explode in the air will be recorded, too.

Beyond the UFO community, pilots, and scientists, Skywitness benefits everyone. It's a citizen-organized project that shows off the best qualities of an independent-thinking, freedom-loving country: Our skillful pursuit of knowledge and cooperation to achieve great things, and our bold willingness to write the next chapter of the human story. Without standing by for official answers, we can accomplish civic disclosure.

# The Impact of Skywitness

Skywitness will confirm the existence of things that are not made by humans. It will give humanity a bigger universe to explore — one filled with stories that we have yet to learn and intelligences to introduce ourselves to. Throughout our history we have wondered whether we are alone. We can now move beyond our imagination into an era in which science — and a spirit of mutual alliance and determination — delivers this answer to all.

We don't know the impact this discovery will have on society, the economy, or our international relations. But we can share the conviction that humanity is curious, resilient, and always leaning into a future where our worldview is expanding. Humanity has sought, forever, to create something better for itself; we recognize in ourselves a need for understanding, an optimism that it's in reach, and the imperative to use this knowledge to improve the lives of our societies, worldwide. The strength of our intellect, relationships, and capacity for change is always growing. NUFORC Skywitness will express these strengths, pointing us toward a new exotic and potentially wondrous reality.

# History

The concept of passive radar for UFO detection was originally proposed by Peter Davenport, Director of the National UFO Reporting Center (NUFORC) since 1994. Davenport proposed that UFOs could be identified by a network of passive radar receivers.

Davenport described how passive radar is economical and does not require technical acumen to operate within a network like Skywitness. He noted that it is a tool for detecting fast-moving targets, and targets at large distances. Construction of a passive radar receiver requires no government license and it can be operated almost anywhere. Not only is passive radar an easy path to monitoring airspace for UFOs, but it has been implemented over and over again by agencies like the U.S. Navy, U.S. Air Force, and U.S. Space Command. An early commercial passive radar system, Lockheed-Martin's 'Silent Sentry,' was announced in 1998. Technologies have improved since then and development of a consumer version of the technology is now practical. Davenport's 2004 presentation, 'Using Multistatic Passive Radar for Real-Time Detection of UFO's in the Near-Earth Environment' is below.

Skywitness is an implementation of Davenport's concept, led by Mitch Randall, an expert in radar, artificial intelligence, machine vision, deep learning, neural networks, and more. Mitch is an inventor, researcher and entrepreneur, responsible for the design of multiple radar systems that set new international standards. His designs are integral to radar systems operated by the National Center for Atmospheric Research, NASA, and the National Oceanic and Atmospheric Administration. He pioneered wireless charging and software defined radio receivers and his work was used in the development of the 5G cell phone network. He is now CEO of Ascendant Artificial Intelligence, serving customers from around the world.


*A Doppler on Wheels 'DOW-1' storm-chasing radar truck in the 1990's built as a collaboration between the National Center for Atmospheric Research and University of Oklahoma. Randall innovated a software Dopplerizer scheme enabled by the PIRAQ data* *system that allowed the magnetron weather radar to sense Doppler. This was later adopted by the greater weather radar industry.*

# Team Capabilities

Mitch Randall, (MSEE 1989, MS Phys 2000), began building scientific instrumentation and research radars in 1984. He joined the National Center for Atmospheric Research (NCAR) in 1989 and was responsible for the design of the receiver/exciter for the Electra Doppler Radar (ELDORA) dual-Doppler airborne radar used for scientific weather research. Randall pioneered the modern Software Defined Radio (SDR) receiver with his patented PC Radar Acquisition( PIRAQ) and Versa Module Eurocard (VME) Radar Acquisition (VIRAQ) digital radar receivers. These and other of his inventions were installed in numerous NCAR, NASA, and NOAA radars. He developed a software-based method for obtaining Doppler from incoherent magnetron radars and applied these technologies to create the Doppler On Wheels (DOW) tornado-chasing trucks, upon which was formed the Center for Severe Weather Research in Boulder, CO. His digital receiver and Dopplerization technologies became the industry standard for the meteorological weather radar community in the mid 1990s. Working for the National Institute of Standards and Technology (NIST) in 2010, Randall developed a high-resolution, Doppler millimeter wave (30 GHz, 70 GHz, and 90 GHz) channel sounder to characterize real-world cell communications, which has been used to develop today’s 5G networks.

*Randall architected the Doppler on Wheels 'DOW-5' rapid scan storm-chasing radar truck in the early 2000's built as a collaboration between the National Center for Atmospheric Research and the Center for Severe Weather Research. The system employed his digital receiver system, data acquisition system, and frequency-steered X-band slotted waveguide phased-array antenna.*

Randall co-founded Binet in the early 1990s to bring bistatic 3D velocity measurement to research weather radars all over the world, including the NCAR system in Boulder, Germany's DLR, and national systems in Japan and China. Randall cofounded, with NCAR, the Advanced Radar Corporation in the early 2000s to commercialize these innovations for applications in the commercial weather radar market. In 2005 Randall cofounded WildCharge to commercialize his wireless charging technology for use with cell phones, laptops, power tools, etc., licensed by Duracell. His invention was featured in TIME magazine's 'Best Inventions of 2007' issue. In 2012 Randall licensed a robot toy bug currently available worldwide.

In 2018 Randall co-founded Ascendant Artificial Intelligence (AAI) and is currently delivering custom AI solutions to global customers. In 2021 Randall became a Research Team member of Harvard's Galileo Project, where he developed the proof of concept of a Skywitness receiver. Randall is the lead author of the paper describing the

Skywitness receiver for the Galileo Project in the Journal of Astronomical Instrumentation.

*Mitch Randall.*

AAI was co-founded by Randall with Robert Banks and David LeFlore. AAI is primarily engaged in computer vision and AI related consumer electronics, embedded design, and AI web services development. In 2023 AAI launched its first consumer app based on generative AI. The company utilizes in-house expertise augmented by outsourcing to keep overhead low and agility and capabilities high.

AAI president and cofounder Robbie Banks, BSEE, has a strong background in consumer electronics, expertise in AI, and is well versed in consumer electronics and medical embedded design, manufacturing, and operations. Banks is an entrepreneur and inventor, and well skilled at defining and managing outsourced talent.

AAI CIO and cofounder David Leflore has a strong background in AI including enterprise web services, backend development, web APIs and UX design. Leflore is a successful entrepreneur having recently sold his previous SEO services company. Leflore brings important skills in server networks, app APIs, outsourcing, and web ecosystem business acumen.

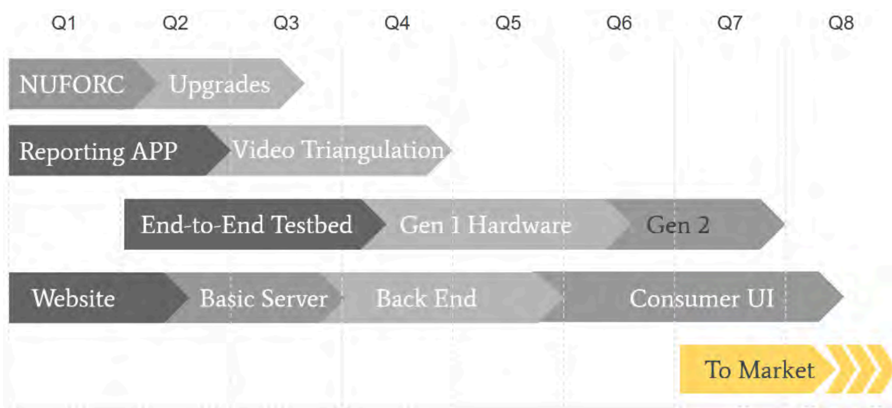
The work outlined to create Skywitness is well within AAI capabilities. The AAI team will utilize its core competencies with specific outsourcing to complete Skywitness development within two years. This includes the set-up of manufacturing, distribution, and support functions to sustain consumer sales on an ongoing basis. This also includes the business model to allow the web services and data management to be indefinitely self-sustaining.

# Budget

| | **Year 1** | **Year 2** | **Total** |
|---|---|---|---|
| Grant Writer | $60,000.00 | $60,000.00 | $120,000.00 |
| Operational Support | $25,000.00 | $25,000.00 | $50,000.00 |
| NUFORC Integration | $500,000.00 | | $500,000.00 |
| NUFORC Director | $100,000.00 | $100,000.00 | $200,000.00 |
| NUFORC Upgrades | $40,000.00 | | $40,000.00 |
| Legal | $40,000.00 | $30,000.00 | $70,000.00 |
| App; Small Network Receiver; Automatic Antenna; Localization Servers; Consumer Receiver | $1,240,000 | $1,280,000 | $2,520,000 |
| | $2,005,000 | $1,495,000.00 | **$3,500,000.00** |

# Timeline

With $3.5M raised, the work to establish Skywitness will begin its 24-month duration. The funds will acquire NUFORC and Skywitness will be established as an initiative of NUFORC. In the first year, funds will be distributed for three positions: The NUFORC director, a grant writer, and a contract administrator. Funds will be distributed to begin planned upgrades to NUFORC including app-based reporting functions. Basic features of a mobile app and upgrades will be available in six months. Full functionality will be available within twelve months. Work will begin on the radar receiver, starting with the deployment of a mock-up network serving as a testbed. The various deliverables and their delivery schedule are below.




Within two years Skywitness will produce a consumer-deployable radar system. At the end of the 24-month development period, Skywitness will have developed a ready-to-manufacture low cost passive radar receiver product; a server infrastructure to assemble and process data as it arrives from across the network of receivers; manufacturing and distribution contracts, and a maintenance and support program to serve receiver owners. Outreach and promotion of sales will begin. The passive radar product will go on sale and consumers will be able to purchase it and begin deploying it across the nation. The data will be available to the public through web servers in the form of an animated map; the public will see data from the network in real time. The app will be a reporting platform for eyewitnesses and sightings will be uploaded to the public records of NUFORC.

# Bona Fides

Early support and endorsement of Skywitness came from [The Galileo Project] for the Systematic Scientific Search for Evidence of Extraterrestrial Technological Artifacts at the Harvard-Smithsonian Center for Astrophysics at Harvard University. The Galileo Project, like Skywitness, has a goal of discovering and revealing extraterrestrial technology through transparent, scientifically valid research. The Galileo Project hosted a proof-of-concept study of Skywitness technology on the Harvard campus.

# Press

Matt Ford interviews Mitch Randall on The Good Trouble Show
https://youtu.be/fLjDDS6m9Cs?si=-eNAt8hVhoW4mmiS

Mitch Randall interviewed by Cheryll Jones on Coast to Coast AM, September 28, 2023
https://youtu.be/gOBF37LJIUk

Mitch Randall provides detail about the Skywitness UFO Radar Network in an interview with Tim Ventura https://youtu.be/jPffL1YFtrU?si=2MLe1ejRd-Um7nh5

Skywitness at the Alternative Propulsion Engineering Conference https://youtu.be/ozYbZOyO5Eo?si=z-eaE28luSuF_YD0

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OPEN ACCESS
Journal of Astronomical Instrumentation, Vol. 12, No. 1 (2023) 2340004 (14 pages)

DOI: 10.1142/S2251171723400044





# SkyWatch: A Passive Multistatic Radar Network for the Measurement of Object Position and Velocity

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*Received August 2, 2022; Revised December 2, 2022; Accepted December 2, 2022; Published April 18, 2023*

Quantitative three-dimensional (3D) position and velocity estimates obtained by passive radar will assist the Galileo Project in the detection and classification of aerial objects by providing critical measurements of range, location, and kinematics. These parameters will be combined with those derived from the Project's suite of electromagnetic sensors and used to separate known aerial objects from those exhibiting anomalous kinematics. SkyWatch, a passive multistatic radar system based on commercial broadcast FM radio transmitters of opportunity, is a network of receivers spaced at geographical scales that enables estimation of the 3D position and velocity time series of objects at altitudes up to 80 km, horizontal distances up to 150 km, and at velocities to $\pm 2$ km/s ($\pm 6$ Mach). The receivers are designed to collect useful data in a variety of environments varying by terrain, transmitter power, relative transmitter distance, adjacent channel strength, etc. In some cases, the direct signal from the transmitter may be large enough to be used as the reference with which the echoes are correlated. In other cases, the direct signal may be weak or absent, in which case a reference is communicated to the receiver from another network node via the internet for echo correlation. Various techniques are discussed specific to the two modes of operation and a hybrid mode. Delay and Doppler data are sent via internet to a central server where triangulation is used to deduce time series of 3D positions and velocities. A multiple receiver (multistatic) radar experiment is undergoing Phase 1 testing, with several receivers placed at various distances around the Harvard–Smithsonian Center for Astrophysics (CfA), to validate full 3D position and velocity recovery. The experimental multistatic system intermittently records raw data for later processing to aid development. The results of the multistatic experiment will inform the design of a compact, economical receiver intended for deployment in a large-scale, mass-deployed mesh network. Such a network would greatly increase the probability of detecting and recording the movements of aerial objects with anomalous kinematics suggestive of Unidentified Aerial Phenomena (UAP).

