Space-Based Radar

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The concept of national air defense against aircraft and cruise missiles has been evolving in parallel with the Strategic Defense Initiative and is being referred to as the Air Defense Initiative. One of the most promising sensor concepts for the Air Defense Initiative is space-based radar. Operated at microwave frequencies as an instrument for wide-area surveillance, space-based radar may be useful in mission areas such as fleet defense and battlefield surveillance.

"IT IS DAWN OVER THE SOUTH ATLANTIC. IN A MILITARY airfield on the Argentinian mainland excitement is mounting. Intelligence sources have pinpointed the location of a British naval battle group that is proceeding seemingly unaware of its precarious position. A squadron of bombers, fully armed with air-to-surface missiles, takes off to deliver a devastating blow, flying low to avoid detection. A short time later reports of the operation come in. The destruction is total. All aircraft were shot down before they were able to make contact with the battle group."

The outcome of this imaginary scenario from the Falklands War was made possible by a hypothetical surveillance system capable of searching with electronic speed large portions of the earth's atmosphere, transcending restrictions imposed by national boundaries and political climates, and conveying instantly accurate information on all traffic within a large radius of any fleet battle group. By instantaneously restructuring this capability on command, an invisible radar fence is erected around North America. This system effectively establishes a mechanism for detecting all airborne intruders, as part of the concept known as the Air Defense Initiative (ADI), and assures maximum response from the Strategic and Tactical Air commands. In response to a sudden military flare-up in some part of the world, the Joint Chiefs of Staff direct a reconfiguration of the resources of the system so that the Secretary of Defense can manage the crisis on the basis of real-time knowledge about armor, supply movements, and air support. Combining data from the various sensor units enables the National Command Authorities to coordinate all of these missions simultaneously, without loss of essential information and with optimum probability of success.

Too good to be true? Perhaps. However, the idea of conducting worldwide surveillance by means of space-based radar (SBR) sensors has been maturing over the years. A number of studies have explored the feasibility of this system within the context of current and near-term technology developments, particularly in the areas of electronic components and devices, signal processing, and phased-array antennas. Architectures (*1*) have been proposed for detecting airborne and surface targets from space-based platforms and fusing such data with information collected by other means in order to provide advance warning in case of attack. What makes this type of sensor system of interest is the increasing credibility with which it is viewed by the defense community for deployment in the near future. In contrast to many candidate sensor concepts for the Strategic Defense Initiative (SDI), space-based microwave radar for wide-area surveillance does not depend on radically new or futuristic approaches or materials; rather, it relies on modest extrapolations of established technology.

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Description of Space-Based Radar

The primary function of SBR is to detect and track certain classes of moving objects, such as aircraft, ships, armored vehicles, and cruise missiles. This may be accomplished with moving target indicator (MTI) radar for the measurement of the Doppler shift of the radar signal as the range between the radar and the target changes with time. This technique is in contrast to synthetic aperture radar (SAR), recently implemented in the Spaceborne Imaging Radar (SIR-A and SIR-B) (*2, 3*) series of instruments. In conventional SAR, the radar energy reflected by the earth's surface is enhanced by signal processing to bring out desired terrain features. In MTI radar, this energy represents unwanted clutter and must be suppressed so that the much weaker returns from moving objects are not obscured. However, both MTI and SAR can be incorporated into the SBR sensor and invoked selectively as the need arises. The SAR would probably be used for the detection of low-velocity (<~10 km/hour) targets that require prohibitively large antenna sizes for reliable detection with MTI techniques.

The most frequently postulated system architecture, and the one assumed here, is based on monostatic radar operation in which the signal is transmitted and received by the same antenna. Other

