MICHAEL J. CANTELLA

Space Surveillance With Medium-Wave Infrared Sensors

To make the coverage of the rapidly expanding satellite population more extensive and timely, current operational space surveillance systems must be upgraded. Infrared sensors can see satellites in the earth's shadow, thereby enabling these sensors to supplement the capabilities of visible-spectrum devices. Sensors that operate in the medium-wave infrared region have good sensitivity and resolution; signal degradation due to the earth's atmosphere is minimal. A practical sensor implementation for space surveillance consists of a large staring array of Si Schottky-barrier detectors. Both ground-based and satellite-borne systems will provide excellent sensitivity and coverage.

The increase in the number of orbiting space objects has created an immediate need to upgrade the United States' space surveillance capability. The population of space objects, which occupies a huge volume, is concentrated at low altitude (100 to 1,400 km). To cover this volume, sensors of adequate sensitivity, coverage-rate, and data-handling capability must be deployed.

Electro-optical sensors, located on the ground, in space, or both, can contribute significantly to the surveillance network capability. These sensors can perform such tasks as post-launch satellite tracking, space-object catalog maintenance, and satellite overflight warning.

Today's electro-optical sensors, which are located on the ground, cover the visible spectrum. At night, when the weather is clear, they offer outstanding performance in data acquisition and in tracking of deep-space objects that are illuminated by sunlight [1,2]. These sensors can also cover low-altitude objects located in the twilight regions, but cannot detect objects in the earth's shadow.

Recently, developmental ground-based visible-spectrum sensors have been used to detect low-altitude objects located on the sun-illuminated (day) side of the earth, but sensitivity is restricted by the high level of background noise due to sunlight scattered by the atmosphere.

By locating visible-spectrum sensors in space, the performance degradation caused by clouds and by atmospheric attenuation and scatter could be avoided. But coverage would be limited to sunlit regions that are above the bright earth-limb. (The earth-limb is the glow region that surrounds the earth.)

The infrared (IR) spectrum offers an opportunity for significant extension of surveillance capability. As shown in Fig. 1, the use of object thermal-emission signatures makes the low-altitude earth-shadow region accessible. For ground-based IR sensors, greatly enhanced performance in the daytime is possible, because of superior atmospheric transmission and scattering characteristics.

Design of an IR sensor for space surveillance requires an appropriate choice of spectral region, detector material, and focal-plane architecture. Most high-sensitivity IR sensors have used a small array of scanning detectors operating in the long-wavelength infrared (LWIR) spectrum (8 to 15 μm). Scanning devices are under development to cover the 15- to 25-μm region.

Recently, significant progress has been made in the development of large focal-plane arrays (FPAs). These arrays have been used in a staring, rather than a scanning format, to achieve excellent thermal sensitivity in the medium-wavelength infrared (MWIR) band (3 to 5 μm). A multispectral capability (down to 1 μm) is also available, which can detect a variety of other signatures. The staring format permits the design of a small, reliable, ground-based or space-borne package.

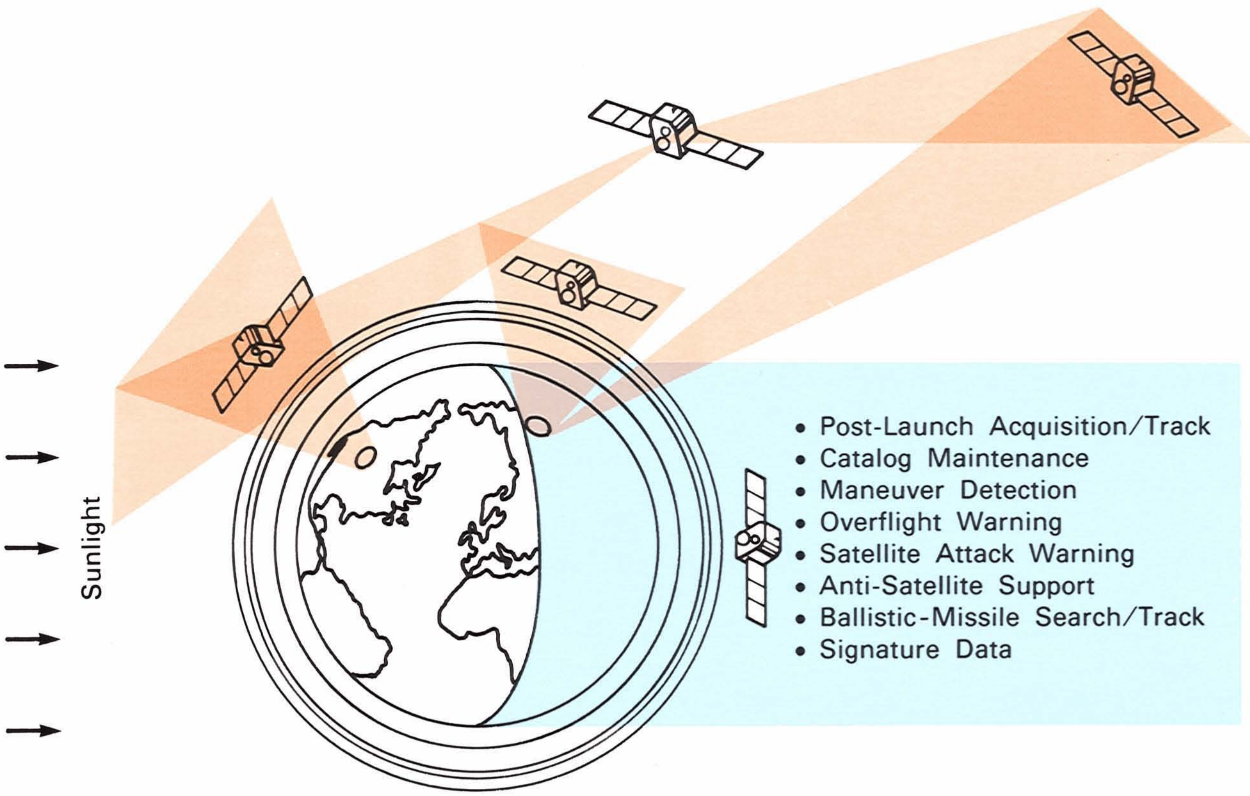


Fig. 1 — Electro-optical space surveillance.

For ground-based systems, atmospheric transmission and path radiance parameters in the MWIR region are excellent. In fact, MWIR sensors provide high performance under a broad range of siting conditions.

