Space debris characterization using thermal imaging systems

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Abstract

Thermal imaging systems continue to improve and become more broadly available for commercial and scientific applications. In particular, continuing improvements in staring infrared imagers are enabling applications involving sensing of cooler objects such as space debris. This paper uses analytical modeling techniques to consider notional schemes for thermal imaging of space debris given assumed thermal and size properties. The modeling uses sensitivity parameters for cooled infrared sensors along with standard methods for dealing with target signature, range, and background. Two modes of operation are envisioned for these schemes. In one, postulated cold-environment platforms are used to overcome limitations associated with optical emissions. Such cold-environment sensing allows the use of ground-based medium-aperture optics as a means of gathering signature data on space debris from an earth-fixed perspective. A second mode of operation is also envisioned in which space-based platforms are used allowing more diversity in the sensed objects, illumination conditions, and viewing aspects. Using typical ephemeris and physical data for a class of debris objects, a feasibility analysis was performed to establish the frequency with which debris objects can be viewed. Notional payload configurations consistent with the assumed viewing range limit and debris properties will be described. Finally, the potential benefits of using such a thermal imaging concept for debris characterization will be shown, including the potential to support efforts to predict debris behavior and develop mitigation or avoidance strategies.

1. Introduction

Space debris continues to attract attention due to the growing threat it poses to high-value assets and personnel that are or will be operating in near-earth space. The threat of debris requires finding solutions to problems such as predicting trajectories and collision effects. These solutions support debris mitigation and protection efforts, both of which require knowledge of debris characteristics. Since custody of space debris is extremely rare, characterization requires an observational solution using space surveillance technologies. Improved debris characterization is being pursued using state-of-the-art facilities such as those at the Maui Space Surveillance System (MSSS) [1]. Improved debris characterization could yield information on mass, shape, and density of objects, which can increase accuracy of orbit propagation and hardening calculations. Secondary characterization objectives include albedo and material composition since these can be used with other observables to estimate characteristics such as mass. In particular, if albedo is known, thermal imaging data can reveal mass properties due to the dependence of temperature on both mass and albedo. The ongoing need to improve knowledge of debris characteristics can be met by combining existing observation systems with expanded capabilities using thermal imagers and remote basing strategies.

Thermal imaging sensors, also known as imaging infrared sensors, represent one potential class of sensors that could be applied to the problem of characterizing debris. Continuing improvements in this technology, in particular staring focal-plane arrays (FPAs) of HgCdTe photodiodes [2], can enable relatively low-cost systems that can be applied to the problem of space debris. Debris observation using thermal imaging is an extension of thermographic methods used for terrestrial problems such as preventative maintenance, fault detection, and medical imaging. While best known for enabling observation in the absence of sunlight, as a substitute for optical sensors that depend on reflected sunlight, thermal imaging also uniquely allows thermal characterization by observing changes throughout the diurnal cycle. Under conditions that allow the object to be spatially resolved, the effective blackbody temperature can be determined using a calibration process, providing impressive thermal accuracy. However, space objects, especially debris objects that are usually quite small, are difficult to resolve with a thermal imager. As a result, detection and characterization will usually be done with data obtained under unresolved conditions. In these instances, an estimate of temperature can still be derived, assuming that the projected area of the object is known. Area estimates can be derived using multispectral techniques or data collected with active sensors.

This paper addresses application of thermal imaging for debris observation using analytical methods similar to those presented by Dynetics at the 2009 Advanced Maui Optical and Space Surveillance Technologies Conference [3]. The emphasis of that paper was on setting design parameters such as aperture size so that explicit operational requirements for a space-based sensor are met. Analytical modeling requires known or estimated source signatures, which provides the rationale for ground-based signature measurements. However, the aperture requirements for the ground-based sensor also depend on the source signature. Given the requirement to view the same object, albeit from different distances, the required aperture size for the ground-based sensor can be established relative to that of the space-based sensor. This is done by determining the increased losses for the ground-based system due to increased viewing range, atmospheric losses, and background conditions. Using an example where the space-based sensor views from a range of 20 km and the ground-based sensor from a range of 1000 km, the ground-based aperture was shown to need an aperture diameter 100 times that of the space-based sensor. The effect of increased range by itself would require an aperture that is 50 times larger. The effects of atmospheric loss and background further doubles the size of the required aperture. The source signature depends on temperature and projected area. Temperature can be estimated by modeling incident flux from the sun and earth, while the area can be estimated from radar cross section (RCS), which is available from a space object catalog. This provides a basis for performance estimates.

