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Applications of Object Detection Using Active and Passive Remote Sensing Systems

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The Defense Systems Information Analysis Center (DSIAC) is a DoD IAC sponsored by DTIC to provide expertise in nine technical focus areas: weapons systems; survivability and vulnerability; reliability, maintainability, quality, supportability, and interoperability; advanced materials; military sensing; autonomous systems; energetics; directed energy; and non-lethal weapons. DSIAC is operated by SURVICE Engineering Company under contract FA8075-14-D-0001.

A chief service of the DoD IACs is free technical inquiry (TI) research, limited to 4 research hours per inquiry. This TI response report summarizes the research findings of one such inquiry jointly conducted by DSIAC.

ABSTRACT

The Defense Systems Information Analysis Center (DSIAC) received a technical inquiry requesting information on a system that uses a detection scheme in the absence of an illumination signal. A DSIAC subject matter expert provided information pertaining to the remote sensing of objects in the presence or absence of an illuminating energy/signal. Most of the applications are pertinent to the terrestrial and atmospheric sciences research fields; however, applications relevant to the autonomous vehicles industry in the civilian and defense sectors are exponentially growing.

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1.0 TI Request

1.1 INQUIRY

What information is available related to the detection or inferring of the presence of an object in the absence of an illumination signal (i.e., negative radar)?

1.2 DESCRIPTION

The inquirer requested information relevant to a sensing system that uses a unique approach in which objects are detected in the absence of a bounced-back return signal. That is, the request was for information on available detection schemes that employ one or more transmitters to illuminate a region using man-made electromagnetic radiation (EMR) and monitor the electromagnetic (EM) flux using receivers that are not colocated. In addition, there was interest in existing schemes that employ Earth's passive blackbody radiation as the EMR "transmitter" or that employ passive cosmic radiation of space as the "transmitter."

2.0 TI Response

2.1 INTRODUCTION

Object detection in remote sensing images is a fundamental image analysis operation for a wide range of applications. Applications of radar include the following:

- Air and terrestrial traffic control
- Radar astronomy
- Air defense systems
- Antimissile systems
- Marine radars to locate landmarks and other ships
- Aircraft anticollision systems
- Ocean surveillance systems
- Outer space surveillance and rendezvous systems
- Meteorological precipitation monitoring
- Altimetry and flight control systems
- Guided missile target locating systems
- Ground-penetrating radar for geological observations

Current applications of radar involving the characterization of natural resources and the built environment have evolved over the past decades, but innovative applications are emerging due to data capture modes for sensors and platforms, including computing frameworks and capabilities. Active and passive radar systems are discussed in Sections 2.2 and 2.3, respectively.

Active radar systems colocate a transmitter and receiver based on a shared antenna system to transmit and receive signals. The range of an object is determined by the time it takes a pulse of synthetic energy to travel to the object and back. Radar and light, detection, and ranging (lidar) are examples of active remote sensing, as the microwave or infrared (IR) energy is pulsed, and the bounced signal is detected by the sensor [1].

Unlike active radar systems, passive sensor systems lack a dedicated transmitter. Instead, they use third-party transmitters in the environment and gather ambient radiation that is radiated or reflected by the object or surrounding areas, which allows bistatic range to be determined. The range of an object is determined by measuring the time difference between the signal arriving directly from the transmitter and the signal arriving via reflection from the object. In addition to bistatic range, a passive radar system also measures the bistatic Doppler shift of the echo and its direction of arrival. These measurements allow the location, heading, and speed of the object to be calculated. In some cases, multiple transmitters and/or receivers can be employed to make several independent measurements of bistatic range, Doppler shift, and bearing and hence significantly improve the final track accuracy [1].

The following resources provide information on sensor systems, including radar classified by related properties:

- “Types of Sensors for Target Detection and Tracking” [2].
- “Basics of Radar Technology” [3].
- “What is a Photoelectric Sensor? How Can it Benefit Your Facility?” [4].

Different types of photoelectric sensors, such as the reflective and retroreflective models, house the transmitting and receiving elements together, but differ in how the light beam will return to the receiving lens on exactly the same axis as the original transmitted light beam. The Thrubeam model, a type of photoelectric sensor, separates the transmitter and the receiver, and the object is detected based on whenever the contact between the transmitter and the receiver is broken.