The form of MWIR FPA that is most practical to manufacture contains an array of Schottky-barrier detectors. The use of standard Si materials permits successful fabrication of very large arrays of high uniformity — making the design and operation of staring surveillance sensors practical.

SENSOR DESIGN REQUIREMENTS AND METHODOLOGY

Surveillance sensor design is an iterative process that requires assessment and control of hundreds of parameters. Figure 2 shows the major building blocks, such as phenomenology, FPA characteristics, and Dwell-in-Cell range performance. Factors that determine sensor design and performance requirements include the composition and density of the space objects being studied, the tasks to be accomplished, the location of the sensor, and the position of the space object. Typical ranges of interest vary from 300 to 60,000 km; angle-rates vary from 5 to 3,000 arcsec/s. The urgency of obtaining surveillance data and the angular resolution requirements also affect the design and performance needed from the sensor and data processor subsystems. Revisit times vary from 10 s to several days; angular resolutions vary from 1 to 10 arcsec.

The design requirements of a sensor's optics need careful consideration. A space-borne configuration must have radiation shields and cryogenic cooling, which reduce IR background. But these components can add to the size and weight burden of a space-borne configuration.

The right choice of spectral band and FPA technology can minimize size and weight. In the MWIR spectral band, for example:

1) Diffraction-limited resolution considerations allow the use of a small aperture;

2) The optics and the FPA can generally be operated at a relatively high temperature.

Historically, little emphasis has been placed on the MWIR band, largely because an FPA

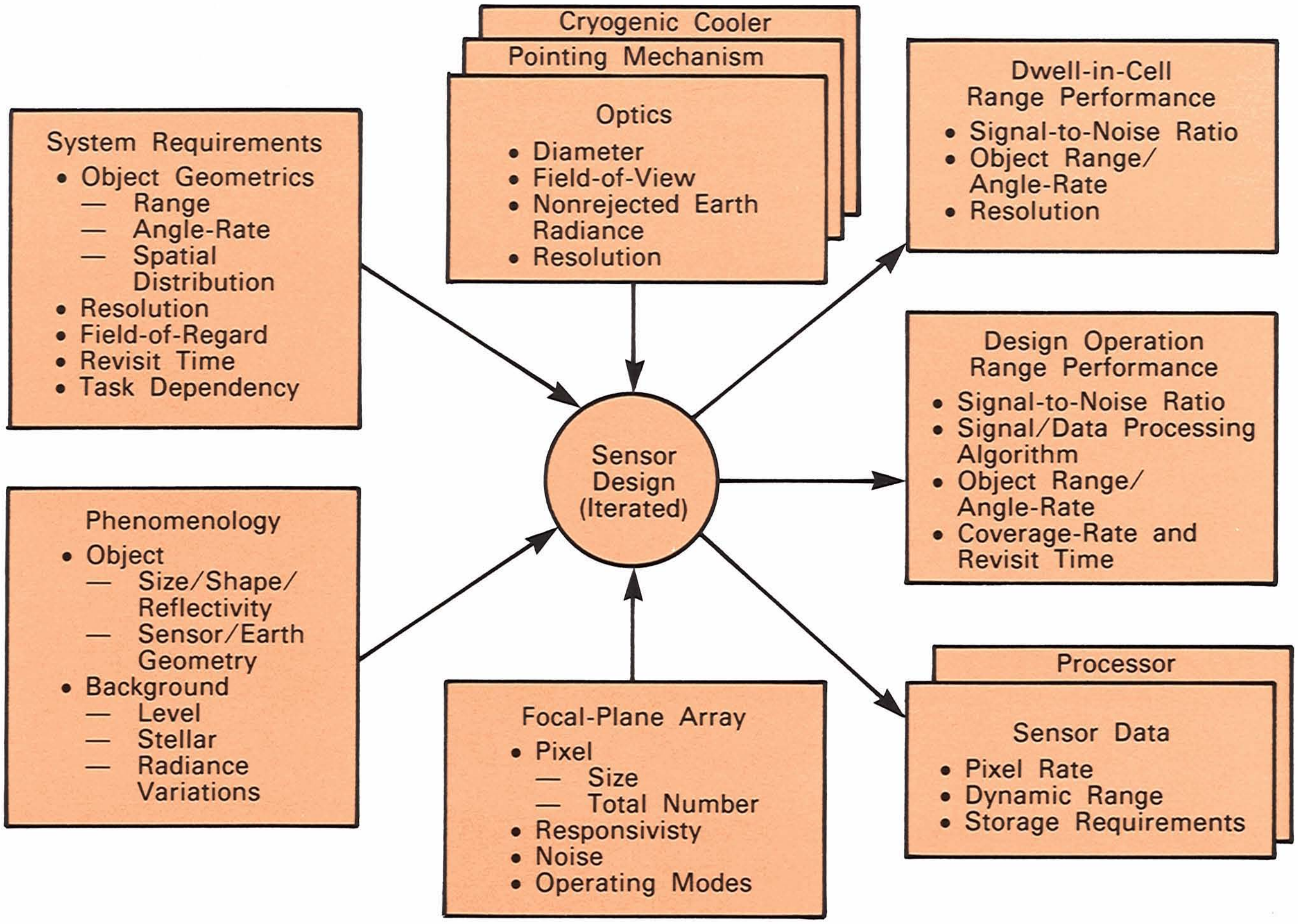


Fig. 2 — Sensor design criteria.

technology, with sufficient sensitivity for the low levels of flux in this band, has not been available. Now that fabrication of very large staring FPAs is becoming practical, high-sensitivity detection and tracking are possible.

CHARACTERISTICS OF THE ENVIRONMENT

An FPA that covers short-wavelength infrared (SWIR) and MWIR spectral bands can detect many signatures, including thermal emission, solar reflection, earthshine, plume radiation, and laser reflection. This article concentrates on MWIR operation with passive, cold-body signatures, which include thermal emission and solar reflection, both supplemented by earthshine.

Figure 3 presents typical signature and earth-limb spectral radiance data for a space-borne surveillance sensor. Historically, deep-space optical surveillance systems have operated at night in the visible spectrum, where sunlight is bright and the sensor can avoid earth and earth-limb backgrounds. But recently, LWIR and very-long-wavelength infrared (VLWIR) systems have been under development which can take advantage of the high level of thermal radiation beyond 8 μm. The bands also contain a high level of earth-limb background, however, and off-axis radiation from the earth is difficult to reject.