A key problem with either ground-based or space-based observations is the emissions from the optics. For instance, consider a small ground-based thermal imager with 30 cm aperture that views a 280 K object with area of 100 cm^2. Assuming that atmospheric emissions can be neglected, the maximum range using 25 °C optics is less than 50 km. However, cooling the optics to -65 °C can increase the range to over 100 km. This phenomenon is consistent with the interest by the astronomical community in observing from Antarctica, where winter temperatures at the Dome C site average -65 °C. The high altitude and dry atmosphere provide further advantages. The analytical modeling that is outlined in this paper shows that 100 cm^2 space debris can be detected with a small thermal imaging system with

80 cm aperture. While a limited capability, such observations could be used to establish debris signatures for further study with a space-based sensor.

Space-based thermal imaging systems provide another means by which debris characterization can be expanded. To allow use of a low-cost approach, close encounters with debris are desired. If optics are maintained at cold temperatures consistent with winter conditions at Dome C, then 25 cm^2 debris can be viewed at ranges up to 50 km with a small system with aperture of 30 cm. This approach could enable an increased understanding of thermal behavior and underlying mass and materials properties.

A notional experiment involving a space-based thermal imager and a controlled breakup event was simulated numerically. The breakup involved debris particles that disperse from a central object in a circular orbit with altitude of 1000 km. The dispersion pattern corresponded to a uniform variation in each velocity component. The delta v for each component varied from -45 m/s to 45 m/s in increments of 10 m/s. As a result, there are 1000 debris particles with magnitudes of velocity differences ranging from 9 m/s to 78 m/s, expanding outward from the original object in what initially appears to be an exploding cube. While strictly notional, such an experiment would provide recurring viewing opportunities for the space debris at ranges within the aforementioned 50 km limit of a small-aperture thermal imager. The total debris volume is 2.5 m^3.

Since 2007, there have been at least three satellites that have broken up and created persistent debris. Increased use of space not only by governments but by commercial entities suggests that similar breakup events will occur in the future. Since rapid-response space missions are under development, there is the possibility of using a space-based thermal imaging capability to observe post-breakup debris during the months following an event. This would afford frequent close-up viewing opportunities which would yield previously unknown data on the thermal and mass properties of debris that could be used to improve tracking performance and debris mitigation strategies.

2. Existing Debris Observations

There are a plethora of existing reports describing efforts to gather data on orbital debris and motivated by the need to understand and manage the risks of collisions between spacecraft and debris. A SPIE conference entitled "Space Debris Detection and Mitigation" was held in 1993 and included one paper describing the use of thermal imaging [4]. However, most efforts for observing debris have emphasized visible and non-thermal imaging technologies. A recent report of laboratory characterization of debris-like objects has likewise addressed non-thermal methods [5]. One advantage of visible imaging is the existence of very sensitive systems for viewing satellites, consistent with one report involving a large-aperture visible system to view debris using zenith-stare mode [6]. This work involved logging occurrences of any space debris passing through the sensor field. Since large-aperture visible telescopes provide the needed sensitivity to see small debris objects, given proper illumination, these have formed a mainstay of efforts to keep up with the population of small debris in low-altitude orbits.

Analytical modeling of detection for the visible band frequently makes use of the apparent visual magnitude to quantify signature. For both CCD-based visible systems and thermal infrared systems, it is convenient to use an approach based on photon radiance. The distinction is that the visible system uses the photon radiance of the sun based on its temperature of 5900 K whereas the thermal infrared uses self-emission based on the object temperature. Photon radiance is used by Eq. 1 shown below for computing SNR of a CCD-based visible surveillance sensor, providing estimates as a function of aperture diameter among other parameters:

$$SNR = \frac{2c\Delta\lambda 10^{-(-M_{sun}+M_d)/2.5}\Omega_{sun}}{\lambda^4\left(e^{hc/\lambda kT_{sun}}-1\right)} \frac{\pi D_o^2 \tau_{atm}\eta_{blur}\eta_q\tau_o t_{\mathrm{int}}}{4N_n} \tag{1}$$