2.2 ACTIVE RADAR SYSTEMS

2.2.1 Object Detection Using Active Sensing

There are many varieties of active radar systems used for object detection that have been documented and are briefly described in this report, including radiometers, Haystack Ultra-Wideband Satellite Imaging Radar (HUSIR), Multiple-Input and Multiple-Output (MIMO) radar systems, bistatic radar, and lidar.

Radiometers

There is ample literature pertaining to applications involving radar systems that measure atmospheric constituents using sensors called radiometers. Radiometers have many applications in the weather industry (e.g., aerosols and fog forecasting) [5].

HUSIR

There is also ample literature pertaining to radar system applications for measurements of space debris using HUSIR and its auxiliary system (i.e., Haystack Auxiliary Radar), which is administered and operated by the National Aeronautics and Space Administration's (NASA's) Orbital Debris Program Office [6].

MIMO Radar Systems

MIMO radar systems have received considerable attention in recent years due to their superior target estimation performance. However, MIMO radar systems are colocated systems that exploit waveform diversity to formulate their superior target estimation performance. Target estimation is based on the creation of a long, virtual array with a number of elements equal to the product of the number of transmitter and receiver antennas [7, 8].

Bistatic Radar

Bistatic radar, however, is a class of radar systems in which the transmitter and receiver are separated by a varying degree of spatial distance equivalent to the target of interest; they are predominantly used in missile targeting systems. A typical configuration includes a 180 ° bistatic angle, such that the transmitter and receiver are opposite each other to create a fence-like configuration. Similarly, a multistatic radar supports a combination of three or more transmitters and receivers [9, 10].

Other applications of bistatic radar systems include imaging E-region ionospheric irregularities using the Ionospheric Continuous-Wave E Region Bistatic Experimental Auroral Radar (ICEBEAR) transmitter-receiver configuration at a distance of about 240 km, providing field of view of about 600 km × 600 km. ICEBEAR is a coherent scatter ionospheric radar operated by the University of Saskatchewan [11].

The publication "Transmit Beamspace-Based DOD and DOA Estimation Method for Bistatic MIMO Radar" proposes a novel angle estimation method in bistatic MIMO radar, which combines the transmit beamspace technique with the unitary ESPRIT model [12].

2.2.2 Transportation Applications of Active Sensing

In the transportation sector, radar plays a key role in the Advanced Driver Assistance Systems (ADAS), which is considered a major development for self-driving vehicles. Radar is particularly useful in two ADAS technologies: the automatic emergency braking system and adaptive cruise control. These technologies use long-range radar (LRR) systems with ranges of 80−200 m or greater. Current LRR systems operate in the 77-GHz frequency band (i.e., 76−81 GHz) [13]; this frequency has several advantages for automotive use, including the following:

- The wide bandwidth improves accuracy and object resolution.
- With a wavelength of 3.9 mm, the antenna can be small.
- Atmospheric absorption limits the interference with other systems.

With the emergence of driverless vehicles, radar is expected to assist the automated platform to monitor its environment, thus preventing unwanted incidents such as collisions and object detection errors [14, 15].

Compared to lidar and other optical sensing technologies, radar is largely insensitive to environmental conditions like fog, rain, wind, darkness, or bright sun; however, technical challenges remain. Increasing automation levels require a system that can analyze complex scenarios and correctly respond to multiple potential hazards. To address these challenges, the inputs from radar, lidar, ultrasonic, and visual sensors can be combined to provide data to individual sensors that work independently; this combination is known as sensor fusion. The sensor fusion process synergizes the benefits of different sensors and measurement techniques most effectively to increase the reliability, range, and accuracy of target detection under adverse conditions. The aggregated data then enable the software to form a detailed map of the vehicle's surroundings [16].