*Keywords*: Unidentified aerial phenomena; multistatic passive radar.

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## 1. Introduction

The Galileo Project (the Project) is developing and deploying a suite of field instruments in support of the scientific investigation of Unidentified Aerial Phenomena (UAP) (Watters, 2023). One of these instruments is SkyWatch, a multistatic network of passive radars based on commercial FM radio stations as transmitters of opportunity. This application of passive radar to UAP was first proposed by Davenport (1999) and later refined (Davenport, 2004). The primary measurement products produced by the instrument are bistatic range, radar cross-section (RCS), three-dimensional (3D) position, and velocity, as functions of time. These values can be derived for each one of multiple simultaneous objects within the detection volume. The SkyWatch radar detects FM-band reflective aerial objects horizon-to-horizon, at ranges up to 150 km, altitudes up to 80 km, at up to 15 times per second. The instrument is software-defined to trade off operating parameters. The SkyWatch radar complements the Galileo Project's suite of optical, infrared, acoustic, radio spectrum, magnetic field, and particle detecting instruments by providing an independent estimate of the range, location, velocity, and acceleration of multiple, simultaneous aerial objects in a comparatively large detection volume. Descriptions of the anomalous kinematics exhibited by UAP that appear to demonstrate advanced technology, including high velocities, high accelerations, abrupt maneuvers, and remaining stationary in high winds at high altitude (ODNI, 2021), make the parameters measured by SkyWatch particularly relevant to the Project.

Section 2 gives an overview of the overall network concept. In Sec. 3, we discuss the SkyWatch data products and their uses, including in conjunction with the Project's other instruments. The basic principle of operation of a single bistatic radar receiver is derived in Sec. 4. We also discuss the performance of a single radar receiver in Sec. 4. Section 5 addresses receiver performance and identifies the primary engineering challenges. The diverse geography anticipated drives the requirement for the various receiver modes discussed in Sec. 6. Section 7 describes the Phase 1 testing of the radar network being carried out at five secondary sites near the Harvard–Smithsonian Center for Astrophysics (CfA) in Cambridge, MA, USA, where the Phase 1 primary observatory-class instrument suite site is located. In Sec. 8, we discuss the next steps toward achieving the end goal of an economical, mass-deployable system with nation-scale coverage.

## 2. Overview of the SkyWatch Passive Multistatic Radar Network Concept

SkyWatch consists of a set of passive radar receivers connected and controlled by a centralized server to form a multistatic radar network, as shown in simplified form in Fig. 1. Commercial broadcast FM radio stations that transmit in the range 88–108 MHz ($\lambda = 3.4$–$2.8$ m, respectively) are used as the transmitters of opportunity. As will be detailed below, each receiver must obtain a sample of the transmit waveform (the reference signal) in order to process echo returns. This can be derived either by receiving the transmit signal directly or, if that is prevented by the geography, obtaining the reference via the internet from a receiver node closer to the transmitter.

The centralized server controls the operational parameters at each receiver node, such as their mode of operation, the reference transmitter chosen, and integration time. The server also facilitates the routing of reference signals to receivers as needed. Each receiver node computes the received power, range, and Doppler shift of the echoes it receives from objects in the airspace. That information is recorded locally and is also transmitted to the central server. The central server performs correspondence processing to relate detections in one radar receiver to detections in another. Grouped detections are then processed by an Extended Kalman Filter (EKF) to estimate 3D positions and velocities of scatterers at regular intervals in near

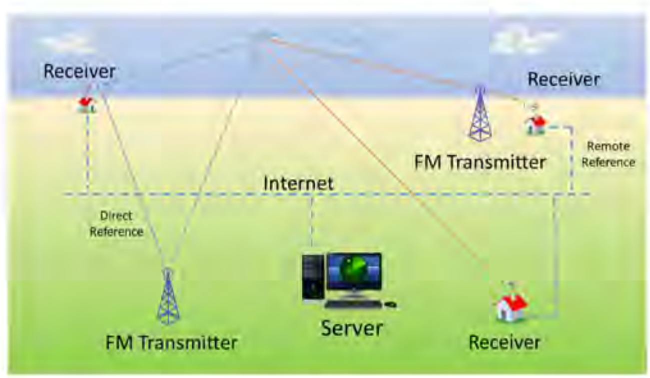


Fig. 1. (Color online) The SkyWatch passive multistatic radar network consists of two or more radar receiver nodes, one or more commercial FM broadcast transmitters of opportunity, and a centralized server. Receiver nodes are connected via the internet to a server. The server controls the operational modes of the receivers, routes reference data, and processes final triangulated results in real time.

real-time. These data are used in both real-time, for detection of objects and flagging of anomalous kinematics, and recorded for later use in combination with data from the rest of the Project's instrument suite, for more detailed object discrimination.

## 3. SkyWatch Data Products and their Uses

### 3.1. *Object position*

Information about an object's 3D location in geographic space derived from SkyWatch can contribute to the Project's target acquisition system. Real-time position information can be used in conjunction with that from wide-field cameras to assist in aiming the narrow-field telescope at targets of interest. In Phase 1, a pan-tilt Beacon 8 security camera (8 MP) is used as the tracking telescope; in Phase 2, a higher resolution mirror-tracking telescope system will be added (Watters, 2023). Once an object is within the field of view of a narrow-field telescope, the camera will autonomously track the object; SkyWatch position information will then assist in maintaining tracking if the target is momentarily obscured by clouds. SkyWatch position information can also assist the wide-field camera AI algorithms to distinguish targets from noise.

Beyond assisting narrow field instruments in tracking objects, the position information provided by SkyWatch shall further assist the interpretation of any objects imaged by narrow-field instruments. The range information is crucial in allowing a single telescope's pointing angle and image data to provide primary independent measurement of physical dimensions, positions, velocity, and acceleration.

In the following, although we assume 3D positions and velocities are derived by combining outputs of multiple, non-colocated SkyWatch receivers, 3D positions and velocities can be determined in other ways. Individual receiver data can be integrated with ray-tracing from a single co-temporal, narrow-field instrument to independently deduce 3D position.

### 3.2. *Object velocity*

The SkyWatch radar 3D velocity information is unique in that it is measured directly by Doppler shift, rather than by finite difference of position. As a result, these estimates are unusually robust and accurate from low speeds up to 2 km/s (5.8 Mach), which exceeds the performance envelope of many known phenomena. Velocity estimates can serve as an input to refine the tracking of narrow-field instruments with pan-tilt servo loops. Velocity information can be used to estimate future position and thus can provide advanced alert of objects that may be on course to enter the operational range of the other instruments. A simple upper velocity threshold can also be used to indicate an object of interest whose flight characteristics mark it as anomalous, possibly representing a UAP, thus marking it out for targeting with the tracking telescope. As well, a threshold set to detect an object with zero velocity (i.e. not drifting with the wind) can provide another indication of an object of interest.

### 3.3. *Object kinematics*

Of primary utility is the instrument's ability to measure rapid time series of 3D object position and velocity (up to 15 samples per second). Such time series, referred to as tracks, are critically important for determining the kinematics that could distinguish anomalous object behavior from prosaic behavior.

The direct measurement of velocity allows the inference of acceleration by first-order finite difference, whereas second-order finite difference is required with position-only measurements resulting in much greater uncertainty. Acceleration is a key parameter that relates directly to the performance envelope of known propulsion technologies and promises to play an important role in distinguishing and quantifying an object's aerial behavior as anomalous and classifiable as a UAP. Acceleration can be estimated in real time and thresholded to serve as an alarm to other instruments of unusual activity and marking an object of interest for the tracking telescope.

### 3.4. *Object reflections*

Radar echoes in the operating frequency range of SkyWatch are to be expected from visible craft such as drones, rockets, other vehicles, but are not to be expected from visible atmospheric phenomena such as clouds and mirages (Watters, 2023). By comparing the Project's optical detections with SkyWatch's radar results in the same location, discrepancies in expected correspondence between the two can help identify anomalous conditions and objects of interest for the targeting telescope.

### 3.5. *Detection volume*

The SkyWatch object detection range of 150 km is approximately an order of magnitude greater than that of the Project's wide-field optical and IR cameras (Watters, 2023). As such, an important feature of SkyWatch is its large detection volume per receiver, even in heavy cloud cover or fog. SkyWatch-derived object positions can provide target acquisition information from beyond the operational scope of the wide-field cameras. Furthermore, a relatively sparse SkyWatch network can cover a large area, even on a national scale. The probability of detecting UAP is expected to increase roughly proportionally to detection volume (Poher & Vallee, 1975). SkyWatch's order of magnitude greater detection range over wide-field optical and infrared cameras translates to about three orders of magnitude increased probability of detecting the presumably rare UAP we seek to study.

## 4. Passive Radar Receiver Principle of Operation

Commercial FM radio stations transmit a sine wave of constant amplitude but whose frequency varies according to the content being broadcast (Federal Communications Commission, 2006). Normalized, the transmit signal $f(t)$ is represented as

$$f(t) = e^{i(\omega t + \phi(t))}, \tag{1}$$

where $\omega$ is the carrier frequency and $\phi(t)$ is the instantaneous additive phase due to the frequency modulation by the source material. For the purposes of this work we shall refer to a normalized replica of the transmit signal as the reference. The transmitted signal reaches objects in the sky and scatters in all directions. The scattered signal that is received is scaled by a constant factor $A$ in amplitude and phase, and delayed by the transit time $\delta$ from the transmitter to the object and then to the receiver. We represent this received echo $g(t)$ as

$$g(t) = Af(t-\delta) = Ae^{i((t-\delta)\omega + \phi(t-\delta))}. \tag{2}$$

We now multiply the received echo $g(t)$ by $f^*(t-\tau)$, the complex conjugate of the reference delayed by an arbitrary time $\tau$. If the reference delay $\tau$ is equal to the scattered signal delay $\delta$, the product $h(t)$ will be a coherent signal

$$\begin{aligned} h(t) &= g(t)f^*(t-\tau)|_{\tau=\delta} \\ &= Ae^{i((t-\delta)\omega+\phi(t-\delta))}e^{-i((t-\tau)\omega+\phi(t-\tau))}|_{\tau=\delta} = A. \end{aligned} \tag{3}$$

If motion of the object gives rise to an additive received-echo path length difference $\Delta r$, and we again set the reference delay $\tau$ equal to the nominal received echo delay $\delta$, conjugate multiplication yields

$$\begin{aligned} h(t) &= Ae^{i((t-\delta-\frac{1}{c}\Delta r)\omega+\phi(t-\delta-\frac{1}{c}\Delta r))}e^{-i((t-\delta)\omega+\phi(t-\delta))} \\ &= Ae^{-i\omega\frac{1}{c}\Delta r}e^{i(\phi(t-\delta-\frac{1}{c}\Delta r)-\phi(t-\delta))}. \end{aligned} \tag{4}$$

Provided the modulation $\phi(t)$ is relatively unchanged over a small change in delay time $\frac{1}{c}\Delta r \ll 1$ ms, the second term reduces to

$$e^{i(\phi(t-\delta-\frac{1}{c}\Delta r)-\phi(t-\delta))} \approx 1. \tag{5}$$

Thus, we see that when multiplying the conjugate of the reference delayed by $\tau$ equal to the nominal delay $\delta$ of a received echo, a small change in received echo path length results in a change in the phase of the product as

$$h(t) \approx Ae^{-i\omega\frac{1}{c}\Delta r}. \tag{6}$$

The phase of $h(t)$ advances by $2\pi$ for each change in wavelength ($\lambda = \frac{2\pi c}{\omega} \approx 3\,\mathrm{m}$) of received echo path length difference $\Delta r$. In this way, the product formed with the conjugate of the reference delayed by the nominal delay of the received echo of a scatterer in motion produces a corresponding Doppler signature.