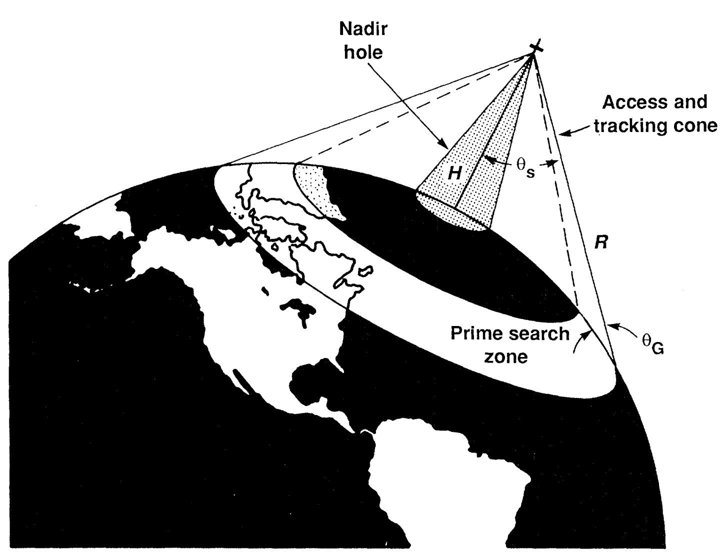


Fig. 1. Space-based radar geometry, where θ_G is grazing angle, R is range to target, H is altitude, and θ_s is angular extent of antenna scan. The prime search zone is usually included in the interval $20° < \theta_G < 3°$. The angle subtended by the nadir hole at the satellite is typically 50°.

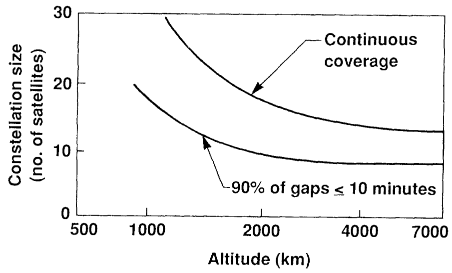


Fig. 2. Typical dependence of constellation size on altitude.

modes, such as bistatic (reception with a sensor on a platform other than the one carrying the transmitting antenna) and distributed aperture (system fragmentation into a large number of relatively small radar sensors with synchronized operation and distribution over a large volume) are also under consideration (*4*).

Optimum radar resource utilization may be achieved by the use of an electronically scanned, planar phased-array antenna. Typically, this antenna contains several thousand radiating elements, each of which is connected to a solid-state transmit/receive (T/R) module that generates the radar power, points the radar beam, and acts as the first stage of the radar receiver. Maximum search efficiency (rate) can be achieved by stabilizing the phased-array antenna so that its perpendicular is directed toward the earth's center at all times and by scanning the area within the prime search zone (Fig. 1) where the elongated shape of the footprint of the radar beam results in optimum coverage. (Conventional reflector antennas can be used if their comparatively low search efficiency and poor beam quality can be tolerated.) Operation of the beam in the vicinity of the nadir (the so-called "nadir hole") is normally avoided for three reasons: the search rate is near minimum, the target Doppler shift is sharply reduced, and the radar signal reflected by the earth's surface (clutter return) becomes large and difficult to handle. The nadir hole of each radar may be covered by one of the other radars in the constellation. Also, the size of the nadir hole increases with satellite altitude. Consequently, the number of satellites required to maintain a given level of coverage tends to stabilize rather quickly with increasing altitude (Fig. 2).

The altitude regime of primary interest for SBR deployment is

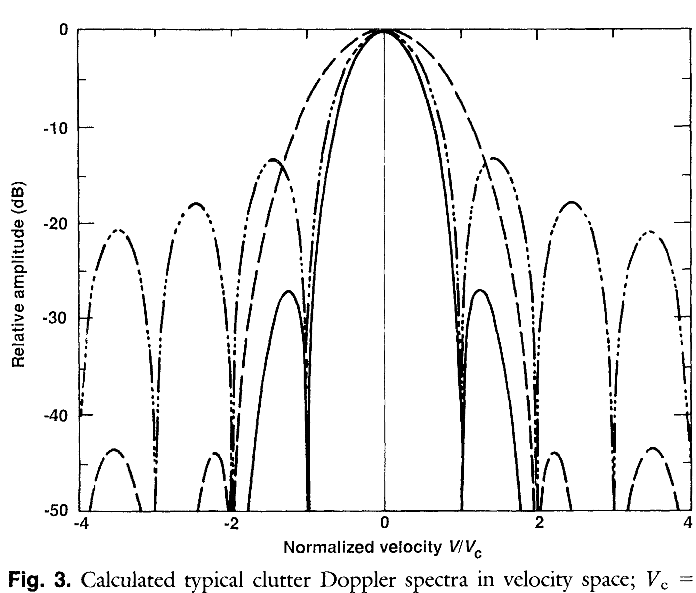


Fig. 3. Calculated typical clutter Doppler spectra in velocity space; $V_c = V_s\lambda/L$, where V_s is satellite velocity, λ is radar wavelength ($\lambda = c/f$ where c is velocity of light and f is radar frequency), and L is antenna length along satellite velocity vector. Transmit beam uniform weighting, dashed-dotted line; receive beam Hamming weighting, dashed line; two-way beam, solid line.

between 1,000 and 12,000 km (*5*). Radar performance against all targets of interest would essentially be constant as a function of altitude. Altitudes lower than 1000 km require smaller satellite sizes but result in substantially larger constellations that have to cope with increased atmospheric drag that may affect their lifetimes. Geosynchronous orbits could be of interest for applications that use the enlarged field of view, although assembly and deployment of the attendant large antenna and power system sizes represent significant problems.