The MWIR band has a lower thermal and solar-reflection signature level than visible, LWIR, or VLWIR bands, but the earth-limb and off-axis earth-radiation components of background are also significantly lower. Therefore, on the basis of background-noise-limited performance, the MWIR band offers sensitivity performance levels comparable to those of

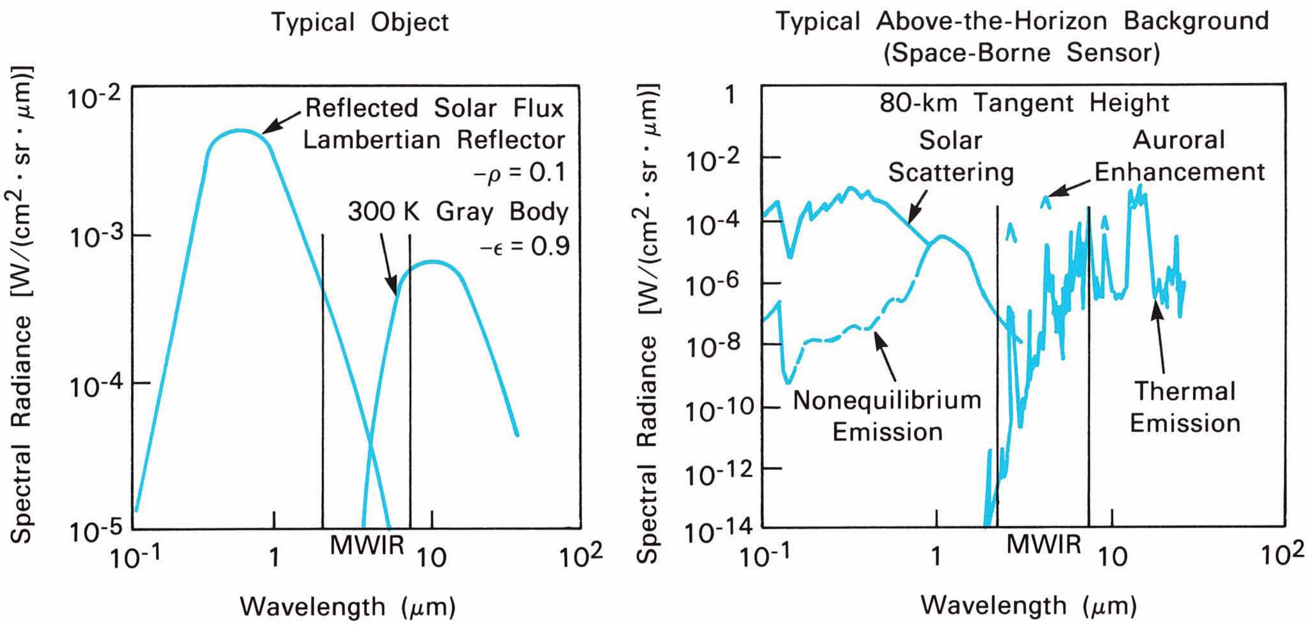


Fig. 3 — Object and background radiance.

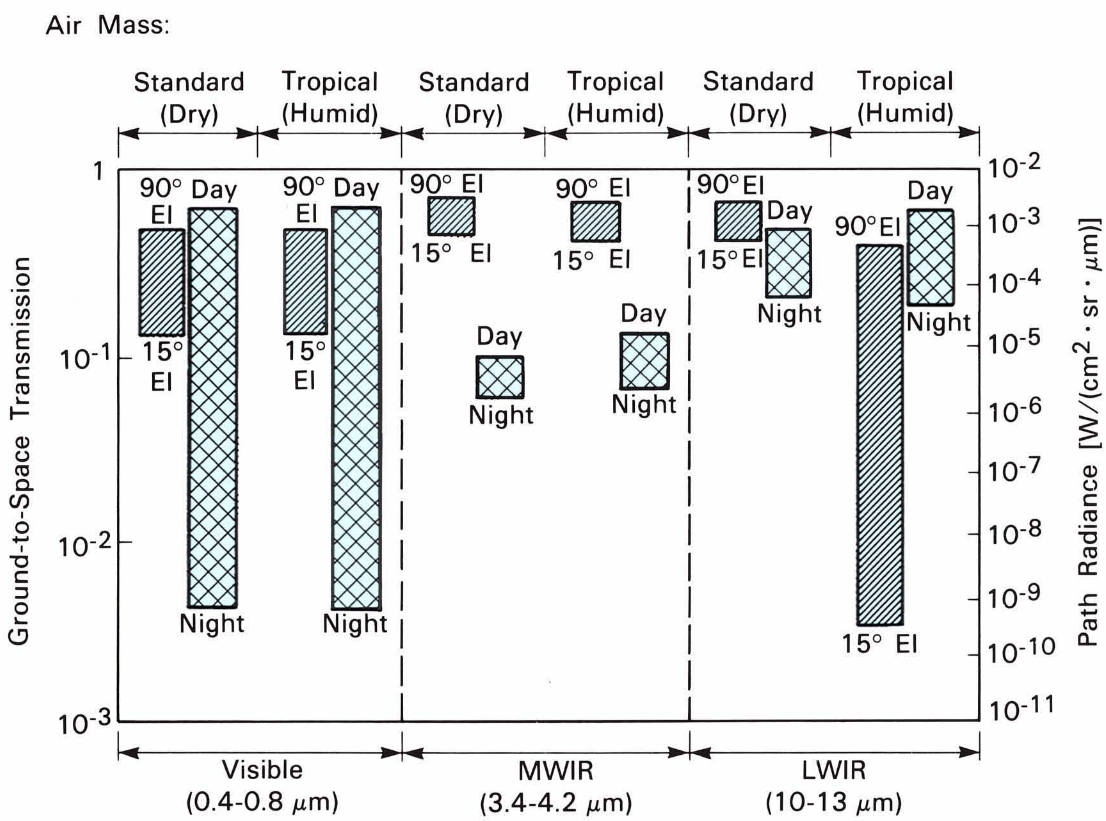


Fig. 4 — Ground-to-space atmospheric transmission and path radiance.

the LWIR band. Moreover, MWIR operation provides the inherent advantage of improved diffraction-limited resolution.

The behavior of ground-based surveillance sensors depends on the properties of the ground-to-space atmospheric path. Transmission losses affect the signal level; radiation from thermal emission and scatter both produce background noise.