The increased use of active remote sensing in vehicles, however, can cause interference issues, in which objects with low radar cross sections go undetected. Also, although the energy exposure of active radar systems was certified by the Federal Communications Commission (FCC), the Food and Drug Administration (FDA), and the International Electrotechnical Commission (IEC) , the long-term health hazard risk is unknown. Nevertheless, important developments are planned to enable drivers to see better in all conditions, such as a unique design with multiple cameras for stereo viewing (object size and depth perception), making objects easily visible and detected. The autonomous vehicles market is expanding rapidly, and several companies have taken an interest in designing and producing autonomous vehicles, including the following:

- Alphabet Inc., which is developing the Waymo car.
- Ford, which operates Chariot, a driverless transportation service.
- General Motors, which is producing the fully autonomous Cruise AV.
- Tesla, which offers electric cars featuring autopilot technology and is developing fully self-driving capabilities.

The company Foresight Autonomous Holdings has attracted attention with its QuadSight system, which is basically a passive remote sensing system that employs two cameras in the visible wavelengths and two cameras in the IR region of the EMR, thus providing an expanded detection range (150 m at 45 fps). It is effective at night and in poor weather conditions [16].

The defense sector is adopting autonomous vehicles faster than the civilian sectors. The Pentagon has already allocated $3.7 billion for research and development focused on the unmanned and autonomous technologies and plans to launch self-driving combat vehicles for the Army [17].

The U.S. Army Research Laboratory's Vehicle Technology Directorate is the main science and technology organization responsible for mobility-related research. Specifically, the intelligent systems focus area of the directorate involves the development of autonomous mechanics and intelligent object control and manipulation [18].

2.3 PASSIVE RADAR SYSTEMS

The passive sensing of two types of radiation, Earth's blackbody radiation and cosmic radiation, is discussed in Sections 2.3.1 and 2.3.2, respectively.

2.3.1 Passive Sensing of the Earth's Blackbody Radiation

The blackbody concept invariably is central to modern physics that pertain to radiation concepts. The framework supposes that a blackbody emits radiation in a three-dimensional space in the form of massless bosons (photons) [19].

Principles of thermodynamics, including spectral distribution involving Planck's hypothesis, led to some of the important foundations of quantum theory and emissive power [20]. The index of refraction in Planck's spectral distribution of emissive power function needs careful consideration. Simply using the index of refraction of air at laboratory conditions is not enough; a combination of the index of refraction of the media used inside the blackbody radiator and the optical path between blackbody and detector must be used instead. A worst-case approximation for the introduced error when neglecting the effects shows that the error is below 0.1% for wavelengths above 200 nm. Nevertheless, the correct consideration of the refractive index is mandatory for the determination of the spectral radiance for the purpose of radiation temperature measurements. The worst-case estimation reveals that the introduced error in temperature at a blackbody temperature of 3000 °C can be as high as 400 milliKelvin (mK) at a wavelength of 650 nm, and even higher at longer wavelengths [21].

In the 1970s, pioneering work concentrating on satellite measurements of Earth's radiation budget began at the NASA Langley Research Center, and evolved into the implementation and success of the Earth Radiation Budget Experiment (ERBE) and the Clouds and the Earth's Radiant Energy System (CERES). Data from ERBE provided a new understanding of the effects of clouds, aerosols, and El Niño/La Niña oscillation on the Earth's radiation. Using ERBE and CERES measurements, scientists could better understand the Earth's climate through analysis of the radiation at the top of the atmosphere, at the surface, and throughout the atmosphere. Additionally, surface radiation products were produced for designers of solar power plants, buildings, etc. as a result of ERBE and CERES measurements [22].

Additionally, the Special Sensor Microwave Imager and the Special Sensor Microwave Imager Sounder are polar-orbiting, passive microwave radiometers that have been on Defense Meteorological Satellite Program satellites since 1987. Most of these radiometer measurements provide information about atmospheric dynamics, such as surface wind speed, atmospheric water vapor, cloud liquid water, and the rain rate [23]. These data sets are available through the National Oceanic and Atmospheric Administration (NOAA) Data Center's Comprehensive Large Array Data Stewardship System (CLASS) [24].