Subclutter Visibility

The fundamental problem confronting MTI SBR is how to neutralize the effects of earth surface clutter. With a stationary radar (with or without a rotating antenna) the signal reflected by the clutter appears at discrete velocities (Doppler frequencies) and can be filtered out. With a radar on a moving platform, the signal is distributed continuously in velocity space, as illustrated in Fig. 3, masking the signal returns from those targets that are embedded in the clutter. The Doppler width of the clutter return is proportional to the satellite velocity, V_s, and to the beam width, effectively the ratio λ/L, of the radar where λ is the wavelength of the radar signal and L is the antenna length along the vector of the satellite velocity. Therefore, the quantity $V_c = V_s\lambda/L$ may be thought of as a characteristic clutter velocity. Whether a target is detectable or not depends on the magnitude of its radar cross section and on the relation of its Doppler velocity to V_c. The minimum detectable velocity (MDV) is a critical system parameter that may be defined as MDV = KV_c, where K is a constant that depends on the parameters of the particular processing method adopted to deal with the clutter. The conventional approach, pulse-Doppler processing (*6*), seeks to reduce V_c by increasing the antenna length sufficiently so as to position the desired MDV outside the extent of the clutter Doppler spectrum for a particular choice of satellite altitude and radar wavelength. In general, pulse-Doppler processing results in MDVs within the range $1 < K < 4$.

An alternative approach is represented by a family of platform motion compensation techniques, collectively known as Displaced Phase Center Antenna (DPCA) processing (*6–8*), which reduce or eliminate the target-masking effects of the clutter by clutter cancellation. The most effective DPCA mode is illustrated in Fig. 4. In the 1970s, at the Massachusetts Institute of Technology, the Lincoln Laboratory Multiple Antenna Surveillance Radar (MASR), an airborne MTI radar system, demonstrated 45 to 50 dB of clutter cancellation by the use of DPCA processing (*9, 10*). Such levels will also be required for many SBR applications. The principal technical challenges in realizing effective DPCA action for SBR lie in matching the displaced beams in amplitude, phase, and pointing direction, and in sufficiently controlling spacecraft attitude. It is necessary to control spacecraft attitude in part because of the need to compensate for the earth's rotation, which would otherwise cause the sequentially radiated radar beams to illuminate slightly different earth surface areas, an effect that is equivalent to incomplete compensation of platform motion. DPCA processing yields MDVs in the range of $K < 1$.

Figure 5 shows the antenna sizes required to neutralize the impact of the clutter for an MDV of 50 m/sec. Such an MDV ensures the generation of sufficient Doppler shift for the detection of a Mach 1 target over approximately 90% of the possible target headings that can be presented to an SBR sensor. Final MTI system sizing would also involve the magnitude of the target radar cross section and other system parameters in order to ensure adequate signal margin against thermal noise as well. In general, with increasing altitude or