To understand the influence of the atmosphere on MWIR and LWIR sensors, ground-to-space transmission and path radiance data have been studied. Using data obtained from published measurements [3] and from the United States Air Force (USAF) Geophysics Laboratory LOWTRAN program, these properties have been plotted (Fig. 4) for standard (dry) and tropical (humid) air masses. Transmission is plotted for elevation angles from 15° to 90°. For maximum coverage from a particular ground site, low elevation angles are desirable.

For both humid and dry air masses, transmission in the visible band is worse at low elevation angles than at high angles. In the LWIR band, transmission is good in a dry air mass, but is essentially unusable in a tropical air mass. In contrast to the visible or LWIR band, the MWIR band provides good transmission in both air masses.

To achieve high sensitivity, atmospheric path radiance must be low. Path radiance data for day and night conditions are included in Fig. 4. (Path radiance varies much less with elevation angle than does transmission, so that consideration has been omitted.) In the visible band, radiance increases by a factor of approximately 10^6 during the daylight hours, which causes a substantial loss in sensitivity. But in the MWIR and LWIR bands, radiance varies much less. The MWIR band exhibits the best potential for daytime operation.

Site placement, coverage, and day/night operation are important to a ground-based system. The transmission and path radiance data show that the MWIR band has the most desirable properties.

SENSOR QUANTUM AND PHOTON-COLLECTION EFFICIENCY

To provide efficient utilization of the photon-collection capability of an optical aperture, a sensor must be efficient in converting radiation flux to photoelectrons. In this process, quantum efficiency plays a major role.

Figure 5 plots the characteristics of commonly available detector materials. The quantum efficiency of Schottky-barrier detectors is considerably lower than that of other solid state detectors, and this has inhibited their use in traditional IR scanning-sensor designs. However, as discussed below, the use of a large number of detectors in a staring format can compensate for the lower quantum efficiency. Furthermore, Schottky-barrier FPAs have attained very low noise levels, yielding outstanding sensitivity.

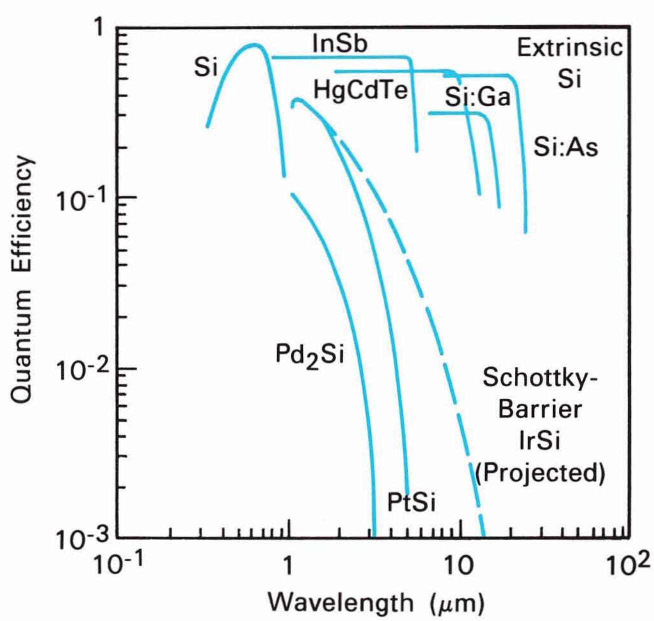


Fig. 5 — Detector quantum efficiency (IrSi projection furnished by Dr. Freeman Shepherd, Rome Air Development Center).

Although quantum efficiency and noise levels are important, an even more fundamental attribute of sensor design is photon-collection