We now introduce the concept of bistatic range defined as the echo path length from transmitter to scatterer to receiver minus the direct path length from transmitter to receiver $R_t + R_r - R_d$. With this definition, the minimum bistatic range of any scatterer is zero, corresponding to a scatterer located somewhere along the line between the transmitter and the receiver.

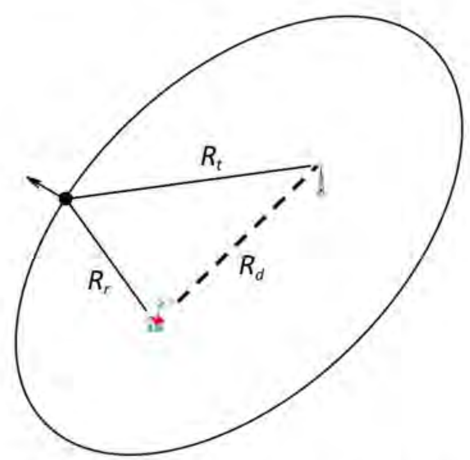


Fig. 2. (Color online) A surface of constant bistatic range forms an ellipsoid (an ellipse in cross-section). A change in path length represents a scatterer motion perpendicular to this surface.

A scatterer of a particular positive bistatic range lies on an ellipsoidal surface as shown in cross-section in Fig. 2. The Doppler frequency of received echoes relates to a constant change in the bistatic range with time; an object velocity component in the direction normal to the ellipsoidal surface of constant bistatic range.

If the reference delay does not match the transit delay ($\tau \neq \delta$), the signal is

$$h(t) = g(t)f^*(t-\tau)$$
$$= Ae^{i((t-\delta)\omega+\phi(t-\delta))}e^{-i((t-\tau)\omega+\phi(t-\tau))} \quad (7)$$
$$= Ae^{i(\tau-\delta)\omega}e^{i(\phi(t-\delta)-\phi(t-\tau))}. \quad (8)$$

We make a change of variables $\gamma = \tau - \delta$, and integrate over an interval $T$

$$\hat{h} = \frac{Ae^{i\gamma\omega}}{T}\int_a^{a+T} e^{i\phi(t)}e^{-i\phi(t-\gamma)}dt. \quad (9)$$

For typical FM radio content, $e^{i\phi(t)}$ behaves much like a unit vector with uniformly distributed random angle (Lauri *et al.*, 2007). Thus, its statistics average like a random walk (Pathria, 1995) so that

$$|\hat{h}| \approx \frac{|A|}{\sqrt{T}}. \quad (10)$$

Suppose that a linear combination of two echoes of amplitude $A_1$ and $A_2$ and of different delays is present in the received signal and we form the product with the conjugate of the reference at a delay $\tau$ that matches the nominal delay $\delta_1$ of the first echo. The resulting product $h(t)$ will contain the linear combination of a coherent signal $A_1e^{-i\omega\frac{1}{c}\Delta r}$ resulting from the first echo, plus a noise-like signal of amplitude $A_2$ from the second echo. We can integrate $h(t)$ over an interval $T$ in order to reduce the magnitude of the noise-like signal to $\frac{|A_2|}{\sqrt{T}}$. The greater the integration interval, the greater the ability to distinguish echoes of differing delays expressed in decibels as $10\log_{10}(N)$, where $N$ is the number of independent samples integrated. Herein, we refer to the process of conjugate multiplication followed by integration as correlation at delay $\tau$.

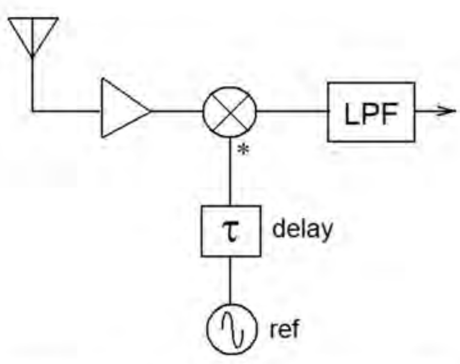


Fig. 3. (Color online) Correlative range processing where the received signal is multiplied by the complex conjugate of a replica of the transmit signal delayed by time $\tau$. The product is passed through a low-pass filter to perform the averaging needed to sufficiently resolve echoes in bistatic range.

We construct a practical realization of our correlation process by multiplying the received echo by a delayed reference and passing the result through a low-pass filter (Hall, 1995) as shown in Fig. 3. For each delay $\tau$, we can determine the received amplitude and Doppler shift corresponding to the implied bistatic range. Assuming a sampled data system, software can step through a span of delays from zero to some maximum and determine the amplitude and Doppler shifts for each of several delays. When triangulated with other receivers or located along a ray by an imager such as a camera, these delays correspond to object ranges and the Doppler frequency shifts correspond to their velocities.

## 5. Receiver Performance

We now wish to explore receiver sensitivity. To compute the received power from a scatterer in the bistatic case, we break the usual radar equation (Skolnik, 2008) into two factors as

$$P_r = \frac{P_tG_tG_r\lambda^2\sigma}{(4\pi)^3R_t^2R_r^2} = \frac{P_tG_tG_r\lambda^2}{(4\pi)^2R_t^2}\frac{\sigma}{4\pi R_r^2}, \quad (11)$$

where $R_t$ is the distance from the transmitter to the scatterer, $R_r$ is the distance from the receiver to the scatterer, $P_r$ is the received power, $P_t$ is the transmitted power, $G_t$ and $G_r$ are the transmit and receive antenna gains, respectively, $\lambda$ is the wavelength, and $\sigma$ is the RCS (Knott *et al.*, 1993) in square meters. We recognize the first factor as the Friis transmission loss over a distance $R_t$ (Stutzman & Thiele, 1998), and the second factor as the geometric loss of an ideal isotropic scatterer over a distance $R_r$. Using the value of 15 dBsm for the RCS of a typical single-engine light aircraft (Patriarche *et al.*, 1976), a transmitter Effective Isotropic Radiated Power (EIRP) $= P_tG_t$ of 100 kW, a wavelength of 3 m, a receive antenna gain of 2 dBi, and a distance $R_t = R_r = 55$ km, we compute an expected receive signal power of $-116$ dBm. Setting $R_t = R_r = 55$ km defines the Signal-to-Noise Ratio (SNR) for the general case regardless of the exact configuration of transmitter, scatterer, and receiver. Assuming a receiver noise figure of 1 dB and a noise bandwidth of 200 kHz, the thermal noise floor is about −120 dBm. Using digital averaging in the receiver to reduce the sample rate to 15 samples/second would afford about 41 dB of processing gain, so that the resulting SNR of the detected signal would be around 45 dB. As we shall see, this favorable result is available only in special cases where the direct transmit signal is blocked by terrain or structures. In practice, sample rates above 15 samples/second are generally impractical, because the associated integration time is too short to result in an acceptable output SNR.

A takeaway from the derivations above regarding correlation is that an echo corresponding to a particular delay $\delta \neq \tau$ will be randomized into a noise-like signal when correlated with the reference as delayed by $\tau$. In many cases, this noise-like signal can be many times greater than the receiver's thermal noise floor. The most troublesome example of a signal of this kind comes directly from the transmitter to the receiver. The received power of the direct signal can be estimated by the Friis transmission loss formula

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 R_d^2}, \tag{12}$$

which is just the first factor of Eq. (11) where $R_d$ is the direct distance from the receiver to the transmitter. In this case, the expected receive power is about −25 dBm. When this signal is correlated against the reference at any other delay, its phase will be randomized into a noise-like signal about 95 dB greater than the thermal noise floor. To generalize this result, we see by inspection that when the three distances $R_t$, $R_r$, $R_d$, are of the same order, the ratio of the amplitude of the echo signal and the direct signal is the second factor of Eq. (11):

$$\frac{\sigma}{4\pi R_r^2} \tag{13}$$

and is typically in the range of about −90 dB. Thus, careful attention must be paid to mitigate ground clutter returns and the direct-path signal so that the desired signals can be adequately recovered from their noise-like interference. For environments where the transmitter of opportunity is nearby, and not blocked by terrain, the mitigation of this signal is the primary engineering challenge of the radar receiver.

If we assume that a 10 dB SNR is sufficient, we can work backwards to determine the largest acceptable amount of power the radar can cope with from the direct signal. We do this for the case at hand as a point of reference. Assuming the echo signal power is −116 dBm, we see the noise floor must be no greater than −126 dBm after the processing gain (averaging). For a processing gain of 41 dB, this means the direct signal must not be greater than −85 dBm. If we were to average for 1 s, the processing gain would be 53 dB, corresponding to a tolerable direct signal power of −73 dBm. This means that the direct signal power of −25 dBm must be attenuated by 48 dB. Greater attenuation is required to achieve the same SNR with higher sampling rate.

A prototype of a single SkyWatch receiver was constructed and made to operate based on a direct reference as per the work of Howland et al. (2005). The prototype system uses two antennas. A first antenna is arranged to provide a null substantially directed towards an area of interest, Denver International Airport (DIA), while directing its main lobe toward the transmitter. A second antenna is arranged to direct a reception null at the transmitter while its main lobe is directed toward DIA. The orientation of the antennas for the prototype system was manipulated by mechanical adjustment. The combination of the manually adjusted antennas and the adaptive noise canceller described by Howland et al. (2005) sufficiently mitigated the direct signal so that the system could simultaneously receive dozens of echoes, presumably from aircraft, out to 120 km and greater.

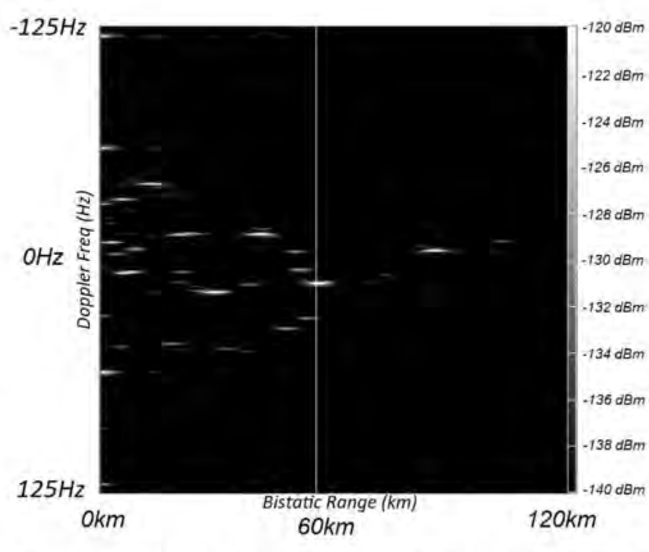


Fig. 4. ARD plot of detections from the prototype SkyWatch receiver located in Boulder Colorado. Detections at the far right indicate objects as far as 120 km in bistatic range.