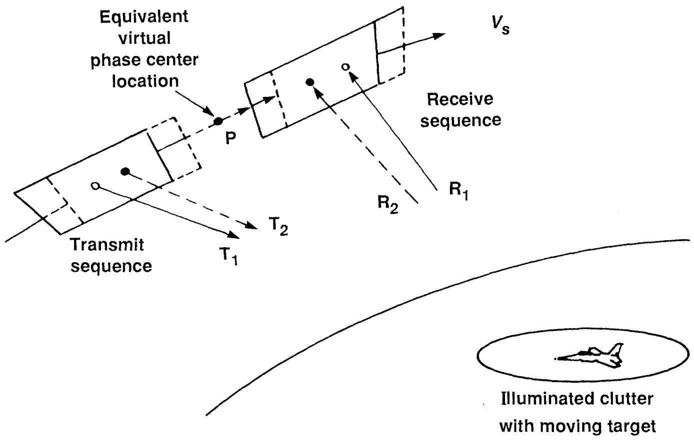


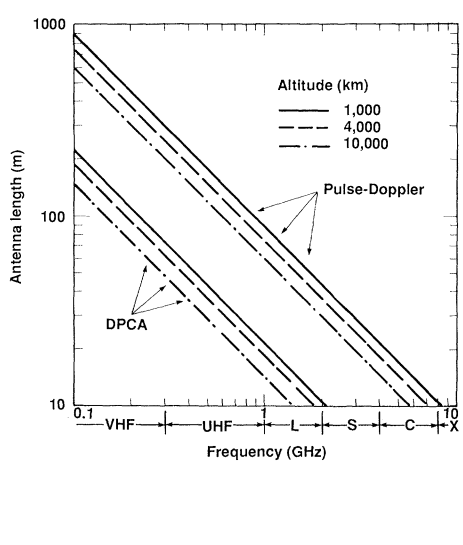
Fig. 4. The DPCA principle applied to space-based radar. The phase center is a specific reference point from which radiation may be said to emanate or to which radiation may be said to converge. The centroid of the radiating or receiving section of a planar array antenna may represent the location of the phase center. The T_1 and T_2 sequences are transmissions that use the entire antenna (phase centers as shown); R_1 and R_2 are the corresponding receptions with selected subsections of the antenna in such a way that the two-phase centers are displaced by equal distances on either side of the centroid of the full antenna. (In general, more than two phase centers can be implemented.) The T_1, R_1 and T_2, R_2 sequences are equivalent to the same spatially fixed geometry characterized by a single, virtual phase center located at point P, exactly halfway between the T_1, R_1 and T_2, R_2 pairs. With the motion of the antenna thus electronically "frozen," the two-way clutter spectrum of Fig. 3 in effect collapses to the zero-Doppler velocity axis where it can be reduced or canceled by signal processing without appreciably affecting the (nonzero) Doppler returns from moving targets.

frequency, the need for motion compensation by clutter cancellation is gradually reduced and may at some point be circumvented, except perhaps when the required MDV is relatively low, for surface-moving targets, for example. If the required MDV is very low or zero, the SAR technique would be more appropriate for detection.

Clutter Effects

A surprising phenomenon encountered by the airborne MASR system was the absence of earth surface clutter strong enough to challenge the full cancellation capability of the DPCA. In SBR, the greatly enlarged earth surface area covered by the antenna beam as well as other characteristics, such as ambiguous range intervals that arise as a consequence of the periodicity of the transmitted pulse repetition pattern (*6, 7*), are expected to generate considerably more clutter. However, no database yet exists for clutter reflectivity measured from space. This fact has forced all calculations of clutter to rely on reflectivity data measured from either near-ground–based or airborne sensors, an unsatisfactory situation given the need for such critical information.

Fig. 5. Space-based radar antenna length required to achieve an MDV of 50 m/sec. This is a plot of the equation MDV = KV_c, where K (see text) is equal to 2 for pulse-Doppler processing and to 0.5 for DPCA processing. The dependence of the satellite velocity, V_s, on altitude, H, is approximated by $V_s = V_e(1 + H/r_e)^{-1/2}$ where V_e = 7.913 km/sec and r_e is the radius of the earth.



Results (*11*) suggest that land clutter reflectivity is constant from ~50 MHz through ~12 GHz, while sea clutter reflectivity is lower from ~50 MHz to ~1 GHz than it is from ~1 GHz to ~12 GHz. Unless accurately calibrated, clutter data are notoriously unreliable. They can also be seemingly capricious, frequently exhibiting an extreme sensitivity to small topographical variations. Near-ground measurements of clutter statistics must be used with caution in extrapolations involving space applications. One of the problems concerns the accurate knowledge of the strength of the dimensionless multipath propagation factor F that, together with the clutter reflectivity σ_o, enters into the actually measured quantity $\sigma_o F^4$.

The individual scattering centers that give rise to the clutter return when illuminated by the beam of the radar may have some random motion. Examples of this motion are ocean waves and ocean currents. This relative clutter motion imparts an irreducible component of Doppler shift to the clutter return, forcing a rise in the quiescent output of the MTI processor, thus reducing the available dynamic range for clutter cancellation. Effects of relative clutter motion were observed with the airborne MASR system where the existence of fairly strong winds over forested terrain was correlated with reduced levels of achieved clutter cancellation. The unpredictable nature of the physical mechanisms that determine the intrinsic clutter Doppler shift makes effective compensation for clutter motion an impossible task. Therefore, relative clutter motion is the ultimate limiting factor in achievable subclutter visibility.

