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Satellite Proximity Detection Using Multi-Function Space-Based Sensors

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As countries enter into space programs, both low earth orbit (LEO) and geosynchronous earth orbit (GEO) satellites are increasingly subjected to an ever-increasing risk of collision with resident space objects. Sensors are becoming necessary to observe and measure the proximity of a satellite to determine the risks posed from kinetically approaching manmade and natural hazards. Volume, mass, and power on satellites is limited and risk management approaches tend to remove such sensors from satellite systems. With newer system engineering approaches, however, the traditional sensors used for navigation and measurement can be modified to sense the environment for hazards and obtain more information from what was previously a single function device.

Nomenclature

A_e	receiver/sensor effective area in square meters
B	noise bandwidth at the sensor
F_N	system noise factor for the receiver, usually an approximation
G_A	transmitter gain factor
G_a	SNR gain owing to coherent pulse integration
G_r	SNR gain owing to range processing/pulse compression
k	Boltzmann's constant (1.38×10^{-23} Joules/degree Kelvin)
L_{mediun}	loss factor owing to the propagating wave in a medium
L_{signal}	SNR loss owing to signal processing
L_{system}	transmission loss factor owing to miscellaneous sources
N_r	received noise power
P_r	received signal power in watts
P_t	transmitted signal power in watts
r_s	range vector to target from sensor in meters
T	temperature in degree's Kelvin
σ	target cross section in square meters

I. Introduction

THE traditional approach to satellite design was a modular assembly of specialized subsystems that performed extremely important functions, but were developed entirely to perform a single function. In the case of navigation, multiple redundancies of sensors are present on satellite busses to ensure a highly reliable performance of desired

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Table 1 Typical satellite subsystems

Sun sensor	Navigation	Detection of objects in field of view
Star tracker	Navigation	Detection of objects in field of view or extended view using additional optics
Telemetry transmitter/ receiver	Communication; typically an S-Band link to/from ground station for commanding, and so on.	Receiver/transmitter (using a changed frequency in band) could perform a localized area scan, detection of objects, or additional space object identification; optional usage of same signal processing and additional antennae for greater field of view
Communication antenna; L, C, Ku, and Ka bands	Satellites communications; voice/data relay between satellites or ground station receivers'	Receiver/transmitter (using a changed frequency in band) could perform a localized area scan, detection of objects, or additional space object identification, but limited to the field of view owing to placement of antenna
Telescopes	Space objects identification and research	Satellite maneuver, multiple optics, and/or robust steering to image space objects in desired orbits
UV and IR sensors	Research	UV and IR are expanding spectral regions open to multiple function sensor design
Space weather	Astrophysics, environmental monitoring, research	Detection of changes in local magnetic fields, particle type, energy and density could be used to alert objects are present in the local region

UV:ultraviolet
IR:infrared

measurements for navigation and detecting environmental conditions. Among these devices were sun, star, horizon, and partial or mass density sensors.

As volume, mass, and power is limited on satellites, a newer systems engineering approach will be to design multifunction sensors to perform the traditional functions with the added measurement or processing to extend performance to proximity detection. Many of these historical receiver and transmission systems operate in designated frequency bands that can be traced to their heritage of single function and spectral separation to prevent electromagnetic interference, improve electromagnetic compatibility, and minimize atmospheric transmissions losses in communicating to and from orbit and the ground stations [1].

With proximity, detection is becoming an increasing requirement for collision risk. Several of these subsystems, outlined in Table 1, can have their functional performance expanded to include detection, identification, characterization, and tracking through programmable electronic circuitry or designed-in multiple functionality. For example, if the telemetry antenna continued to perform only its original operations (primarily health-and-status and payload data), it would be dormant, or in a stand-by mode, for extended periods of time [1,2]. If the receiver or transmitter changed frequency and performed a localized area scan, detection of objects or additional space object identification could be performed with minimum impact on satellite volume, mass, or power.