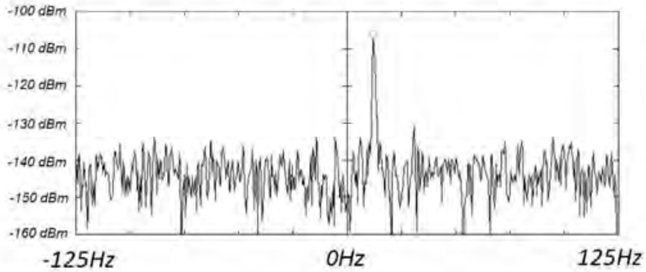


Fig. 5. (Color online) Frequency spectra of the correlation at gate 37 ($\tau = 185\,\mu s$) showing an echo amplitude of $-108$ dBm with a Doppler offset of 24.4 Hz corresponding to the vertical line in Fig. 4.

Each column of pixels in the Amplitude Range Doppler (ARD) plot of Fig. 4 will represent a spectrograph of the low-pass filter output of Fig. 3 computed with unique reference delay $\tau$. A slice of the ARD indicated by the vertical white line of Fig. 4 at a bistatic range of 55 km is shown as the spectrograph of Fig. 5 to demonstrate quantitatively the nature of the processed returns. As can be seen, the echo received from an airplane is about 30 dB above the noise floor with narrow spectral width.

The removal of the direct signal from the receiver has proven to be the greatest engineering challenge associated with the direct reference reception mode. The two primary methods of direct signal mitigation are digital adaptive antenna null steering (Zhenwei, 1984), and adaptive noise canceling. Both of these methods are computationally intensive, to the point of affecting system complexity and cost.

## 6. Receiver Operational Modes

There are two primary operational modes dictated by site and transmitter geography. In one mode, the reference is derived by directly receiving the transmit signal. In a second mode, the reference is provided via internet by another receiver located closer to the transmitter. These modes of operation are required to accommodate the variety of situations expected to be encountered in the mass deployment of a network of receivers.

In the context of mass deployment for mesh systems, it is expected that site selection will more often be dictated by site availability rather than by system performance or desired operation mode. For any given situation, there remain a few system parameters that can be varied in order to optimize results. A first choice is the transmitter of opportunity to be used. It is possible the site could be near an FM transmitter that allows operation in the direct reference mode. Alternatively, there may be no FM station near the site that can support the direct reference mode, in which case a remote reference can be provided from another node via the internet. A third possibility is that the site is located where the receiver could operate in either mode depending on which FM transmitter of opportunity is used. The geography that influences the modes of operation also affects data collection. When the transmitter power is attenuated by the curvature of the Earth, its ability to illuminate low altitude objects is correspondingly diminished. Deployment in a valley can be challenging, because transmitters would likely be located high on the surrounding ridge, giving rise to unfavorable ground clutter issues. In light of the number of choices at hand, the SkyWatch receivers will allow remote control of their variable operation parameters. The centralized server can then find the best configuration by simply cataloging the performance of several combinations of FM transmitters received in the various modes.

### 6.1. *Direct reference mode*

When the power from the direct signal of the transmitter is greater than about 30 dB above the thermal noise floor, the receiver may operate by receiving the direct signal and creating a reference from it as demonstrated by Howland *et al.* (2005). The method relies heavily upon a means of canceling the reference signal from the echo signal using a joint Gradient Adaptive Lattice (GAL) predictor and Normalized Least Means Square (NLMS) adaptive noise canceling filter. The method requires the use of multiple antennas in order to create statistically independent channels (Haykin, 2002), as well as to provide additional attenuation of the direct signal from the transmitter in the echo channel. Digital adaptive null steering is used to maximize the attenuation of the direct signal in the echo channel (Zhang *et al.*, 2011).

### 6.2. *Remote reference mode*

When the power from the direct signal of the transmitter is less than about 30 dB above the thermal noise floor, the receiver may operate by using a reference transmitted from a remote monitor as was demonstrated by the Manastash Ridge passive radar in Washington by Sahr & Lind (1997) and Hansen (1994). In this method, a monitor receiver is located near the transmit antenna and receives the transmit signal with good fidelity. The data is compressed and sent in time-stamped packets via internet to the echo receiver system where range gates are correlatively processed for echo detection. In this mode, there is no need for digital antenna null steering nor adaptive noise canceling. However, this mode requires precise time and frequency synchronization between nodes. The SkyWatch receivers achieve this using GPS disciplined oscillators and 1 pps GPS time stamps marking the packets.

### 6.3. *Hybrid reference mode*

When the direct signal of the transmitter is around 30 dB above the thermal noise floor, the direct signal may be too contaminated with multipath interference to be useful as a reference, and yet the direct signal may be strong enough to limit the detection of smaller objects. The two modes discussed above present very different but not mutually exclusive engineering and design challenges that allow a hybrid mode. In this case, a combination of the two modes can be used to achieve acceptable performance. In this case, a remote reference is used to perform the correlations, but digital antenna null steering and adaptive noise canceling are used to limit the strength of the direct signal to the extent possible. Without good SNR on the reference signal, a great deal of cancellation cannot be expected of adaptive noise cancellation. However, every 1 dB of direct signal cancellation ultimately translates to 1 dB of SNR improvement. So, even 20 dB of direct signal cancellation can bring the system to acceptable performance levels.

## 7. Phase 1 Multistatic Experiment

Fig. 6. (Color online) Initial prototype SkyWatch receiver deployed in the initial multistatic experiment. A three-element, vertically polarized, circular dipole array is used for adaptive null steering and direction-of-arrival interferometry.

Several experimental SkyWatch receivers as shown in Fig. 6 have been installed at secondary sites around the observatory system at the CfA, where the full Galileo Project Phase 1 instrument suite is located as part of a proof-of-concept study. The SkyWatch receivers are designed to use commercial FM broadcast stations as transmitters of opportunity. They employ receivers and vertical dipole antennas capable of receiving signals in the commercial FM band from 88 MHz to 108 MHz at a sample rate of up to 1 Msps. This testing phase will continue for several months. There are many objectives for this phase, including performance validation, testing and evaluation of operation and data processing algorithms, assessment of the utility of the data product, and gaining experience that will inform the design of a future mass-deployable version. This section describes a subset of these objectives, opportunities for development, and areas for improvement and study.

### 7.1. *Geographic configuration*

The system as currently envisioned requires receivers spaced on a geographic scale well outside the perimeter of the primary instrument site at CfA in order to retrieve 3D positions and velocities. Figure 7 shows the placement of six receiver sites and the three chosen transmitters of opportunity. Selection of these sites was based on requirements for power, internet, security, as well as the willingness of cooperative land owners to host sites. Four of the sites are within 30 km of the primary installation while two are located much further (103 and 148 km), nearer distant transmitters.

Three transmitters of opportunity are considered for this experiment: a first transmitter A with an EIRP of 50 kW located generally to the south, a second transmitter B transmitting an EIRP of

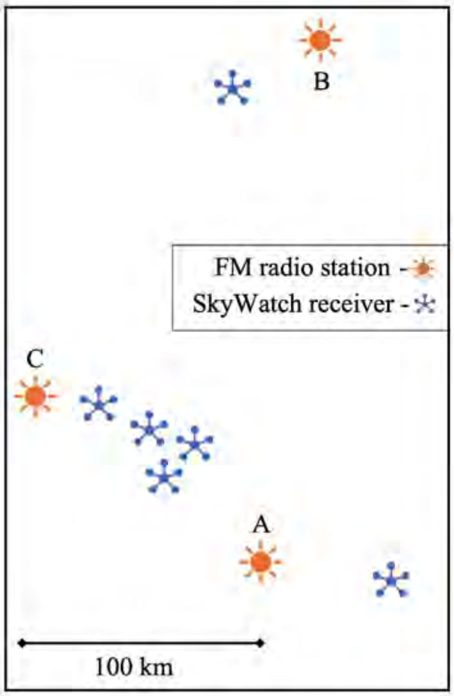


Fig. 7. (Color online) Geographic configuration of Phase 1 SkyWatch receiver deployment showing the relative placement of six radar receiver locations and three FM radio transmitter sites.

100 kW located generally towards the north, and a third transmitter C with an EIRP of 37 kW located generally towards the west. Various combinations of receivers and transmitters can be formed with this configuration. Further, receivers can act as remote reference receivers to support operation of other receivers in remote reference mode. Transmitters at a range of distances and transmit powers were chosen to allow study of pairing permutations. The latitude, longitude, and elevation of receivers is determined using GPS. The latitude, longitude, and elevation of transmitter antennas is determined using satellite imagery and Federal Communications Commission (FCC) data.

## 7.2. *Data collection*

For the Phase 1 system, all receivers intermittently record unprocessed samples to disk. All of the receivers follow the same predetermined schedule of recording for 300 s every 1024 s (about 17 min) synchronized to the same GPS time epochs. The receive frequency is stepped through a list of the three transmitter frequencies at each recording interval so that all receivers are receiving the same frequency at the same time. Each interval generates one file per receiver. With three receiver channels, at the sample rate of 1 Msps and 8-bit in-phase and quadrature (complex) samples, this amounts to a file size of about 1.8 GB per receiver every 17 min. Each receiver is equipped with a 5G telecommunications modem allowing it to establish a high-speed data connection to a server. A background task syncs the local files to the server and then removes them locally. The recording of raw data was chosen as the preferred method for the purpose of development. In this mode, post processing can be done to pair any receiver with any transmitter, and operate in any reference mode, allowing A/B comparisons of operating modes and algorithms with invaluable real-world data. Each data file contains a header indicating several operational parameters such as the Unix time epoch corresponding to the beginning of data collection, receiver latitude, longitude, and elevation as determined by GPS, receive frequency, sample rate, gain setting, and descriptive name. Data file names include the receiver latitude, longitude, frequency, date, time, and file type to assist in post-processing data management and organization.

## 7.3. *Receiver performance study*

An engineering objective of this experiment is to better understand receiver performance in real-world geography. Several parameters will be studied to understand better how they trade off with performance. One of the most consequential trade-offs relates to the reference mode, whether direct or remote. A receiver that is geographically shielded from the direct transmit signal could potentially have extraordinary sensitivity as well as design simplicity in remote reference mode. However, that comes at the expense of potentially poor illumination of low-altitude objects. On the other hand, a receiver operating in direct reference mode does not suffer from this problem, but at the cost of considerably more computational complexity as well as a much larger antenna.

## 7.4. *Adaptive beam forming*

To support economy and mass deployment, an approach using electronic beam steering rather than manual or mechanical antenna steering is employed. Each receiver is equipped with a three-element, circular, vertical dipole array. Digital beam forming is used to synthesize the two required independent apertures needed to satisfy the conditions required for adaptive noise cancellation (Haykin, 2002) as used in direct reception mode. In addition, an antenna pattern with a sharp null can be synthesized to mitigate the direct signal as much as possible (Zhenwei, 1984; Zhang *et al.*, 2011). Beam forming is achieved as a weighted sum of the signals received by each antenna.

$$X_1 = \sum_{i=1}^{3} w_i x_i, \tag{14}$$

where the $x_i$ are the three received signals, $w_i$ are three complex weights, and $X_1$ is the received signal of the synthesized beam. Figure 8 shows a simulated steerable null formed with a three element array. The recorded data allow beam forming and adaptive null steering to be performed in post processing.

### 7.5. *Tracking algorithm development*

Observations of an object by multiple receivers can be used to determine object position and velocity by triangulation. This is done most directly by use of the EKF (Sorenson, 1985). The EKF is the ideal tool in this application because it provides an optimal estimation with awareness of measurement errors, and is forgiving of intermittent or overdetermined data. It further does not require explicitly solving the geometric triangulation problem. Any method of triangulation, however, requires the association of individual detections of one receiver with the corresponding individual detections of another receiver. This is a challenging problem for SkyWatch as its detection volume is so large, and by nature it sees all detectable objects in this volume simultaneously. This is a nontrivial problem and the choice of the best approach to solve it is an area of current development. Candidates include the Kuhn–Munkres (Hungarian) algorithm (Kuhn, 1955), Multiple Hypothesis Tracking (MHT) (Blackman, 2004), Probability Hypothesis Density (PHD) tracking (Lin *et al.*, 2004), and algorithms that employ AI such as DeepSort (Wojke *et al.*, 2017). The trade-offs and applicability of these approaches can be studied using the data collected during this experiment. It is noteworthy that echo amplitude and interferometric azimuth angle may aid in resolving the echo associations (see below).