Receivers for Earth Exploration Satellite Service (EESS) and Radio Astronomy Service (RAS) activities are extremely sensitive, as they must respond to very weak, natural radiations. The following characteristics of EESS and RAS measurements must be considered regarding radio frequency interference (RFI) [25]:

- Technology improvements are enabling more ambitious and sophisticated Earth remote sensing and radio astronomy experiments. Thus, system sensitivity requirements (and hence RFI thresholds) are steadily tightening.
- The spectral requirements of the RAS and EESS continue to increase, and some observations in the bands allocated to the active services are essential.
- Weak RFI can generate erroneous scientific results even when it is essentially undetectable. RFI is only detectable after a long period of observation, and then the entire observation is ruined.
- Radio astronomy bandwidths are large, up to 1 GHz and more, and integration times are often long, typically hours or days, and can extend to months in certain uses.
- Radio astronomy studies extend out to redshifts of greater than six, so that for the most distant objects, frequencies of the spectral lines are reduced by up to a factor of more than seven. For the important hydrogen line at 21 cm (1.42 GHz), for example, this means that sensitive studies need to be made at essentially all frequencies from 1.42 GHz down to the very-high-frequency range (i.e., 30−300 MHz).
- Satellite-based, passive, Earth remote-sensing measurements occur continuously and over the entire globe. A set of line and window frequencies extending from approximately 1 GHz to higher than 500 GHz is used.
- EESS observations of trace gases such as ozone or compounds of nitrogen usually require the measurement of several spectral lines for every molecular species under study. This means that many specific frequency bands are required, and it is not practical to restrict measurements to the bands assigned to the passive services.

One of the limitations of remote sensing of Earth's surface is that the source of incoherent microwave radiation is represented by a layer of two temperature nonequilibrium ionospheric plasmas at an approximate altitude range of 80–110 km. This layer is below a low Earth-orbiting satellite and is formed under the influence of solar activity. As a result, the satellite receives direct radiation from this layer as well as reflected radiation from the Earth's surface. Another limitation relates to the attenuation of the intensity of the incident radiation as a result of the scattering of radio waves by charged aerosol layers below the luminous layer. Aerosol particles are affected by solar and cosmic radiation and electronic and ionic attacks; as a result, they become charged. Aerosol particles directly take part in the formation of a complete balance of charges in the atmosphere and are an effective catalyst for many physicochemical processes in neutral gaseous media. The processes related to the formation of aerosol particles, the kinetics of formation of their charge, and the processes of their interaction with incoherent microwave radiation must be considered, and a fundamentally new scheme of passive location must be developed.

Three possible versions of the collection of measurements are analyzed. In the first version, a complete set of measurements is implemented when the receiving equipment is simultaneously installed on the Earth, an aircraft, and a low Earth-orbiting satellite; in the second version, the receiving equipment is simultaneously installed on an aircraft and a satellite; and, in the third version, the receiving equipment is only installed on one satellite. The contributions of direct and reflected incoherent radiation received by the satellite can be separated only by using a special mathematical approach to the information processing (wavelet analysis), which has been actively developed in recent years [26].

Interestingly, space-borne transmitters have been used in bistatic geometries for several planetary surface studies, including the inference of topography; Fresnel reflectivity; and root mean square (RMS) surface slopes on the moon, Mars, and Venus. For the moon and Mars in particular, the bistatic geometry has enabled remote probing in regions and under conditions not obtainable with Earth-based radar systems, yielding information about surface characteristics and properties on scales of centimeters to hundreds of meters, which complements monostatic radar observations. A new generation of planetary spacecraft provides opportunities for further experiments, including a nearly complete definition of the surface-scattering function and, possibly, imaging. Targets of interest include the polar regions of Venus (by *Magellan*) and Mars (by Mars *Observer*), the enigmatic icy Galilean satellites of Jupiter (by *Galileo*), and Saturn's largest moon, Titan (by *Cassini*) [27].

2.3.2 Passive Sensing of Cosmic Radiation

Normal radio wave emission from the Sun and other stars is discussed in "Earth-Based Remote Sensing of Planetary Surfaces and Atmospheres at Radio Wavelengths" [28]. Important reasons for remote sensing from the Earth include the following:

- Space exploration, particularly below the surfaces or underneath cloud layers, is limited to only a very few planets.
- A program of regular monitoring, currently impractical with a limited number of space probes, is required.