II. Background

Satellite passive sensors are most commonly used for navigation and environmental monitoring. The receivers and transmitters are primarily for communication with ground stations. A system engineering design was applied to a passive sensor and active transmitter to demonstrate multiple functions are possible with a designed multi-function approach.

A. Passive Sensor

Passive sensors measure levels of energy that are emitted, reflected, or transmitted by an object. The main differences between the active and passive sensors are that the sensor does not directly illuminate the object. The passive sensor must be capable of detecting whatever is being emitted from the object of interest. The passive sensor is therefore capable of detecting radiation in several different portions of the electromagnetic spectrum and uses a combination of several channels to collect and process faint emissions. These spectrally separated energy bursts could be time sequenced, phase shifted, amplitude varying, and exhibit patterns that are unique to an object's materials or its electrical switching and computer processing system.

If the selected range of wavelengths emitted were maximized, the design of the passive sensor system could be optimized for performing detection, characterizing and identification. As electronics have specified bus speeds, microprocessor operating rates and known crystal oscillators used in commercial products, these were specifically analyzed.

B. Active Sensor

Active sensors provide their own energy source directing a burst of radiation at the target and use sensors to measure how the target interacts with the energy. The sensor detects the reflection of the energy, measuring the angle, amount of time it took for the energy to return, and Doppler shifting of the return energy pulses. This provides estimates of range, range rate or velocity, and the angle or direction of the target. Active sensors provide the capability to obtain measurements but require generation of large amount of energy adequately to illuminate targets and are not directly measuring the reactive emissions of the materials that could be faint and in other spectral bands.

Some active sensors are used to detect various forms of energy and take measurements of the density of the materials and provide detailed data about a wide variety of phenomena including material composition. These sensors radiate in bands, using specified wavelengths, and measure the returned energy in other bands to determine if absorbed energy is re-emitted: the sun's energy is either reflected, as it is for visible wavelengths, or absorbed and then re-emitted, as it is for thermal infrared wavelengths.

C. Detected Signal Strength

The basic principle of both sensors is received power. In Eq. (1), the power received, P_r, is dependent upon reflected or transmitted power, P_t, and the ability to collect and measure the signal strength and spectral characteristics [1,3,4]. The proportionality factor, K, accounts for gains and losses in transmission through a system and medium, which for space the losses are minimal. Further analysis involving wavelength, timing, system losses and signal processing can be used to determine range, range rate, angle, and other signal properties of interest.

$$P_r = K P_t \tag{1}$$

In a sensor system, P_t is highly dependent upon wavelength and cross section reflectivity of the object of interest. The minimum level of signal therefore becomes the dominant factor. This signal-to-noise ratio (SNR) is therefore one of the most important system design factors and can be very complex. Equations (2) and (3) are two forms of an SNR relationship which shows the relationships between several design factors that must be accounted for in a system design [3–7]. The difference is the design gains and losses associated with system designs. A single function sensor could maximize design performance; however, multiple functional designs will need to make design decisions to reach acceptable performance across several requirements. For example, if a minimum level of signal is exceeded, at a desired range, the power requirements could be reduced. Alternatively, "narrowing the bandwidth (B)," has the effect of increasing SNR in Eq. (2). The increased SNR directly translates to improved detection, but reduces signal analysis of Doppler shifting used to measure range accuracy, angle, and velocity of the object [6].

In Eq. (3), if gains, G_r (range processing/pulse compression) and/or G_a (coherent pulse integration), are improved through application of advancing electronics, you have the option to increase range or reduce transmit power. For example, NASA's Tracking and Data Relay Satellite System (TDRS) uses 26-Watt power amplifiers in their S-Band telemetry system with an omnidirectional antenna. This conical log spiral antenna is used during the satellite's deployment phase and as a backup in the event of a spacecraft emergency. For every doubling of the gain through processing, you could reduce power by half: that is a 13 Watt potential reduction in TDRS. Not all of this power savings will, however, be achieved because the additional power requirements of signal processing, power and cooling management, and so on, will need to be included in the design trades. With electronic devices moving to lower voltage, power, and field programmable gate array technology, however, existing electronics demand less volume and perform multiple time-shared operations in a central dual core processor, some savings are anticipated.