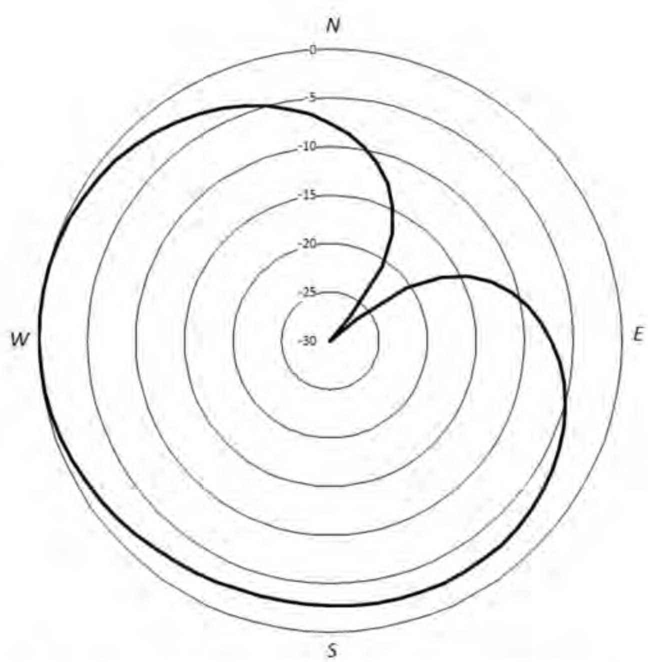


Fig. 8. Plan-view polar plot of simulated null steering with a three element array. The rings mark amplitude in 5 dB steps. The polar angle represent azimuth as viewed from above. A null can be synthesized to point in any azimuthal direction by adjustment of three complex weight factors.

### 7.6. *Triangulation with narrow field instruments*

Full triangulation can be achieved with one pan-tilt camera and as few as one SkyWatch receiver. A narrow-field pan-tilt camera accurately estimates a ray in the direction of the object it is tracking. However, the camera alone cannot determine the range to the object. On the other hand, a single SkyWatch receiver detects the range of many objects simultaneously, but cannot alone determine their direction. A finite list of range hypotheses can be produced by finding the intersections between the object direction ray and the set of ellipsoidal bistatic range isosurfaces associated with the objects detected by a single SkyWatch receiver. Further, the Doppler shift associated with each detected object implies a velocity for each range hypothesis. An area of study is to develop an algorithm to determine the corresponding echo and thus locate the object in three-space. This is a 1D analog to the 3D association algorithms required for SkyWatch-only triangulation, and is expected to be commensurately less complex.

### 7.7. *Radar cross-section estimation*

A further product of the radar is RCS estimation. We can use the measured receiver power to estimate the RCS as

$$\sigma = \frac{P_r(4\pi)^3 R_t^2 R_r^2}{P_t G_t G_r \lambda^2}. \tag{15}$$

The transmitter antenna gain can depend on object position and altitude, adding uncertainty to the RCS estimate.

Typical FM transmitters employ linear antenna arrays that shape the beam toward the horizon (Shively Labs, 2006; Federal Communications Commission, 2010) as shown in the elevation pattern of Fig. 9. The RCS estimate can be improved by employing gain maps in both azimuth and elevation from the transmitter. Scattering angle can also play a role (Kenyon & Dogaru, 2017). Despite these challenges, if the RCS can be estimated to reasonable accuracy (i.e. $\pm 5\,\mathrm{dB}$), this could be used for direct comparison between receivers for the purposes of associating echoes as needed for the tracking algorithms described above. Note that radar minimum detectable RCS depends not only on distance, but also on elevation angle to the transmitter antenna as described by a curve of Fig. 9 with its peaks and nulls. The receiver dipoles have a cosine elevation response that also affects minimum detectable RCS. This is not an ideal situation and introduces RCS estimation uncertainties as well as adverse position-dependent effects. For example, an object traveling at constant altitude in a trajectory over the transmit antenna from horizon to horizon will pass through detection voids, causing detection of the object to be discontinuous over time. This also prevents a simple statement as to the sensitivity of the radar, because it depends on object elevation angle, not just range. In terms of RCS, this means that a final estimate cannot be made until object position is obtained. Notwithstanding, knowledge of the transmitter and receiver antenna patterns can be used to form an expression or numerical lookup table that can be used to help MHT and PHD association algorithms. In these algorithms, a position is assumed, and used as a hypothesis in a forward manner. Only good hypotheses should result in consistent RCS estimates from receiver to receiver.

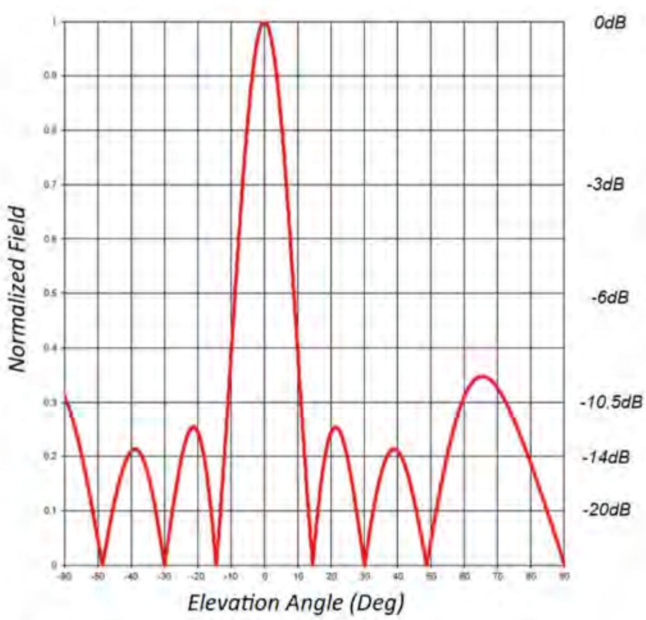


Fig. 9. (Color online) Elevation pattern of typical FM transmission antenna arrays showing main lobe directed towards the horizon. Sidelobes and nulls extend above the horizon affecting RCS estimation.

### 7.8. *Interferometry for angle of arrival estimation*

Determination of angle of arrival (AOA) of echoes would prove helpful in associating echoes of multiple receivers with one-another in MHT or PHD tracking algorithms. Such measurement could further aid in associating radar detections with objects viewed by narrow-field instruments. In cases where the network is sparsely populated so that 3D solutions are underdetermined, AOA information could potentially be used to put upper and/or lower bounds on an object's position and/or velocity. In remote reference mode, the three-element, vertically-polarized, circular, dipole array allows for azimuthal AOA estimation by interferometry (Pan *et al.*, 2015). However, in direct-reference mode, reception of weak echoes is not possible through just one dipole, because sufficient direct signal mitigation requires a null formed by the circular dipole array. Thus, AOA interferometry in direct-reference mode is a fruitful area of future research to be explored. The SkyWatch platform with its raw recorded data provides an ideal test bed upon which various techniques for AOA determination in direct-reference mode can be attempted. Results of the various attempts can be evaluated against ground truth aircraft position and velocity data provided by Automatic Dependent Surveillance–Broadcast (ADS-B) transponder (Federal Aviation Administration, 2002) data either recorded locally, or captured historically by any number of available services.

### 7.9. *Validation*

SkyWatch receivers have ample sensitivity to detect single-engine and commercial airliners, of which there can be dozens aloft within its detection volume at any one time. We exploit these detections to aid in validating position and velocity estimates obtained by the network by comparing them to known aircraft positions and velocities as provided by their ADS-B transponders. Known aircraft position can also be used to directly validate measurements from single SkyWatch receivers. These aircraft position and velocity data are readily available on the internet (FlightAware, 2017), and can also be received locally in real time (Laufer, 2018). We will also use the ADS-B aircraft type information to validate the estimated RCS. In this case, we will create a scatter chart of aircraft type versus estimated RCS to catalog the accuracy and reliability of the estimate between multiple receivers.

## 8. Next Steps

Data collected in the experiment described here will provide ample opportunities for algorithm development and system engineering. The Phase 1 SkyWatch system is designed for observatory-class systems, but the Galileo Project intends to use what it learns to develop more cost-effective passive radar systems for mass deployment in a mesh network (Watters, 2023). An important next step towards these ends is the design of a real-time version of the receiver with the goals of being smaller, less expensive, and easier to deploy. Much development is also required on the server in order to monitor and control the receiver network, as well as to interpret the data to deliver triangulated results in real-time. All of this is in service of developing an economical and truly mass-deployable receiver suitable to provide nationwide coverage (Davenport, 1999, 2004) using the many available commercial FM broadcast transmitters (the 60 dB$\mu$ service area of which is shown in Fig. 10 (Davis, 2017)) to monitor aerial objects and detect and record anomalous kinematics indicative of purported UAP. Such a system would integrate well into the small "mesh" optical, IR, and acoustic monitoring systems described in Watters (2023).

Interestingly, economy plays a nontrivial role in the quality of the science return. This is because a simple receiver solution could enable a more densely-populated network and hence better results. On the other hand, the more complex design may appear superior in its individual performance, but ultimately result in a sparsely populated network with less accurate estimates and a lower probability of detecting radar-reflective objects exhibiting anomalous kinematics that might be classified as UAP. At the nation-wide scale, pairing observatory-class SkyWatch receivers with

Fig. 10. (Color online) Visualization of FM broadcast radio coverage in the US. Note that useful radar operation extends significantly beyond the power contours plotted (Visualization courtesy E. Davis https://erdavis.com).

mass-deployable versions of Galileo Project's wide-field and narrow-field optical instruments as mesh nodes has great advantages. The higher degree of corroboration would increase the certainty of measurements acquired during any captured UAP activity. Further, the greatly expanded detection volume would raise significantly the probability of detecting UAP.

## 9. Conclusion

A network of multistatic passive radar receivers based on commercial FM transmitters of opportunity shows great promise in providing key quantitative real-time data to complement the suite of instruments being developed by the Galileo Project. Real-time position and velocity data can provide advance notice of aerial craft with anomalous kinematics that might be indicative of UAP activity and help steer narrow-field instruments to them. Rapid sampling of the hemisphere in a 150 km radius will allow unprecedented estimation of the high aerial accelerations and abruptly changing kinematics that are characteristics of particular note in UAP reports. The basic theory of operation is presented, and key engineering challenges identified. Basic passive radar receiver operation has been confirmed and reproduces the results of others. A Phase 1 design has been implemented in order to test SkyWatch receivers as a network. The experiment calls for the receivers to intermittently record their raw samples and transmit these data to a server. These data are used in post processing to test several geographical and operational variations. The resulting study will inform the engineering of a system that is hoped to be smaller, more economical, and more easily deployable. It will further aid the development of the necessary server-side software and algorithms needed to support the network and to generate object positions, velocities, and radar signatures in real time. The experiment calls for validation of derived object 3D position, velocity, and radar signature against known aircraft data as recorded from ADS-B transponder messages. The vision for SkyWatch is an economical, mass-deployable instrument fielded on a nation-wide scale that maximizes the probability of detection and characterization of UAP activity.

## Acknowledgments

Special thanks to Peter Davenport of the National UFO Reporting Center for the vision and inspiration for the SkyWatch passive radar network concept. The author also wishes to thank Jeff Keeler, Paul Howland, and Darek Maksimiuk for their help and support in understanding the issues and achieving first results. Many thanks go to the entire Galileo Project team for their support.