Propagation Effects

The wave propagation phenomena that most influence the performance of SBR are ionospheric backscatter, ionospheric scintillation, and Faraday rotation. (Weather and atmospheric absorption are intrinsically tropospheric phenomena and do not play important roles for the frequencies most suitable for wide-area surveillance. Beam refraction is small and can be calibrated out.) The significance of each of these mechanisms depends on factors such as the instantaneous alignment of the radar beam axis with respect to the earth's magnetic field lines, the sidereal time, and the radar frequency. A sizable body of experimental evidence exists on this subject and warrants special attention, particularly throughout the lower microwave frequency region (<1 GHz). Some residual effects are still present above 1 GHz, but their impact is minimal.

A space-based radar sensor could encounter serious performance degradation as a result of rapidly moving, magnetic field–aligned clutter while attempting to detect targets located behind ionospheric regions with high backscattering properties. In the vicinity of the equator, the effect is present only during nighttime, but in the northern latitudes it persists during daytime as well. There, the presence of E-region (auroral) backscatter compounds the difficulty. One improvement would be to deploy an enlarged constellation that makes available a diversity of observation angles.

Ionospheric scintillation may affect radar performance by limiting the useful coherent integration time. Figure 6 shows the effect of severe scintillation on received signal amplitude as observed simultaneously by the ALTAIR [ARPA (Advanced Research Projects Agency) Long-Range Tracking and Instrument Radar] and TRADEX (Target Resolution and Discrimination Experiments) systems. Similar effects have been observed in received signal phase. From such results, bounds on the coherent integration time can be estimated. Above 2 GHz, other phenomena unrelated to wave propagation will supersede ionospheric scintillation in limiting the coherent integration time. For effective DPCA action, path length invariance is required, typically during a fraction of a millisecond, and natural ionospheric scintillation does not appear to impose serious limitations at such time scales. However, if the radar has to operate through an ionospheric environment perturbed by nuclear explosions, the estimated coherence times could be curtailed by one or more orders of magnitude, clutter cancellation capability would be affected, and frequencies well above 2 GHz could be influenced as well (*12*).

Faraday rotation (*6*) of the plane of polarization of the radar signal may significantly degrade radar sensitivity at frequencies below 1 GHz unless dual polarization is implemented in the antenna. Some evidence suggests that at 1 to 2 GHz single polarization could suffice. The phenomenon becomes negligible for frequencies above 2 GHz.

Structures and Power

A major mechanical and structural problem in obtaining the desired radar performance is the maintenance of adequate antenna surface flatness. For surface distortions that are small compared to the radar wavelength, performance degrades because of reduced clutter cancellation and diminished rejection of interfering electronic signals. In the case of more severe distortion, other key parameters, such as the signal-to-noise ratio, can be degraded as well. Flatness control with conventional techniques that rely on the use of low expansivity materials and the maintenance of isothermal conditions becomes progressively more difficult as the antenna size increases. For large antennas (more than 50 to 100 m in length), new methods for assembling, testing, deploying, and stabilizing structures with low natural frequencies (<0.01 Hz) will be needed. To ensure acceptable radar performance over the lifetime of the system, novel techniques for measuring and controlling antenna surface flatness by means of adaptive mechanical or electronic compensation may be required.

The prime power source for SBR will be either solar or nuclear. For power plant requirements of up to about 100 kW, solar arrays appear to be suitable. These arrays should be backed by sufficient energy storage capacity in the form of batteries or regenerative fuel cells to enable the radar to continue operating during periods when the satellite is blocked from the sun by the earth's shadow. Radioisotopic thermoelectric generators are inefficient, generate large amounts of heat, and do not appear to be promising (*13*). Dynamic isotope power systems use a Brayton or other thermodynamic cycle; they have much higher efficiencies and could become candidates for SBR applications. In advanced, high-power applications, designers may have to use nuclear reactors. The Department of Energy has embarked on the development of a prototype nuclear reactor plant for use in space (the SP-100 project) that has a 300-kW design goal (*13*).