$$\mathrm{SNR} = \frac{P_t \cdot G_A \cdot A_e \cdot \sigma}{4\pi^2 r_s^4 L_{\mathrm{medium}} \cdot L_{\mathrm{system}} \cdot k \cdot T \cdot F_N \cdot B} \tag{2}$$

$$\mathrm{SNR} = \frac{P_t \cdot G_A \cdot A_e \cdot \sigma \cdot G_r \cdot G_a}{4\pi^2 r_s^4 L_{\mathrm{medium}} \cdot L_{\mathrm{system}} \cdot k \cdot T \cdot F_N \cdot B} \tag{3}$$

III. Engineering Example

A. Star Tracker: Passive Sensor

Star Trackers detect stellar backgrounds, usually in the fifth to sixth magnitude “brightness” range, and compare this measurement to star mapping data to determine present position. The brightness of a star is usually expressed as a magnitude [2,8]. The magnitude scale is logarithmic and, by convention, defined so that brighter stars have smaller magnitude values. A first magnitude star is therefore very bright; while a sixth magnitude star is at the limit of normal vision.

The Star Tracker normally measures this visibly dim illumination for navigational information, but can be adjusted passively to detect scattered or reflected energy from an object in proximity of this sensor. If a scanning or steering mechanism is used, the sensor could perform as a detector. The re-design would need to include the ability to detect stellar magnitudes of much dimmer objects. These objects could be in the apparent visual magnitude range of 15 to 20. As shown in Fig. 1, the optical telescope requirements are demanding. If the requirement is simply to detect, then dim objects in the proximity of a satellite could be sensed and notification sent to a ground station.

In most cases, a visible wavelength sensor will have difficulty filtering out the brighter magnitude six stars from the magnitude 15 dim objects. An extensive redesign of the telescope and optical components is required first to perform the navigation function and then increase sensitivity to a much dimmer range or selected wavelengths of interest. NASA and the Jet Propulsion Laboratory are investigating several methods to improve sensitivity and power

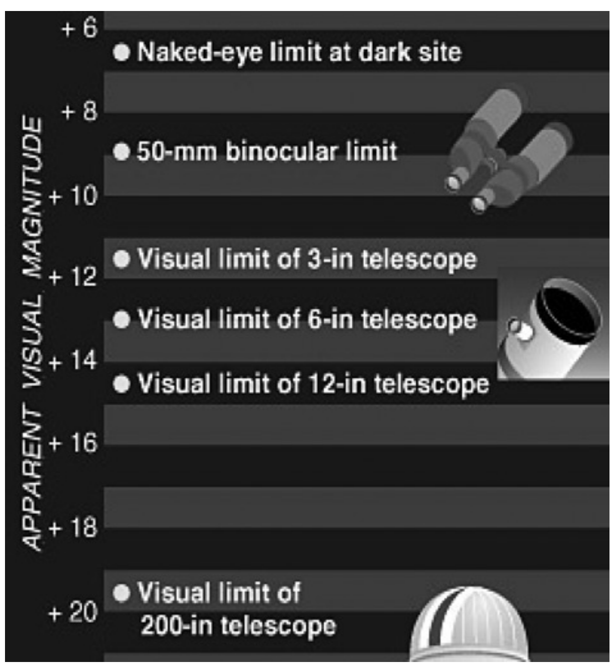

Fig. 1 Visual magnitude [8].

reduction through active pixel analysis and usage of lower voltage electronics [10]. This research topic will be examined further in a follow-up publication.

B. Telemetry Subsystem:Active Sensor

The S-Band (2–4 GHz) telemetry is used to provide a data command and control link to the satellite [11,12]. This subsystem is in high usage, but is a good example of an active sensor that can be converted to a simple detector, or high-performance radio amplification detection and ranging (RADAR) system.

Space qualified telemetry units are used for geostationary orbital satellites that transmit at ranges of about 42,000 km to their ground stations. Modification to the design would include waveform, pulse width, data processing, and scanning methods. The changes would measure and provide basic detection or range, range rate and angular data used to describe relative positional location.