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# USING MULTISTATIC PASSIVE RADAR FOR REAL-TIME DETECTION OF UFO'S IN THE NEAR-EARTH ENVIRONMENT



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## ABSTRACT:

The author proposes a system for the remote, real-time detection of UFO's in the near-Earth environment, using passive, multi-static, frequency-modulated (FM) radar. The system capitalizes on the use of multiple, time-synchronized radio receivers to capture high-frequency radio signals reflected from a target. The time-lapse between received signals, together with three-dimensional Doppler-shift analysis, permits calculation of a target's location, velocity, acceleration, flight path, and other parameters, possibly to include target size estimation. Signal analysis of the reflected signal, combined with analysis of target characteristics, will permit discrimination between suspected UFO's, and targets of terrestrial origin, e.g. aircraft, satellites, space debris, meteor trails, upper atmospheric conditions, weather phenomena, migratory birds, the Moon, etc.. One application proposed may allow detection of UFO's out to a range of at least 27,600 kilometers from the Earth's surface.


## PREFACE

The national debate over whether UFO's are real objects, i.e. sophisticated, extraterrestrial craft under intelligent control, was sparked on June 24th, 1947, by the now famous sighting of a cluster of disc-shaped objects near Mt. Rainier in Washington State by Mr. Kenneth Arnold, a former World War II fighter pilot. Upon landing at Pendleton, OR, after his sighting, Arnold was interviewed by reporters, to whom he reputedly described the objects as "saucers," a statement which quickly gave rise to the term, "flying saucer."

Whether personnel in the U. S. Government were aware of the existence of UFO's, and of their significance, prior to the Arnold sighting is unclear. However, the reports by air crews during World War II of "Foo Fighters," peculiar objects seen to pace military aircraft over Europe, must have captured the attention of senior military and intelligence personnel, even if those personnel were unaware of their cause or origin.

Since those early events, the field of UFO investigation has relied primarily on eyewitness accounts, hundreds of thousands of which have been collected by UFO investigators and organizations over the last 57 years. Some of those sightings have been supplemented by photographic evidence, physical trace evidence, or radar data, the latter collected almost exclusively by government agencies, e.g. the Federal Aviation Administration, the National Weather Service, or military facilities.

Many radar intercepts of suspected UFO's have been captured since the early 1950's, but because of the limitations of traditional radar, those events have not been convincing, to everyone's satisfaction.

## PURPOSE

This is not a technical paper. Rather, it is intended to convey a general concept to a non-technical community of readers in the field of UFO research. Its principal purpose is to alert the UFO community to the fact that new developments in passive, multi-static radar, and in related technologies, will permit, for the first time in the history of ufology, remote, real-time detection of UFO's in the near-Earth environment. Moreover, not only will the proposed system detect the presence of suspected UFO's, but also, it will permit determination of their flight characteristic, e.g. velocity, acceleration, flight path, and perhaps size.

The technology described here is not theoretical. Rather, it already exists, it is relatively inexpensive, and it does not require a great deal of technical acumen to operate. Passive radar is a quantum improvement over traditional radar, with regard to its capability to detect fast-moving targets, and targets at large distances.

The author does not fail to recognize that this paper may cause some discomfiture in certain circles within the U. S. government, and perhaps elsewhere. The technology addressed here will permit detection of UFO's in the vicinity of our planet, if in fact such objects exist, and if they reflect electromagnetic radiation. This new technical capability may represent a challenge to the traditional monopoly that the world's governments seem to have enjoyed with regard to "hard" evidence surrounding the possible visitation of Earth by alien life forms. In brief, the technology may allow the resolution of the question as to the existence of UFO's.

## DEFINITIONS

**Electromagnetic Radiation**—A term synonymous with "radio waves." Radio waves can vary in frequency, with the higher frequency radio waves having shorter wavelength, and lower frequency radio waves having a longer wavelength. All radio waves propagate at the speed of light. Examples of electromagnetic radiation are radio and television signals, microwaves, infrared, visible light, ultra-violet, X-rays, gamma rays. All of these forms of electromagnetic energy differ only by virtue of their respective frequencies.

**Radar**—Any system that uses reflected electromagnetic radiation to detect the presence of an object. Analysis of the reflected radio signal can be used to calculate certain characteristics of a target.

**Active Radar**--Traditional radar employs 1) a transmitter, which radiates a (usually) narrow beam of radio waves, and 2) a receiver, which detects the reflected signal.

**<u>Passive Radar</u>**—A type of radar system which uses one (or more) receiver(s), but which has no active transmitter. The system detects ambient radio signals, emanating from nearby radio transmitters. Potential sources of electromagnetic radiation that can be exploited by a passive radar system include 1) commercial radio and television signals, 2) signals from cell telephone towers, 3) sources from space-borne platforms, and others.

**<u>Mono-static Radar</u>**—A radar system in which the transmitter and receiver are 1) stationary, and 2) located at the same position.

**<u>Bistatic Radar</u>**—A radar system in which its elements, either the transmitter(s), and/or receiver(s), are 1) stationary, and 2) in different locations.

**<u>Multistatic Radar</u>**—Similar to bistatic radar, except that it employs more than two stationary transmitters and/or receivers.

**<u>Frequency Modulation (FM)</u>**—Alteration of the <u>frequency</u> of a transmitted radio signal.

**<u>Amplitude Modulation (AM)</u>**—Alteration of the <u>amplitude</u> of a transmitted radio signal.

**<u>Signal Analysis</u>**—Measurement of various characteristics of a radio signal, to include its shape, duration, time of transmission or intercept, etc.. Many aspects of a signal can be measured quite accurately, and very quickly, by modern electronic circuitry.

**<u>Doppler-shift Analysis</u>**—Measurement of the shift in frequency of a reflected radio wave, caused by the motion of the target either toward, or away from, a receiver or transmitter. Often, the frequency-shift usually is very small, but it nevertheless can be measured quite accurately.

**<u>Phased-Array Antenna</u>**—A type of antenna, which employs a number of small elements, instead of a single, large element. Phased-array antennas can be used either for transmitting, or receiving, a radio signal. By precise timing of when each of the individual elements transmits its respective portion of a radio signal, the direction in which the overall signal is transmitted can be precisely controlled. If the time at which a signal is received by each element in a receiver array is measured precisely, the direction from which the signal was transmitted (or reflected) can be measured.

**<u>Continuous Wave</u>**—A radio signal, which is transmitted as an un-modulated sine wave. Hence, its frequency is constant.

**<u>Global Positioning System</u>**—A system, referred to as "GPS," which allows very precise determination of location. The system employs time-synchronized radio signals transmitted from overhead satellites, which allows very precise determination of not only position, but time, as well. The system uses very precise time-lapse measurement to calculate the distance from each of several transmitting satellites, which, in turn, permits very precise calculation of the distance from each of the satellites transmitting the signal.

## INTRODUCTION

The principle of radar employs the fact that some materials reflect electromagnetic radiation ("ER"). Examples of objects that reflect ER are most metallic items, the Earth's ionosphere, ionized "trails" behind meteors, satellites, re-entering space debris, the Moon, the surface of the Earth, migratory birds, etc.. Many materials, e.g. air, wood, plastic, most glass, etc., may not reflect electromagnetic radiation. Whether a target reflects a radar signal can depend on its size, the material it is made of, and the frequency of the impinging electromagnetic radiation, etc..

### Active Radar

Radar technology has become dramatically more sophisticated since its invention during the 1930's, but traditional "active" radar, which uses a co-located transmitter and receiver, operates fundamentally the same as it did over half a century ago. The transmitter radiates usually a very narrow, high-power beam of radio waves, which is scanned over the target area. When the beam strikes a target, if the transmitted signal is reflected by the target, that reflected signal is detected by the system's antenna and receiver. With signal analysis of the reflected wave, azimuth and elevation of the target can be calculated. In addition, the range to the target can be calculated from the elapsed time required for the signal to reach the target and return to the receiver antenna.

As effective as traditional, active radar has become since its invention in the 1930's, it nevertheless has certain characteristics, which make it less than optimal, particularly for detection of very high-velocity targets. Some of those characteristics are the following:

- Given that active radar requires both a transmitter and receiver, an active radar system usually is expensive and bulky.
- Because an active system requires a high power output, it is expensive to operate.
- Most active radar systems are not easily portable.
- When an active radar system is in operation, its transmitter is easily detectable.
- Operation of the transmitter requires an FCC operator's license.
- Detection of a target often is intermittent, e.g. every few seconds, not continuous.
- Range and altitude data usually are limited by the power of the transmitter.
- Some systems require multiple transmitters and/or receivers for obtaining three-dimensional information.

- “Raw” radar returns often have to be filtered, in order for an operator to be able to make sense of them.

- An active system can be defeated by ground clutter, or debris in the atmosphere.

- False signals, called “aliases” or “ghosts,” can appear in the system, making interpretation difficult.

Several of the characteristics listed above combine to limit the effectiveness for detection of UFO’s with traditional, active radar. The intermittent nature of the system, i.e. illumination of the target only very briefly every few seconds, limits the system’s ability to identify some targets unambiguously. If the target moves a large distance between subsequent detections of the target, for example, the system operator might conclude that the target is an anomaly, i.e. an “alias” or “ghost” return, and not realize its significance.

In addition, the expense of building and operating such a system can be prohibitive for the average researcher, and operation of a transmitter requires a federal license. Except for low-power navigational radar systems on private boats and aircraft, most radar systems in the United States are operated by government agencies. Hence, government employees are often the only ones to see the radar data collected by present-day, active radar systems, and the information may not be freely available to the public.

Although there are many instances in the UFO archives of detection of UFO’s by active radar, such intercepts are relatively few, compared to the number of eyewitness accounts of reported UFO sightings. Hence, there is considerable room for improvement in radar detection of UFO’s, beyond what has been possible over the last half century with traditional, active radar systems.

## Passive Radar

The concept of passive radar detection, using reflected ambient radio signal emanating from a distant transmitter, is not a new concept. The idea was first addressed seriously as early as the 1950’s. The fact that various U. S. Government agencies have been interested, for decades, in the possibility of detecting aerial or surface targets by using passive radar is indicated by the conferences held during the late 1960’s, and the research projects that those conferences addressed. The Project “May Bell” Technical Workshop, sponsored by Raytheon Company, and held in Burlington, MA, on May 18-22, 1970, is evidence of an early interest in this the application of passive radar. The list of attendees of that conference reads like a “Who’s Who” of the defense and intelligence communities.

One of the subordinate projects within Project “May Bell” that was discussed at that conference was “Project Aquarius,” sponsored by the Advanced Research Projects Agency (ARPA Order No. 1459), and conducted by the Sylvania Electronic Defense

Laboratories, Mountain View, CA. “Project Aquarius” was a research project, designed to test the feasibility of detecting submarine-launched ballistic missiles and low-flying aircraft, using a bi-static, passive radar system.