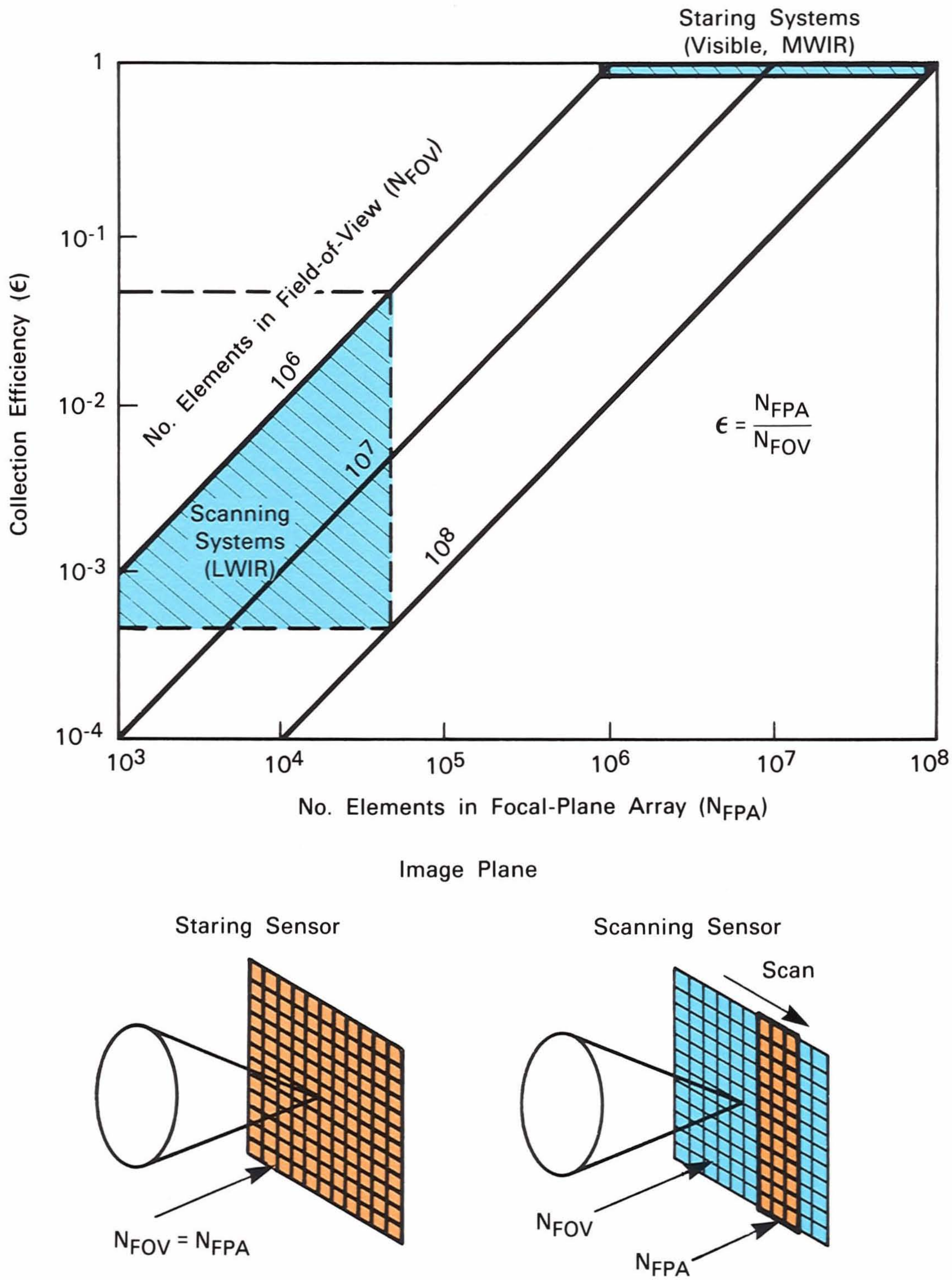


Fig. 6 — Sensor photon-collection efficiency.

efficiency. Figure 6 illustrates the significance of photon-collection efficiency. At the lower left of the figure, a staring sensor occupies the entire image plane defined by the sensor field-of-view. Photons are collected on all FPA pixels simultaneously, so this configuration captures all flux that impinges on the system's optics. In contrast, a scanning sensor (lower right) contains an FPA that occupies only a small fraction of the image plane, so it can intercept only a small portion of the flux collected by the optics. The collection efficiency can be approximated by the ratio of occupied to total number of pixels in the focal plane. The graph in Fig. 6 plots this relationship.

The range of total number of pixels plotted covers virtually all perceived design requirements for future space surveillance systems. These requirements range from coarse-search to fine-track capabilities and are driven by overall system requirements for resolution, coverage, and revisit time. Also outlined in Fig. 6 is the availability, projected for the next two decades, of number of pixels for scanning LWIR FPA technologies and for staring visible and Schottky-barrier MWIR FPA technologies. As shown in this figure, the collection efficiency of staring sensors is superior to that of scanning sensors. This high efficiency compensates for the relatively low levels of photon flux available in the MWIR range. Thus, an MWIR staring sensor can achieve high overall sensitivity and provide an alternative to conventional LWIR scanning sensors.

For a large staring Schottky-barrier FPA, the photon-collection efficiency is sufficient even to offset the relatively low quantum efficiency of the detectors. The ease of production of these FPAs makes them attractive for near-term deployment.

SCHOTTKY-BARRIER FPA TECHNOLOGY

Schottky-barrier FPAs have been under development [4-6] since the early 1970s. They offer a promising possibility for implementation of an advanced space surveillance sensor. Currently, these sensors operate in the SWIR and MWIR bands, so they can detect a wide variety of signatures, including thermal emission and reflected sunlight. To enhance thermal response, advanced materials that permit extension of operation to the LWIR band are under development.

Table 1 — Attributes of Schottky-Barrier FPA Technology

Monolithic Si Construction
Standard integrated circuit materials and processing
FPAs can resemble advanced visible CCD designs
Large Staring Sensors Feasible
High resolution
High uniformity for simplified signal processing
Multispectral/multifunction capability
Low refrigeration load

Table 1 lists the key attributes of these arrays. The monolithic Si construction permits realization of very large arrays operating in a staring mode. The Schottky-barrier FPAs can incorporate the advanced techniques developed for multiplexing and readout of visible and other FPAs. The high uniformity (nonuniformity $<1\%$) exhibited by this technology makes operation of the sensors in a staring mode practical. And the realization of large staring FPAs makes possible the design of a mosaic of taskable sensor segments of high resolution, high sensitivity, and high traffic-handling capability.

Schottky-Barrier Detection Principles

The principles of Schottky-barrier detection developed by Walter Schottky (see page 87) are illustrated in Fig. 7. On the left side of the figure is a basic photodiode structure and a corresponding energy diagram. The diode consists of a metal deposited on a semiconductor (p-type Si in this example), a source of internal photoemission. Infrared radiation passes through the semiconductor and excites electrons in the metal, which raises the electrons' energy above the Fermi level. A portion of the resulting energy distribution is high enough to exceed the metal-semiconductor Schottky barrier (ψ_{ms}), so a hole is transported into the semiconductor — leaving a net negative charge stored in the metal. The height of the Schottky barrier determines the cutoff wavelength for photoemission; the

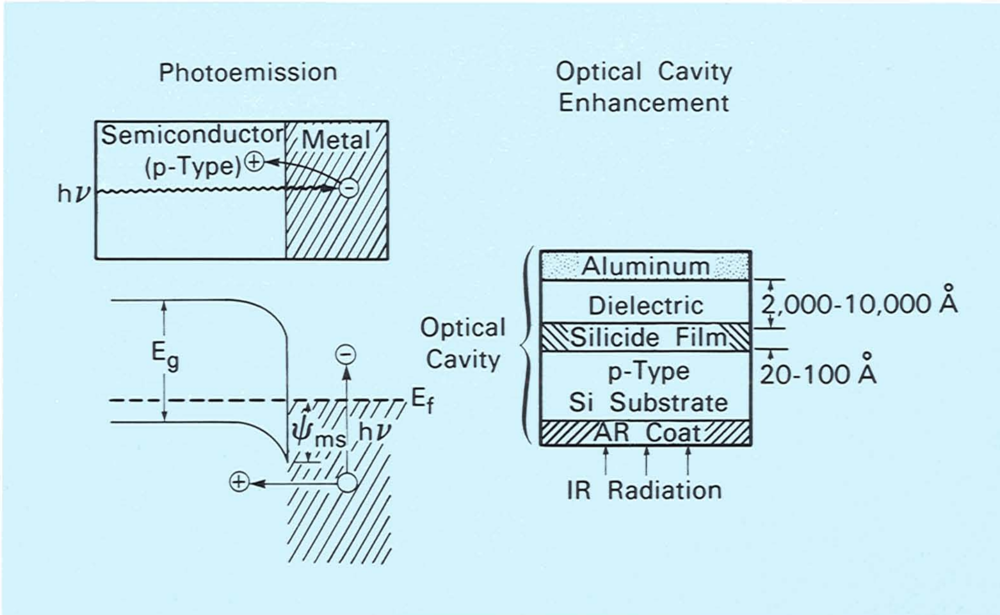


Fig. 7 — Schottky-barrier detection principles.

electron energy distribution determines the shape of the roll-off (which is different from that observed in other solid state detectors). Since photodetection occurs at the surface, the device has essentially no susceptibility to imperfections in the substrate material. A Schottky-barrier array, therefore, can achieve outstanding uniformity performance.