A typical antenna is rigidly mounted "pointed towards the earth" and would only provide limited field of view. A conformal antenna molded into the satellite surface structure would provide full coverage. Figure 2 illustrates the typical flat panel array antenna and Fig. 3 illustrates an S-Band candidate conformal "skin" sensor array used in missile testing.

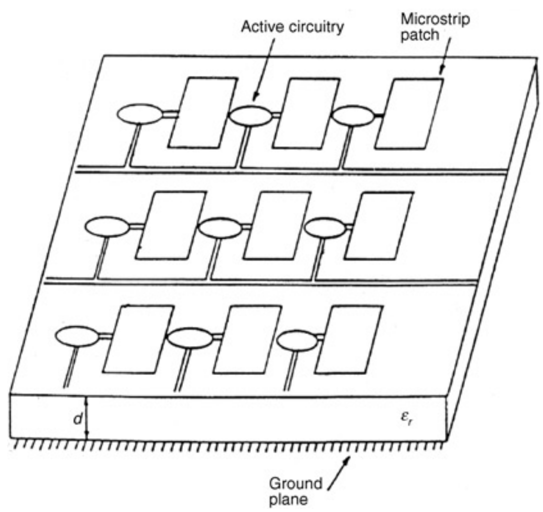

Fig. 2 Typical phased array with active circuitry and microstirp patches.

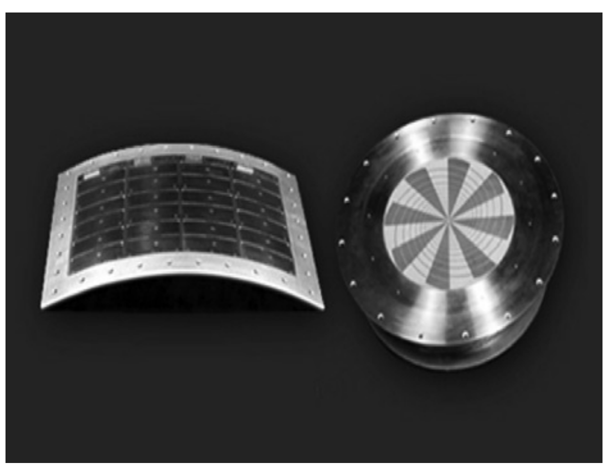

Fig. 3 S-Band conformal antenna array (courtesy of Northrop Grumman).

In both the passive and active cases, the original navigation and communications functions could be accomplished [12]. The added complexity of multiple functions could be integrated into the existing designs and through time sharing of digital processing and common components, minimal impact could be realized upon volume, mass, and power.

IV. Comparison of Passive and Active

The initial studies for star sensors have shown potential to perform multiple functions, while retaining their navigation role. The probability of detecting an object is dependent upon a major design change allowing for detecting both faint and comparatively bright signals from magnitude six stars and orbital objects. Government, academic, and industrial teams are currently investigating this fundamental design approach and their results are pending.

The active sensor offers a clear advantage in detection range, probability to detect, and positional measurements. This will require adding complexity to designs that are currently simple with demands on power and field of view. As technology advances (and the need to perform proximity detection of objects increases), these obstacles can be easily overcome with current state of the art hardware and software systems after modifications for space environment.

V. Conclusion

The Air Force Research Laboratory is continuing its investigation in multiple usage sensors for space applications [13]. The dual or multiple usages of sensors for navigation and detection offers a new approach to combining functionality and reducing mass, volume and power on satellites. The Star Sensor effort is under investigation and laboratory demonstrations will be performed in 2007.

Active sensors are currently being tested in millimeter and submillimeter wavelengths for space applications. Their potential functions will be investigated for communication cross links, proximity detection, RADAR, and telemetry operations. In particular, phase array structures, conformal and two-dimensional planar arrays will be investigated providing multiple beams patterns for diverse functional missions.

Both approaches will be reported in future publications as data and analysis proceed.

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