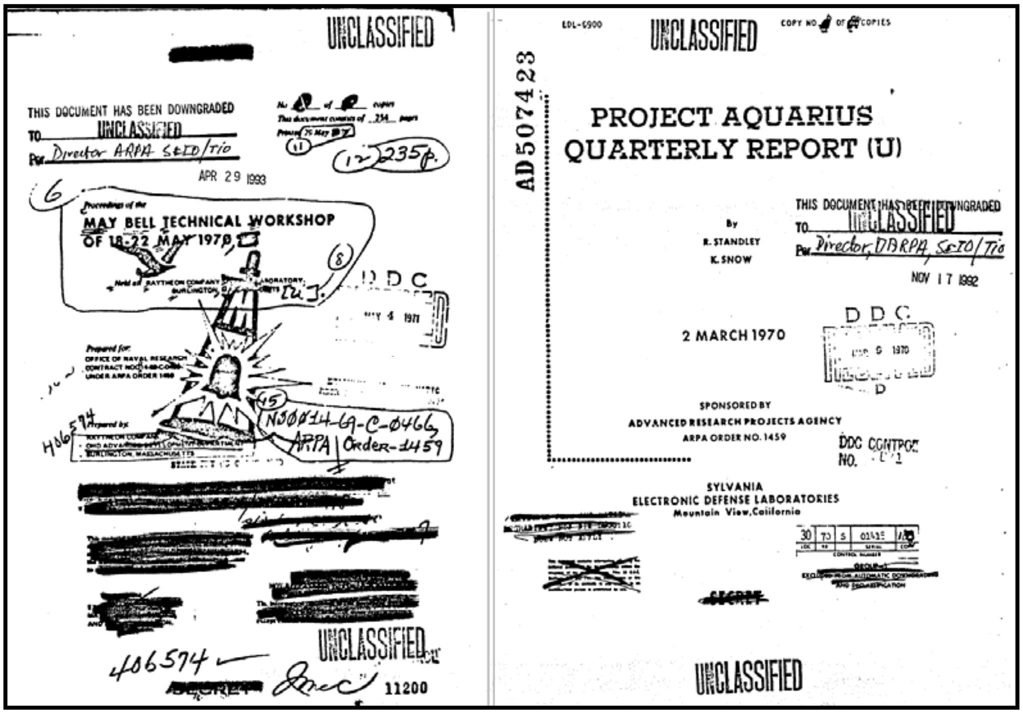


***Figure 1: Cover pages of the Project "May Bell" Technical Workshop and Project "Aquarius" Quarterly Report ( 1970).***

The fact that interest in passive radar for defense applications continues into the 21st Century is indicated by the Third Multinational Conference: Passive and Covert Radar (PCR: 2003), held at the Applied Physics Laboratory, University of Washington, Seattle, Washington, on October 21-23, 2003. The attendees included personnel from the Office of the Secretary of Defense, the Defense Intelligence Agency, the U. S. Air Force Research Laboratories, the U. S. National Intelligence Council, NATO, the Lockheed-Martin Company, The Boeing Company, and from several U. S. and foreign academic institutions. The ranks and titles of personnel present at that conference underscore the professional interest in passive radar, and the fact that it is a technology that today is being viewed as having become technically feasible.

The principal host of the Seattle conference was Professor John Sahr, Ph.D., from the Department of Electrical Engineering, University of Washington, in Seattle. Professor Sahr currently operates a passive, FM radar for imaging small, i.e. meter range, changes of the Earth’s ionosphere, using reflected FM radio signals from commercial radio and television stations. Details of that system are discussed later, and can be seen at the following website: http://rrsl.ee.washington.edu/Projects/Manastash/

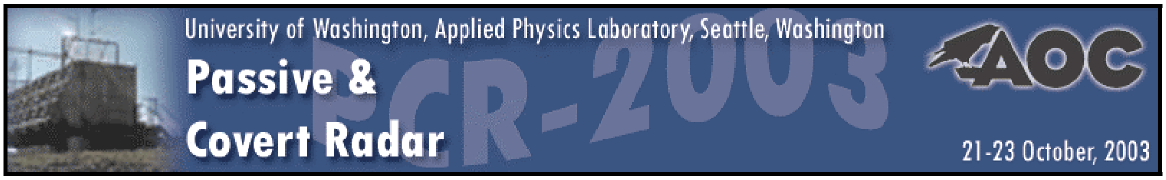


***Figure 2: From a website announcing the University of Washington symposium on passive and covert radar, held October 21-23, 2003.***

That governmental, military, and intelligence offices are interested in passive FM radar systems is explained by the fact that it has certain properties which make the technology ideally suited to present day demands for surveillance and defense. Some of those advantages, and some of the other attractive characteristics of passive radar, are listed below:

- Passive radar requires no active transmitter, only multiple receivers.
- A passive radar system detects targets continuously, often, multiple times per second.
- A passive radar system cannot be detected when in operation, since it has no active transmitter as an element of the system.
- Passive radar can detect targets over a wide area, whose radius often is measured in hundreds, or thousands, of kilometers.
- A passive radar system is relatively inexpensive, requiring nothing more than a receiver, a very accurate time source, and adequate signal processing capability.
- Construction and operation of the system requires no government licenses, and therefore, is not controlled by any governmental licensing agency.
- A passive system can be operated in virtually any location.

The principal hurdle encountered in the development of sophisticated passive radar systems has been having enough computer computational power be able to process very large volumes of data. Real-time signal processing for a small-scale passive system, using two receiver stations, typically requires computer computational capacity in excess of 10-giga operations per second (GOPS). Such computational capacity has become available only relatively recently. Hence, computational capacity no longer is a limiting factor, a fact which has given rise to renewed interest in passive radar systems for applications other than just large-scale military purposes.

The relatively recent deployment of the U. S. Global Positioning System is another development that has made passive radars feasible. GPS allows very accurate time measurement, which is a necessary for very precise time synchronization of radio receivers. The GPS system also allows very accurate measurement of the location of receiver antennas.

**<u>Examples of Passive Radars</u>**

Although passive radar systems have been relatively rare over past decades, the concept behind the principles they employ, i.e. reflecting a transmitted radio signal to a remote receiver, has not been without precedent. Several examples of the use of reflecting a radio signal to a remote receiver are cited below:

**<u>The Moon</u>—**The U. S. Navy began experiments in 1954, designed to bounce radio signals off of the surface of Earth's moon. The project was called "Communication by Moon Relay" ("CMR"), and its principal objective was to allow direct radio communication between Washington, D.C., and Hawaii.

**<u>Echo I and II</u>—**The Echo I and II satellites, little more than gas-filled balloons with an aluminized coating, were launched by NASA on August 12, 1960, and January 25, 1964, respectively. The purpose of the project was to create a high-altitude (800-900 km) "reflector" for radio transmissions emanating from surface-based transmitters. The satellites permitted "skipping" a transmitted signal to a remote receiver at a location over the horizon from the transmitter's location.


***Figure 3: Postage stamp issued to commemorate the launching of Echo I. Note simulated radio signals being reflected off the surface of the satellite.***

**<u>Over-the-Horizon Radar</u>**<u>--</u>Military agencies have been interested in the concept of increasing the range of a radar system by reflecting a transmitted radar signal off the Earth's ionosphere (e-region), thereby projecting it a signal to targets over the horizon. Projects designed to achieve that goal have experienced varying degrees of success.

**<u>Meteor-Scatter Communications Technology--</u>**Ham radio operators have known for years that the ionized trails of hot gas, generated by meteors entering the Earth's atmosphere, could be used for as short-lived, e.g. 1-5 seconds, reflection points for transmitting radio signals over the horizon to a distant receiver. The system has been in use for many decades, and commercial technologies have been built on the principle of using ionized trails behind meteors for bouncing radio waves to distant receivers. Meteor Communications Corporation, Kent, WA, has built "meteor-scatter" systems since 1975.

**<u>U. S. Space Command</u>**<u>--</u>The U. S. Navy operates an extensive radar system, often referred to as "The Fence," elements of which stretch from San Diego, CA, to Ft. Stewart, GA. The system is designed to detect, and measure, the trajectories of objects in Earth orbit. The transmitters radiate an extremely high-power (768 kW radiated power), high-frequency (216.98 mhz) continuous-wave ("CW") radio signal, which is broadcast through a series of phased-array antennas, forming a thin “fan” of electromagnetic energy, radiating out into space above the Earth. When an orbiting object penetrates the radiated beam, the signal reflected by the object is recorded by multiple, time-synchronized receivers on the surface. The system is reported to be sensitive enough to be able to detect an object 10 centimeters in diameter out to a distance of 27,600 kilometers from the surface, a distance equal to approximately two Earth diameters. Presumably, larger objects can be detected to a considerably greater distance.

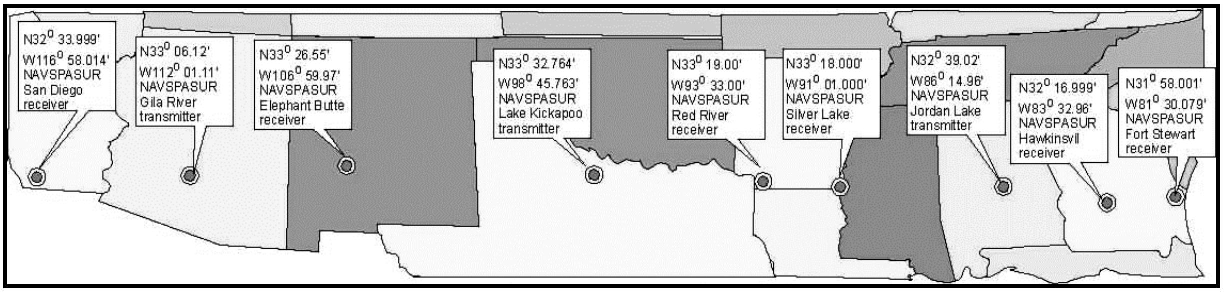

***Figure 4: Map showing locations of elements of the U. S. Naval Surveillance System, also called “The Fence.” (Illustration provided by Ray-Paul Nielsen.)***

**<u>Lockheed-Martin “Silent Sentry” Passive Surveillance System</u>**—A passive, all weather surveillance system, designed to detect targets using reflected radio signals from commercial FM radio stations. The system was first announced in 1998, and was awarded the *Aviation Week & Space Technology* “Technology Innovation Award” in 1999.

**<u>University of Washington Passive Ionosphere Imaging Radar System</u>**—The University of Washington Department of Electrical Engineering maintains a passive FM radar system for imaging small-scale fluctuations the Earth’s ionosphere, a project supported by the National Science Foundation. The system employs commercial FM radio signals (88 to 108 mhz) as a source, which are reflected off the ionosphere and detected by receivers several hundred miles distant, on the opposite side of the Cascade Mountains.

## FUNCTIONAL ELEMENTS OF A PASSIVE RADAR SYSTEM

A detailed technical description of a passive, multi-static radar system is beyond the scope of this paper. However, an attempt is made below to describe in general terms, and step by step, the operational elements of a passive radar system.

### Construction of System

Construction of a passive, multi-static FM radar system is a relatively simple matter, compared to the complexity of building an active system. The principal elements of a single, bi-static, passive radar system include the following items:

- A sensitive FM receiver, designed to detect a radio signal, typically in the 30-230 mHz frequency range, depending on the type of target to be detected.

- A modern, high-speed computer with sufficient capability to record a large number of intercepts per second, and to perform very rapid signal processing.

- Appropriate software for rapid signal processing, to include calculation of three-dimensional Doppler-shift information.

- Access to GPS equipment for accurate time and position measurement.

- Knowledge about, or access to, the original transmitted radio signal.

## Operation of System

### Interception Phase

1) Multiple receiver antennas are deployed, such that they are shielded from direct, line-of-sight communication with the FM transmitter of choice, but which are able to detect any reflected signals from the target area.

2) The system antennas are connected to a radio receiver, which is tuned to the original transmitter frequency.

3) Accurate time-measuring equipment (usually from the GPS system) is applied, such that the time of arrival of a reflected signal at each receiver antenna can be measured very accurately.

4) The precise frequency of each of the reflected signals received by each of the receiver antennas is measured and recorded.

### Signal Processing Phase

Once an intercept of a reflected signal is recorded, a process that can be effected hundreds or thousands of times per second, the intercepted signal can be analyzed in a number of ways, in order to extract information from the signal.

5) The time that a reflected signal is intercepted at each of the respective multiple antennas can be applied to triangulate the location of the reflected signal.

6) Multiple calculations of location of the target can be applied to calculate velocity, acceleration, and flight path of the target.

7) Any very subtle shift in frequency (Doppler-shift) of a reflected signal, caused by the movement of the target relative to the location of a fixed antenna, can be

compared with the frequency of the original transmitted signal in order to calculate velocity of the target.

## Target Discrimination Phase

Once data are obtained for any given target or event, these data then can be used for analysis of what the source, or cause, of the reflected signal might have been. Probably the most useful elements information for determining what may have been the nature of a target are its location, elevation, duration, velocity, acceleration, and flight path.