The size of the prime power system is determined principally by the total power radiated by the aggregate of solid-state transmitters, each of which is a part of the T/R solid-state module associated with each radiating element of the phased-array antenna. Although useful modules can be produced with current technology, lowering their overall power consumption would result in substantial size reductions of the power systems and in increased reliability. The T/R module will also include monolithic microwave integrated circuits and gallium arsenide substrate materials in order to produce modules of low weight, small size, and high radiation resistance. The T/R module represents the most technology-intensive component of a phased-array SBR. It will be a challenge to the industrial establishment to develop lightweight units that meet performance requirements and are amenable to low-cost mass production.

Survivability

Background radiation, electronic countermeasures, and direct attack will influence the survival of a SBR system. The radar is expected to operate at ambient radiation levels that may be increased by nuclear explosions, as could happen in peacetime if a high-altitude nuclear test is conducted by a country that has not ratified the atmospheric nuclear test ban treaty. Low-altitude (≤50 km) radioactive release is not expected to be a problem since the released electrons and ions are absorbed in the atmosphere before reaching satellite altitudes. The danger posed to solar cells and to the electronic parts of the radar by Van Allen belt electrons, which constitute the most significant component of the radiation spectrum, may be inferred from Fig. 7, which also shows the relative advantages of the lowest and highest altitudes in this context. Such data can be translated to total allowed dosage over the design lifetime of the sensor in order to meet specifications that will ensure the required levels of reliability.

Electronic countermeasures degrade the effectiveness of SBR and must be considered in the design of the antenna and signal

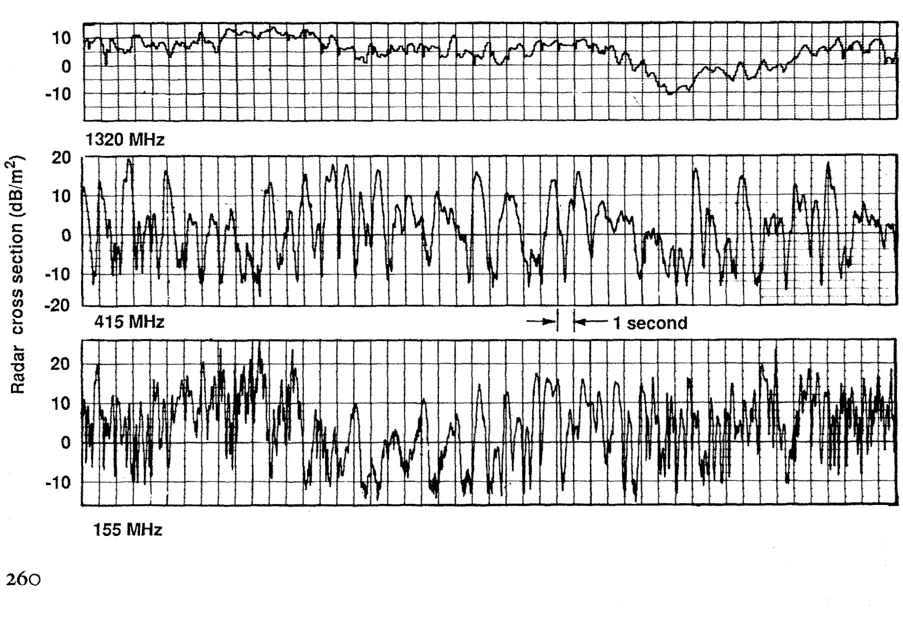


Fig. 6. Actual simultaneous three-frequency track (ALTAIR-TRADEX) of a stabilized cylindrical satellite showing effect of severe ionospheric scintillation on received signal amplitude. Satellite altitude is 1000 km, near peak of sunspot cycle, 2200 local time. Radar location is 9.5°N, 167.5°E.

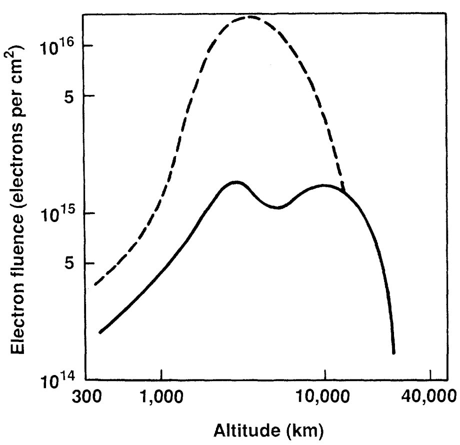


Fig. 7. Estimated natural background electron density (solid curve, 5-year exposure) and possible geomagnetic field saturation (dashed curve, 20-day exposure). Circular orbits, 60° inclination.