A more accurate picture of a practical Schottky-barrier detector is presented on the right side of Fig. 7. The metal is actually a very thin silicide film. To enhance the interaction between incoming IR radiation and the silicide surface, a tuned optical cavity is formed on the opposite side of the silicide.

Presented in Fig. 8 is a highly developed 160 × 244-pixel interline-storage charge-coupled device (CCD) made by RCA [7]. The signal-integration and readout process is illustrated in the cross-section, which contains a Schottky diode and storage well. During the integration time period, charge accumulates on the back-biased Schottky diode and at the n^+ diffusion. At the end of the integration period, the transfer gate is pulsed, and charge is dumped into the CCD storage register. Clocking signals are used to accomplish serial readout by charge transfer, first line by line into a serial storage register and then to the output amplifier.

The photon-collection efficiency of an FPA structure depends on the fraction of detector area in the focal plane (fill-factor). The RCA FPA in Fig. 8 has a fill-factor of 0.39.

In another form of a Schottky-barrier staring FPA, Hughes constructed and tested a 256 × 256 hybrid array [8]. This structure features an In-bump bond, which connects each Schottky-barrier diode to a busing structure (used for readout). The device has attained a fill-factor of 0.85.

Another device, demonstrated by RCA, has a Schottky silicide formed as a continuous surface on the IR radiation side of the structure [9]. To provide a drift region for emitted electrons journeying to the CCD wells on the opposite side of the substrate, the Si is thinned to approximately 25 μm. A field gradient across the substrate prevents lateral spread of charge. This structure provides a fill-factor of 1.0 and can be used to adapt a Schottky-barrier IR response to almost any type of Si multiplexing structure (such as visible frame-storage CCDs).

Schottky-Barrier FPA Quantum Efficiency

Typical quantum-efficiency characteristics are shown in Fig. 5. The Pd_2Si device, which operates at a temperature of approximately

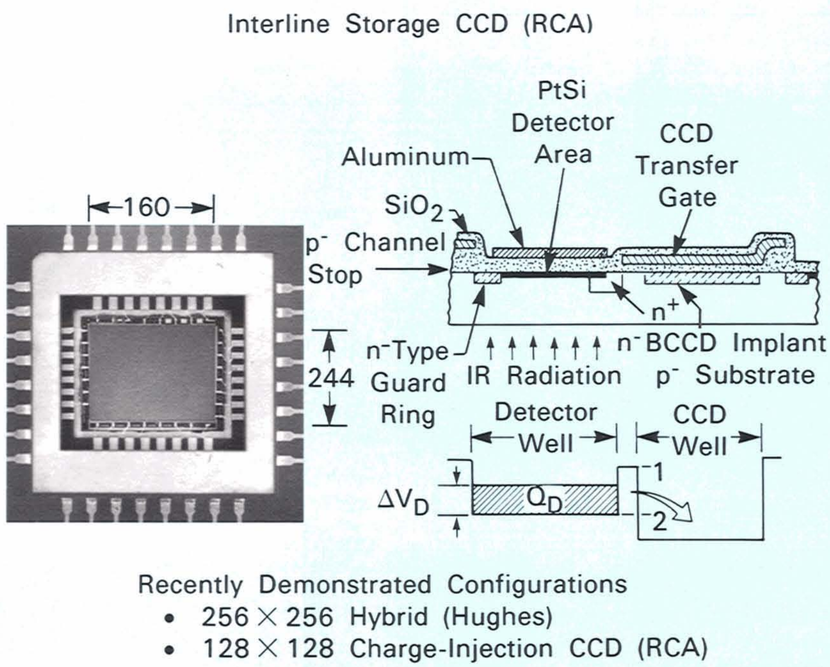


Fig. 8 — FPA signal integration and readout.

140 K, detects photons in the SWIR band. Both frame-storage and line-scan devices have been operated successfully.

The PtSi surface can detect light in both SWIR and MWIR bands; it requires cooling to approximately 80 K. This device has been applied principally in the frame-storage mode, and extremely good thermal sensitivity has been demonstrated.

For future low-background, space-borne surveillance applications, the thermal sensitivity of Schottky-barrier FPAs should be extended even further. Various approaches are being pursued. The projected spectral response of an advanced IrSi surface is also presented in Fig. 5. This surface is expected to have a cut-off wavelength of 16 μm and to operate at approximately 40 K. Combined with staring-mode operation, the extended-wavelength response would provide significant improvement in system range performance.

Thermal Imagery

The concept of using a Schottky-barrier FPA for high-sensitivity thermal imaging has been put into practice. A 160 × 244 element Schottky-barrier FPA camera (Table 2) has been constructed. Using an unsophisticated, 12-bit, linear-offset signal processor, a thermal sensitivity of 0.03°C has been achieved. Presented in Fig. 9 is a thermal image of a man's face. Note the excellent thermal detail. This image also includes a cigarette lighter, which has a thermal radiation level approximately 10^7 more intense than the facial thermal detail. The simultaneous imaging of these radiation extremes demonstrates the outstanding dynamic range performance of this device.

Table 2 — Schottky-Barrier Imaging Camera Specifications

Optics:	100 mm, f/3.5
FPA:	160H×244V pixels, interlaced
Video format:	30 frames/s, standard TV raster
Fixed-pattern noise correction:	12-bit additive
Sensitivity:	Noise-equivalent ΔT=0.05C

Fig. 9 — Thermal image of man's face.

SURVEILLANCE SENSOR RANGE PERFORMANCE

Computation of sensor sensitivity requires numerous parameters (Fig. 10). Besides the quantities discussed previously, signature components include earthshine; background components include telescope and cold-shield radiation, as well as FPA dark current. Also included are system requirements for angular resolution and for coverage. To compute exposure and noise, these parameters must be combined appropriately. For a fixed signal-to-noise criterion, sensor performance can be expressed in terms of range vs angle-rate for different environmental conditions. A more mathematical and quantitative description of these performance computations can be found in the literature [10,11].