Analysis of any one of these parameters might be sufficient to rule out the likelihood of one, or more, categories of targets. For example, migratory birds would not be expected above a certain altitude or velocity. Similarly, most aircraft would be observed below a certain altitude, and would not be expected to be stationary. A meteor would not be stationary. Other categories of targets could be ruled out by similar lines of reasoning.

A typical bi-static system is illustrated in Figure 5. It indicates 1) exploitation of a commercial FM transmitter, 2) the shielding (by a landmass) of the remote receiver from the transmitter, 3) access to the original transmitted signal, and 4) the path of a reflected signal.

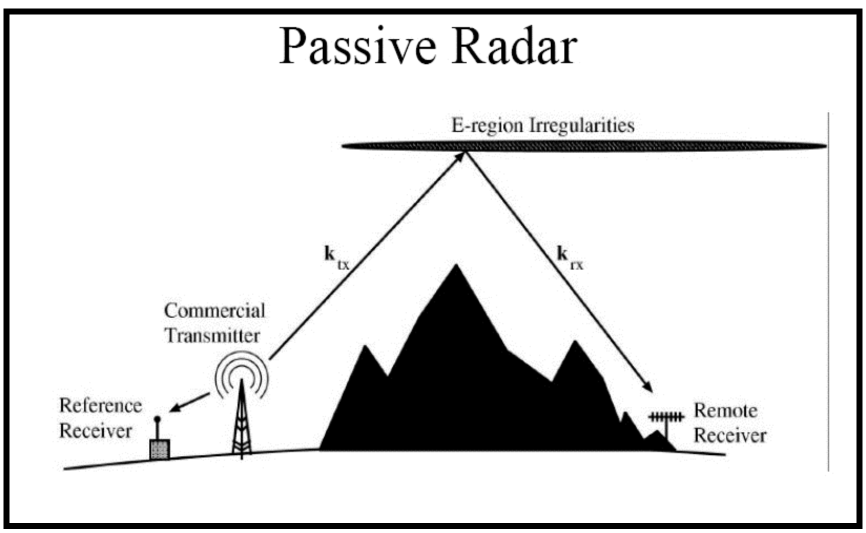


***Figure 5: Schematic of typical passive, bi-static radar system. ( Note Reference Receiver on left,, necessary for registering original transmitted signal.). (Source: Prof. John Sahr, jdsahr@u.washington.edu; http://rrsl.ee.washington.edu/)***

A multi-static system has at least three receiver sites, necessary for three-dimensional triangulation to the reflection point, and also to allow calculation of Doppler-shift in three dimensions. Figure 6 illustrates a multi-static passive system, which 1) employs two transmitters, and 2) two sets of four antennas for each station. As the number of transmitters and receivers is increased, the amount of information generated by the system grows rapidly, and the amount of computational capacity grows exponentially.

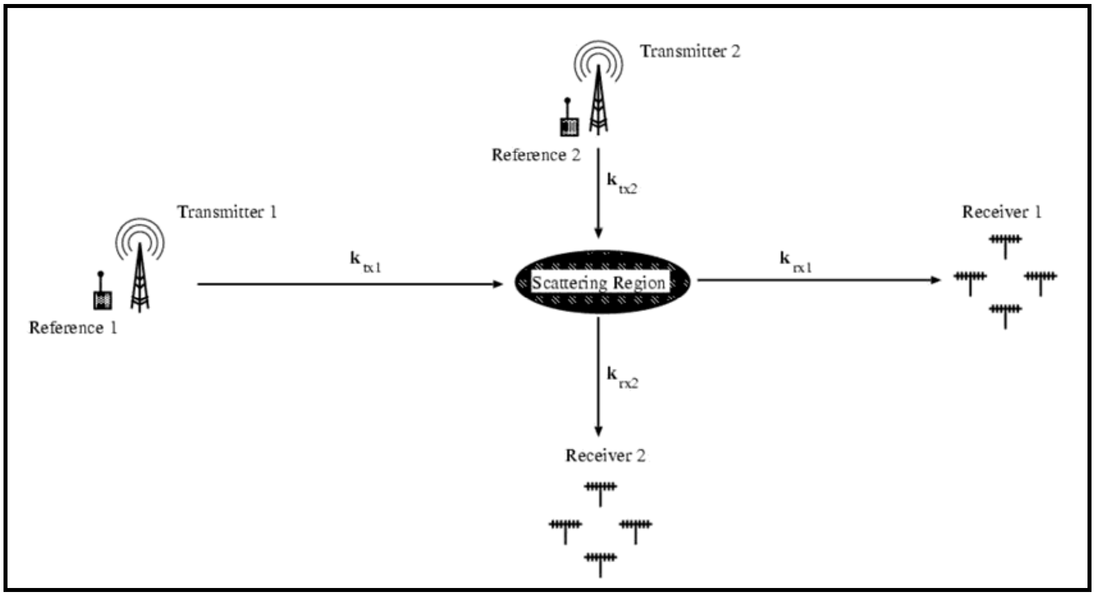


***Figure 6: A multi-static, passive array, employing two transmitters, and two sets of receivers, each with four antennas.*** ***(Source: Prof. John Sahr, jdsahr@u.washington.edu; http://rrsl.ee.washington.edu/)***

## PROPOSED DETECTION SYSTEMS

### Scenario 1: Use of Commercial FM Radio and Television Signals

Given the large number of high-power commercial broadcasting stations in the United States, they offer a readily available source of broadcast FM signal (88-108 mHz, for radio) for use by a typical multi-static radar system. Pre-requisites for operation of a passive radar system are that 1) the signal processor have access to the original broadcast signal, which serves as a reference, and 2) that the transmitter not be "visible" by the receivers, i.e. it is over the horizon from the receivers, or somehow "shielded" from them.

With the receiver tuned to the operating frequency of any broadcasting station, intercepts by the system can be ascribed to a nearby reflection point, either in the atmosphere, or on the surface. Comparison of the received signal with the original broadcast signal will provide information as to the nature of the target. With sufficient signal analysis capability, location of the target, its velocity, acceleration, and flight path, and perhaps estimates of its size, should be able to be calculated. This information should be adequate for performing discrimination between different types of targets.

### Scenario 2: Use of the U. S. Navy Surveillance System Transmitter

The nature of the phased-array transmissions used by the U. S. Navy Surveillance System for detecting and tracking orbiting objects makes it ideal for amateur tracking of targets in the near-Earth environment, or beyond. The system transmitters broadcast a very high-power (768 kW), high frequency (216.98 mHz) continuous-wave signal, which should permit of easy detection, and high-resolution, of objects in the vicinity of the system's three transmitters. Given that the system is designed to permit the detection of a target approximately 10 centimeters in diameter out to a distance of 27,600 kilometers, detection of a target whose diameter is on the order of ten meters out to that range would be a trivial process.

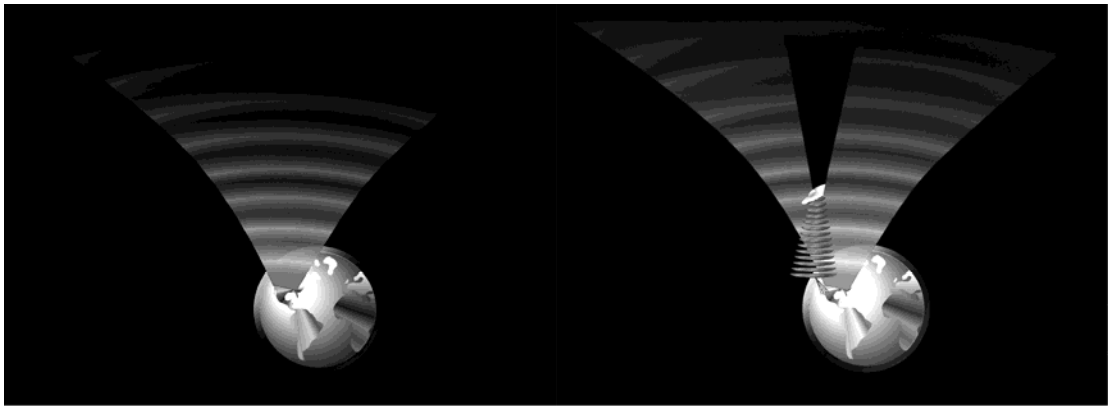

***Figure 7: Artist's conception of the "fan" of radiated electromagnetic signal from the U. S. Navy's Surveillance System, and how a target might reflect the signal. (Illustration by Ray-Paul Nielsen.)***

**<u>Scenario 3: Adaptation of University of Washington Passive System</u>**

Personnel at the University of Washington, Seattle, have developed a working bi-static radar system, sponsored by the National Science Foundation, for meter-scale imaging of the e-region of the Earth's atmosphere. The system may be able to be duplicated, and adapted, for tracking objects in the near-Earth environment. The system probably would have to be transformed into a multi-static system, with multiple antennas, in order to permit three-dimensional imaging capability, and the signal processing capability might have to be expanded dramatically to permit real-time processing of rapidly moving targets. However, with sufficient resource and technical personal, such a project seems feasible.

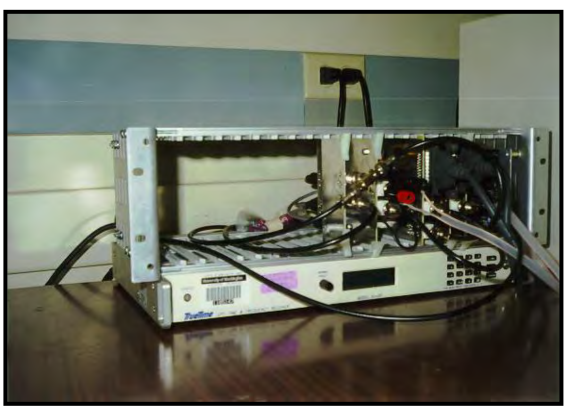

***Figure 8: Photo of bi-static system currently in operation at the University of Washington, Seattle. (Source: Prof. John Sahr, jdsahr@u.washington.edu;http://rrsl.ee.washington.edu/)***

**<u>CONCLUSIONS</u>**

- Within recent decades, because of both 1) the advent of high-speed computers, and 2) the deployment of the Global Positioning System, passive, multi-static radar systems have become technologically feasible. Passive radar technology has developed to the extent that it is now being discussed for use not only in defense and intelligence applications, but in the civilian sector, as well. The day is rapidly approaching, or perhaps has already has arrived, when the UFO community will have the technical ability to operate radar systems, which should allow unambiguous determination as to whether UFO's visit the near-Earth environment.

- Whereas some projects, dedicated to detecting intelligent life in the Universe, cost tens of millions of dollars per year to operate, a system of multi-static, passive radar receivers may permit detection of UFO's for vastly less expense.

- If the application of passive radar for detecting UFO's is successful in confirming their existence in the near-Earth environment, the application of new technology proposed by this paper will serve to challenge the apparent monopoly that the U. S. Government, and other governments, presently enjoy with regard to knowledge of that fact. Governments no longer will be able to conceal the existence of the UFO phenomenon from the world community.

**ACKNOWLEDGMENTS:**

Many individuals, companies, and institutions contributed to my understanding of the subject of passive radar, and to the preparation of this paper. I owe a large debt of gratitude to all them, as well as to others, who made minor contributions. I list below the major contributors in the order in which they appeared on the stage of this production: Mr. Fred Johnson, Enumclaw, WA; Meteor Communications Corporation, Kent, WA; Mr. Robert B. Frost, Seattle, WA; Christian Stepien, NUFORC webmaster, Seattle, WA; Dr. Donald Johnson, Ph.D., Seattle, WA; Mr. Mark Cashman, State Director (former), MUFON/Connecticut; Mr. Robert S. VunKannon, Kennewick, WA; Prof. John Sahr, Ph.D., Dept. of Electrical Engineering, University of Washington, Seattle, WA; Mr. Jim Klotz, Computer UFO Network ("CUFON"), Seattle, WA; Mr. Ray-Paul Nielsen, Illustrator, Seattle, WA.

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