Reflected solar and nonthermal radiation, as well as relativistic electrons, is trapped in large magnetospheres on Saturn and Jupiter [28]. Relativistic electrons create synchrotron radiation and interact with the ionosphere to produce bursts of low-frequency emissions. Most objects are blackbodies; therefore, continuum radiometry is emphasized, and spectroscopic techniques and the measurement of nonthermal emissions are also discussed in the publication [27, 28].

Powerful EM waves can exert a well-defined influence on the atmosphere, ionosphere, and magnetosphere, and can provide spatiotemporal information on the near-Earth space environment (i.e., geospace) [29]. Important applications include the mitigation of atmospheric pollutants and solar power satellites. Studies of EM wave interactions also contribute to the knowledge of anthropogenic effects in the geospace environment, such as the increasing use of EMR. There is a growing interest in using powerful radio waves to study properties of the geospace environment itself, in addition to plasma turbulence. The research areas include the upper atmosphere, ionosphere, magnetosphere, solar-terrestrial physics, and space weather. The term “space weather” refers to energy-releasing phenomena in the magnetosphere, including magnetic storms, substorms, and shocks from the solar wind. For example, the stimulus-response type of experiments that are possible with powerful EM waves provide interesting possibilities to investigate electric currents in the ionosphere, as well as the atmospheric and ionospheric layers. Further, ionospheric layers can be literally visualized by illuminating the layers with powerful EM waves.

Natural EM signals of extremely low frequencies (ELFs) (i.e., 3 Hz–3 kHz) can be used to study many of the EM processes and properties occurring in the Martian environment. Sources of these signals, related to electrical activity in the atmosphere, are very significant since they can influence radio wave propagation on the planet, the atmospheric composition, and the ionospheric structure. In addition, such EM signals can be employed for many purposes such as surveying the subsurface of Mars or studying the impact of the space weather on the Martian ionosphere. As ELF waves propagate on very long distances, it is possible to explore properties of the entire planet using single-station recordings. An experiment has been proposed that allows measuring ELF signals from the Martian surface. Such measurements can be used for the detection of electric discharges in the atmosphere and water reservoirs in the planetary subsurface [30].

The RAS, the EESS, and the Space Research Service use ultra-sensitive receivers to measure natural emissions from objects in space and from the Earth’s atmosphere and surface. These services help to improve our understanding of the Earth and our universe and have practical implications that may not be obvious, such as weather tracking, land use management, and other essential sciences [31].

Radio astronomy involving measurements of radio spectral line emissions has identified and characterized the birth sites of stars in our own galaxy and the complex distribution and evolution of galaxies in the universe. It has also provided unique insights into the structure and composition of the atmospheres of the planets in our own solar system. Radio astronomy measurements of the cosmic background both from Earth-based radio telescopes (RAS) and from space-based radio telescopes such as NASA's Cosmic Background Explorer (COBE) have detected ripples generated in the early universe, which later formed the stars and galaxies we see today.

Much of the research involving cosmic background is conducted on portions of the radio spectrum through the use of “passive” operations, which do not employ any sort of transmitter, but measure EM energy. As passive users of the spectrum, radio astronomers and Earth scientists have no control over the frequencies that they must use for their observations or over the nature of the signals they receive. These parameters are determined by the laws of nature. Generally, the emissions that radio astronomers receive are extremely weak; a typical radio telescope only receives about one-trillionth of a watt from even the strongest cosmic source, and routinely receives radiation from sources one million times weaker than that. Radio astronomy receivers are designed to detect such remarkably weak signals; therefore, spectrum management and spectrum policy decisions are very significant to this scientific community.

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BIOGRAPHY

MAHESH RAO, Ph.D., is a senior image scientist at MTEQ and an adjunct professor at the University of Mary Washington. He has 18+ years of professional experience in environmental applications of remote sensing and geospatial analysis. Prior to joining MTEQ, he served as a faculty member at three universities researching and teaching image processing and geospatial sciences at both undergraduate and graduate levels. He served as a principal investigator on several site characterization projects funded by several local, state, and federal agencies on change detection analysis and impact assessment of land management practices using a suite of electro-optical, hyperspectral imaging, and active sensor data including lidar and radar. More recently, he has focused efforts on workflow development and implementation of machine learning techniques for geospatial intelligence applications involving situational awareness and military sensing.