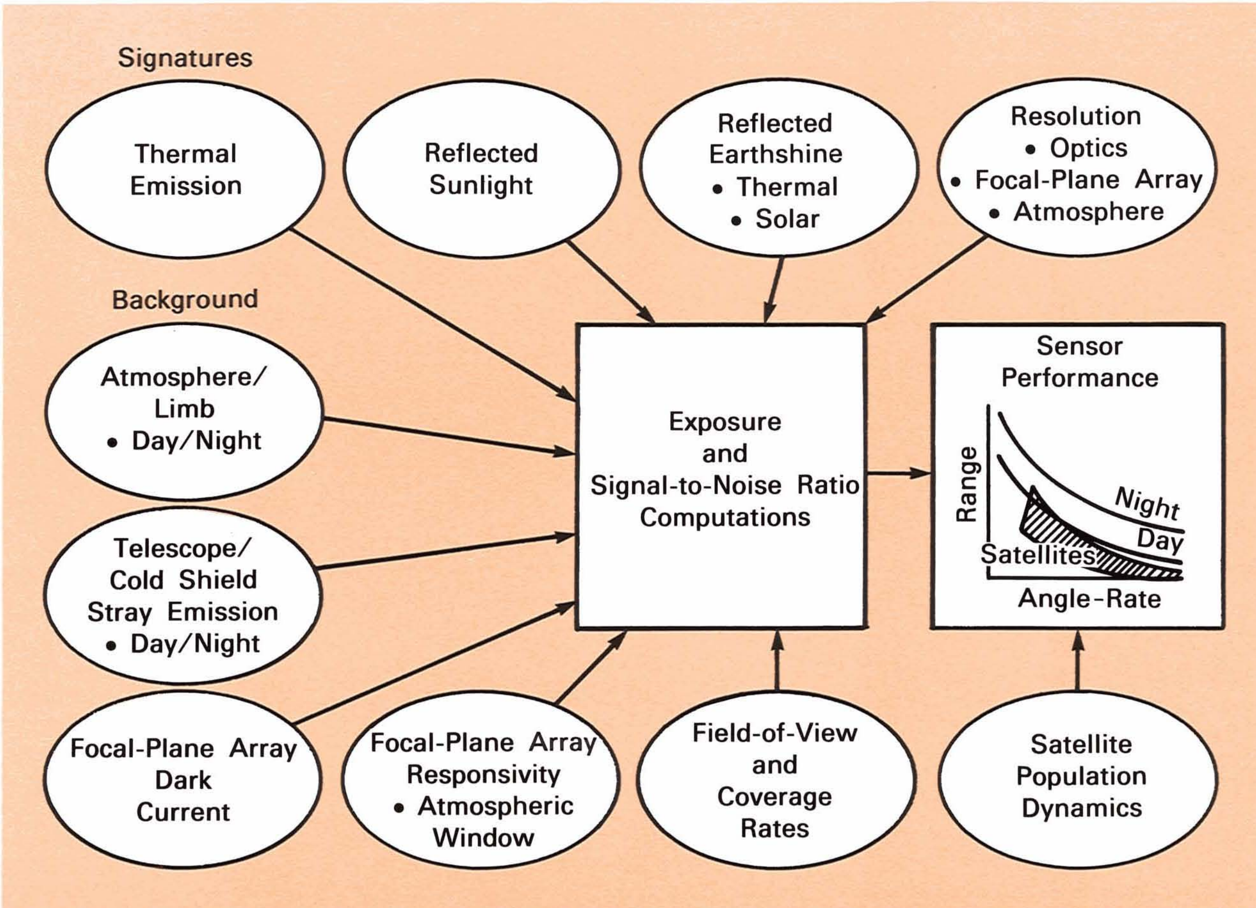
For this discussion, the Dwell-in-Cell type of range performance can illustrate the basic capability of Schottky-barrier FPA technology. In Dwell-in-Cell performance, sensor integration time is adjusted for each value of angle-rate, so the object moves just one resolution element in that integration time. This gives a nearly optimal performance for a simple threshold detection processor and provides good first-order assessment of any sensor design. The utility of this type of sensor-detection performance can be assessed by comparing it with an overlay of separately determined range vs angle-rate characteristics for satellite populations of interest.

Ground-Based MWIR Sensor Performance

For a PtSi type of Schottky-barrier FPA mounted in a telescope at Lincoln Laboratory's Electro-Optical Test Site, the range performance is expected to follow the predictions given in Fig. 11. This graph plots the detection performance for fairly large satellites under day and night conditions.

Because of reduced resolution-element integration time, range decreases with angle-rate. Day performance is somewhat higher than that of night both because solar radiation adds substantially to thermal emission and because daytime atmospheric path radiance is low in the MWIR region.

Figure 11 includes the range vs angle-rate region associated with low-altitude circular-orbit satellites that have elevation angles of 15° to 90°. These angle-rates have a sidereal refer-



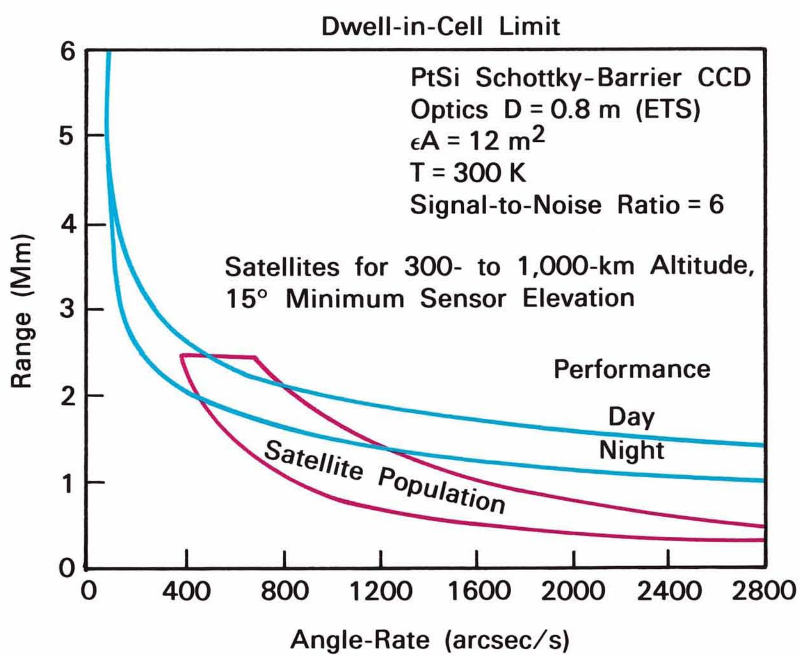


Fig. 11 — Ground-based MWIR sensor performance.

ence and correspond to operation of the sensor in an autonomous, open-search mode. Stars are immobilized during the integration time period, so they can be rejected by a moving-target indicator (MTI) type of signal processor. Although this open-search mode is very demanding, Fig. 11 indicates that essentially all satellites can be detected in the daytime and approximately 75% of them can be detected at night. For ground sensors of this type deployed as a surveillance fence, observed satellites will cluster near the lower boundary of the population presented in Fig. 11. This clustering effect will permit the detection of virtually all satellites under both day and night conditions.