processor. Neutralization by jamming is a primary concern at all altitudes and frequencies. The lower microwave frequencies have the disadvantage of limited operational bandwidths, on the basis of current frequency allocations. Also, it is difficult to design components to operate efficiently over substantial bandwidths for these low frequencies. High altitudes reduce the effectiveness of ground-based jammers, but platforms at low altitudes can make better use of horizon shielding to minimize exposure to a jammer. In either case, the capability to null a jammer will have to be included in the signal processor. The design of this component represents an area of major technical challenge, perhaps second only to T/R module design in importance. (Bistatic operation may offer an additional countermeasure since the receiver platform is supposed to be electromagnetically silent, therefore difficult to locate and jam.)

Ensuring physical survivability probably constitutes the most complex problem confronting the deployment of any military space asset (*14*). The higher altitudes have been traditionally associated with an increased probability of survival in an environment in which the principal threats are ground-based, such as antisatellite weapons and lasers. It will obviously take longer for a direct-ascent interceptor to reach and destroy a satellite at high altitude than at low altitude, but, when overall system performance degradation as a consequence of attrition of entire constellations is considered, this advantage may not be significant. The ground-based laser threat points to the need for satellite hardening. Such hardening need not impose an unreasonable weight penalty, but it would become impractical if space-based lasers are considered. Sensor proliferation, through active redundancy or by means of silent spares, is an option, but a costly one at any altitude. As envisaged by the U.S. Air Force's Project Forecast II (*15*), the distributed aperture architecture may offer new possibilities of enhanced survivability and lower incremental cost, if early projections can be sustained. A comprehensive space defense system incorporating secure data links represents the most reliable long-term solution to the problem of survivability.

Frequency and Altitude

Interest in frequencies below ~1 GHz stems primarily from the increased radar cross section for some targets as their dimensions become comparable to the radar wavelength (*11*). This property, coupled with high transmitter efficiency and low component number density, must be weighed against restrictions imposed by ionospheric propagation effects, limitations associated with available bandwidths, and problems attendant to the assembly and deployment of the required larger antennas. These restrictions and limitations become particularly severe in the very high frequency regime from 30 to 300 MHz. Frequencies below 100 MHz are not deemed practical at this time primarily because of the necessity of deploying large antennas, which may exceed half a kilometer in length. The virtual absence of degraded propagation, in addition to comfortable search rates, reasonable system sizes, and not unduly difficult electronic component technologies, have made L-band (1 to 2 GHz) the front runner at this time. Some of these favorable attributes are diminished as the frequency is raised through S-band (2 to 4 GHz). Frequencies above S-band are much less attractive for wide-area surveillance because of drastically reduced search efficiency, difficulty in maintaining tolerances, weather and atmospheric absorption effects, electronic component technology, and high parts density, among other problems.

The choice of altitude revolves around two factors, survivability and system hardware cost. Survivability has been discussed; cost depends on the total count of constellation parts. High altitudes minimize the number of satellites, but low altitudes minimize the total amount of hardware in a constellation. This may be deduced from Fig. 8, which shows a normalized altitude comparison per satellite, and from Fig. 2. However, the overall cost of a deployed constellation will depend on many other factors besides total parts count.

Conclusion

The ADI concept involves the development of a layered network of surveillance, tracking, and engagement systems to counter the threat posed to the continental United States by strategic bombers and air- and sea-launched cruise missiles (*16*). Ground-based, airborne, and space-based architectures are under consideration for this role. An interesting sensor for ground-based defense is over-the-horizon (OTH) radar (*11*), which can overcome line-of-sight limitations imposed by the curvature of the earth and can detect moving targets at large distances by refracting a beam of high-frequency (3 to 30 MHz) radio waves off the ionosphere. A network of OTH radars could perhaps provide coverage to ranges between 1000 and 4000 km from the perimeter of the continental landmass of the United States. Shorter ranges could be covered by conventional, direct line-of-sight radar sensors at microwave frequencies on a sufficient number of moving or stationary airborne platforms. For example, modified Airborne Warning and Control System sensors (*17*) could be used in this capacity. The possibility of using airships is also being studied as a less expensive way to provide constant surveillance.