At low angle-rates, sensor range performance is substantially higher than the maximum range of low-altitude satellites. This performance margin permits detection, tracking, and signature analysis of much smaller objects, when some *a priori* knowledge of location is available.

Space-Borne MWIR Sensor Performance

Figure 12 plots predicted range vs angle-rate performance for a space-borne sensor with an advanced IrSi FPA. The performance is plotted for object cross-sections of 0.5 m^2 and 5 m^2. Superimposed on this plot are near-earth and deep-space satellite populations, as observed from a sensor located on a 5,600-nautical-mile platform and with line-of-sight stabilized to inertial space. This represents a completely autonomous open-search requirement. Figure 12 shows that this capability can be realized for objects of 0.5 m^2 in the near-earth population and 0.5 to 3 m^2 in the deep-space population. At low angle-rates, the indicated range performance margin can permit the observation of even smaller objects, when some *a priori* knowledge of location is available.

The projected performance for these advanced FPAs will give a future surveillance-sensor network outstanding sensitivity and coverage.

SUMMARY

Ground-based and space-borne space surveillance sensors must now be able to cover the earth's shadow and operate at night, and in full daylight. This capability will provide timely coverage of both high-altitude and low-altitude satellites.

Current surveillance sensors detect satellites by using reflected sunlight in the visible spectrum. For deep-space objects, these sensors provide excellent sensitivity and coverage. But

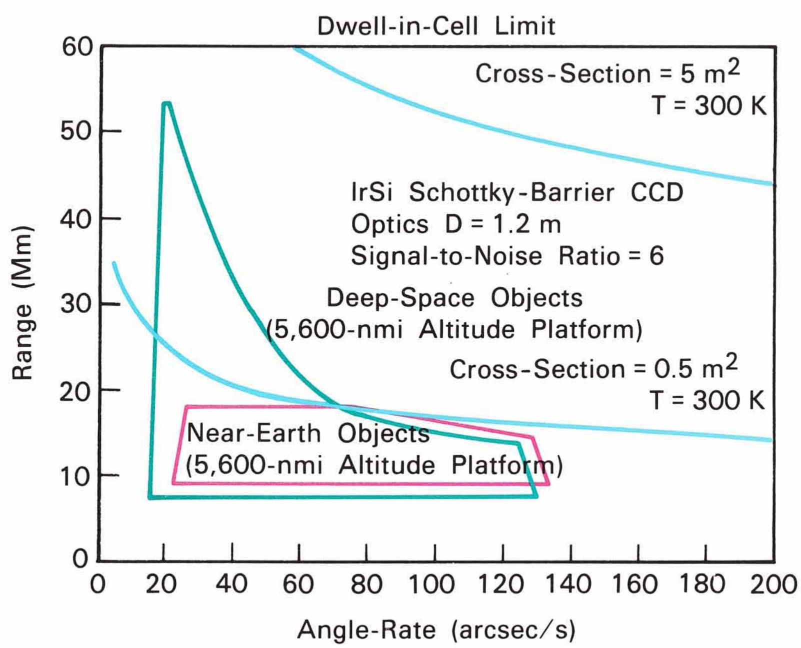


Fig. 12 — Space-borne MWIR sensor performance.

these sensors need to be complemented with IR sensors that can detect thermal radiation.

Because large staring arrays are now practical, a new approach to the design of IR surveillance sensors is possible. A staring array of IR sensors with high photon-collection efficiency can provide excellent sensitivity, so this configuration can operate efficiently with a wide range of MWIR (3 to 5 μm) signatures.

For space-borne systems, the MWIR band yields high angular resolution and low earth-limb background. For ground-based systems, atmospheric transmission and path radiance parameters are excellent, so a wide range of siting conditions can produce good results. By using a staring (rather than a scanning) format, the system can handle high traffic yet avoid mechanical complexity.

The most practical staring FPA device is a monolithic Si structure that contains Schottky-barrier diodes coupled to a CCD. With room temperature backgrounds, high thermal sensitivity has been demonstrated. Moreover, these devices can be built into very large arrays.

Theoretical performance estimates indicate excellent potential for both ground-based and space-borne Schottky-barrier systems. In ground-based systems, currently available PtSi detectors can give an impressive level of performance. Unlike visible-spectrum sensors, these sensors can cover low-altitude satellites in the earth-shadow region and in full daylight. A modest space-borne capability is also possible.

To increase the thermal sensitivity of future space-borne systems, the long-wavelength quantum efficiency of Schottky-barrier materials should be extended. Initial developmental efforts on IrSi look promising. Such a material will increase the range performance of space-borne sensors and provide coverage of small objects in near-earth and deep-space orbits.

Walter Schottky

Walter Schottky (1886 to 1976) developed the space-charge and surface-barrier theory of crystal rectifiers, which led to the Schottky-barrier photodiode described here. In his earliest research, he developed screen-grid and tetrode tubes. In 1918, Schottky discovered the super-heterodyne principle with intermediate-frequency amplification, which became an essential factor in the development of radio and television. As a professor at Rostock University (1923 to 1927) and as an industrial scientist at Siemens (1927 to 1958), he studied the statistics and thermodynamics of defects in crystals. Schottky retired in 1958, but continued to receive wide recognition for his many contributions. Schottky emission in cathodes, the Schottky diode, and Schottky transistor-transistor logic are terms we use today that remind us of this great scientist's brilliant research. (H. Welker, *Solid State Electron.* **19,** 817 [1976].)

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MICHAEL J. CANTELLA is a senior staff member in the Space Surveillance Group, where he specializes in electro-optical sensor systems. Before joining Lincoln Laboratory four years ago, he worked for RCA. At RCA, Michael pioneered development of systems for space surveillance, laser target designation, night vision, and real-time reconnaissance. He received a bachelor's degree in electrical engineering from Rensselaer Polytechnic Institute and a master's degree in electrical engineering from MIT. In his spare time, Michael sings with his church choir, plays the piano, and sails.