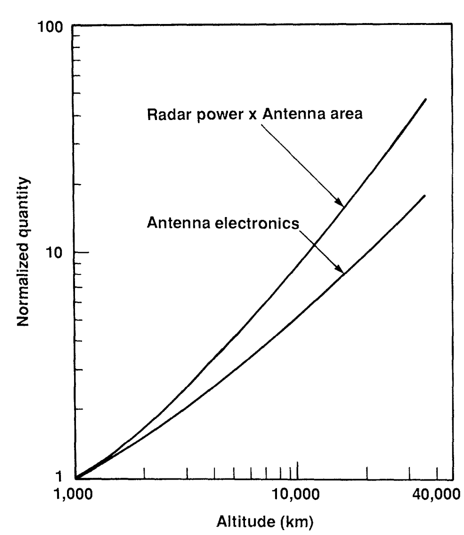


Fig. 8. Normalized altitude comparison (per satellite) of the product of radiated radar power times antenna area (effectively satellite size) and antenna electronics (effectively amount of hardware). Grazing angle is 3°.

The SBR approach enjoys the potential advantage of global coverage and multipurpose capability. Surveillance protection can be extended to force concentrations anywhere, such as naval battle groups, and to the territories of allied nations; it can prove valuable in a world periodically convulsed by outbursts of regional conflict. Tracking of aircraft can in many cases be initiated as soon as they leave their operating bases, thereby providing a measure of identification and mission purpose. The system could also be used for assisting international air traffic control and search-and-rescue operations. On the negative side are two often-cited drawbacks, vulnerability to attack and high cost. These are valid concerns that apply to many space-based applications of military technology.

Currently SBR is in a phase of concept definition and technology development. The Department of Defense is interested in bringing together the various mission requirements to see if the system can be justified. A decision to deploy an operational system will probably depend as much on budgetary considerations as on perceived usefulness, which is generally held to be considerable. The required advances in technology appear to be reasonable, and the development of a baseline system could proceed at this time. A precursor system with the capability to demonstrate the usefulness of the concept to prospective users could consist of one radar sensor at a reasonable altitude. This satellite could be hardened at least against natural background radiation effects and could incorporate some level of resistance to electronic countermeasures. Properly instrumented, this system would also function as an invaluable test-bed, yielding results that could reduce significantly the technical risk inherent in the deployment of an operational system.

One could conceive of a future system architecture that uses a versatile space-based instrument to perform object discrimination tasks (as in SDI) in addition to carrying out wide-area surveillance missions (as in ADI). Although the possibility of such synergism is appealing, effective surveillance and high-quality discrimination with a common sensor have traditionally been deemed incompatible. It would be an impressive achievement in radar technology to demonstrate a unified sensor concept that accommodates both missions without compromising the required levels of performance.

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4. Perhaps the most interesting bistatic configuration consists of space-based transmitters and airborne receivers. This arrangement has the advantage of receiver placement close to the targets, and it is particularly suitable for regional surveillance purposes. However, global coverage is probably not realizable because of the likely exclusion of the airborne receivers from the airspaces of some national sovereignties.
5. The following convention with respect to SBR altitude nomenclature is often followed: low (1,000 to 2,000 km), medium (2,000 to 6,000 km), high (6,000 to 12,000 km), and geosynchronous altitude (~40,000 km). The 12,000 to 40,000-km regime does not appear to offer specific or significant advantages and is currently not actively being explored.
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18. Sponsored by the Department of the Air Force. The views expressed are those of the author and do not reflect the official policy or positions of the U.S. government.

Artificial Intelligence and Natural Resource Management

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The use of artificial intelligence (AI) in natural resource management began with the development of expert systems for problem-solving and decision-making. The use of expert systems in turn led to the development of other AI procedures pertinent to natural resource management. Of particular significance are (i) integrated expert systems, which link management models with natural resource models; (ii) intelligent geographic information systems, which permit interpretation of relations within and among landscape data themes; and (iii) AI modeling of animal behavior and interaction with the environment. These procedures provide new ways to view classic problems in systems analysis.

RESEARCH IN ARTIFICIAL INTELLIGENCE (AI) HAS BEEN performed mainly in computer science and cognitive psychology. The issues have been straightforward: (i) definition and classification of principles of intelligent behavior; (ii) design and development of computer systems (hardware and software) capable of mimicking intelligent behavior; and (iii) use of such systems to solve problems of perception, analysis, and adaptation. The recent availability of dedicated AI workstations and knowledge-systems software has hastened the introduction of AI techniques and products into other sciences. In the literature on AI, which has been developed principally for potential practitioners of

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