The parameters of this equation include physical constants speed of light c, visual magnitude of sun M_{sun}, subtended solid angle of sun Ω_{sun}, temperature of sun T_{sun}, Planck constant h, and Boltzmann constant k. Further parameters include system properties diameter of optics aperture D_o, center wavelength λ, spectral bandwidth $\Delta\lambda$, blur circle efficiency η_{blur}, quantum efficiency η_q, optics transmittance τ_o, noise electrons N_n, and integration time t_{int}. The source brightness is given by visual magnitude of debris M_d. Assuming SNR=10 and integration time of 30 s, an efficient CCD-based telescope with 2 m aperture diameter should be able to view objects as dim as magnitude 20. This value reckons the blurring effects of turbulence by using η_{blur}=1%. The visual magnitude of an object depends on the illumination phase angle, reflectivity, and viewing range. For instance, an object with albedo of 50% and diameter of 10 cm would have visual magnitude of 13 when viewed from a range of 1000 km. Using Eq. 1, this implies a telescope with 8 cm aperture would suffice for detection if it uses t_{int}=30 s. Smaller debris objects with diameters down to 1 cm would require a large telescope with aperture around 100 cm. With the capability to view small debris objects at significant ranges, the preferred use of visible systems for viewing debris can easily be understood. The limitations are mainly the inability to see objects that are not sunlit and limited characterization capabilities. In contrast, thermal imaging, while limited to larger objects in low altitude orbits, provides a means of using thermal behavior as a means of obtaining improved characterization and thus expanding overall capabilities.

3. Analytical Modeling of Ground-Based Thermal Imager for Debris Viewing

Detecting space debris using a thermal imaging system is a difficult task. The difficulties result from the small sizes typical of most debris objects combined with the high background associated with warm optics. Another problem is the errors of propagating orbits of debris objects for which the drag properties are poorly known.

Optical emissions are modeled using photon radiance based on reflected solar or emitted target flux assuming the target is resolved. The combined flux establishes the SNR for a fully resolved object and is computed based on the Planck law [7]. Signature measurement requires that the read-out wells of the FPA are not saturated. A reasonable upper limit on the well fill is 90%. Given the read-out capacity, the integration time must be set such that the combined total flux results in the desired number of electrons N_e for 90% fill. This results in the relationship shown in Eq. 2, which disregards effects from dark current:

$$\frac{N_e \lambda^4 \left(1+4F^2\right)}{2 t_{\text{int}} \eta_q A_d \Delta\lambda \pi c} = \tau_o \left[\exp\left(\frac{hc}{kT_d \lambda}\right)-1\right]^{-1} + \left(1-\tau_o\right)\left[\exp\left(\frac{hc}{kT_o \lambda}\right)-1\right]^{-1} \tag{2}$$

In addition to the previously used parameters, Eq. 2 uses sensor parameters focal ratio *F* and detector area A_d. There are two sources of emissions in Eq. 2. The signal component depends on the debris temperature T_d, while the background component depends on the optics temperature T_o. The optical transmittance τ_o affects both components. A lower value for optical temperature allows the signal component to dominate the background component. Lower optical temperatures will increase the SNR when viewing a resolved target with nearly full wells as long as the dark current limit is not reached. The background-limited SNR is given by Eq. 3, showing the advantage of using an FPA with large read-out wells and cold, clear optics:

$$SNR_{BL} = \left[1 + \frac{1-\tau_o}{\tau_o}\left(\exp\left(\frac{hc}{kT_d \lambda}\right)-1\right)\left(\exp\left(\frac{hc}{kT_o \lambda}\right)-1\right)^{-1}\right]^{-1} N_e^{0.5} \tag{3}$$

This shows the strong influence of the optics temperature on the background-limited SNR. This appeal of cold optics provides the rationale for the use of sites in Antarctica for thermal imaging instruments such as International Robotic Antarctic Infrared Telescope (IRAIT) [8], due to the low air temperature which greatly reduces thermal emissions from the optics. Furthermore, Antarctica provides inherent thermal stability, due to the lack of any significant diurnal cycle. One particularly appealing location in Antarctica is Dome C, which has a median temperature of -65 °C in winter and -26 °C in the summer [9]. Given that astronomers are using this site for thermal infrared sensing, this provides a useful example for considering debris sensing.

To illustrate the benefit of cold optics such as would be the case of Dome C in winter, the SNR versus debris temperature is shown Fig. 1 using optics with 70% transmittance and temperature -65 °C and FPA with N_e is 45E6 electrons. In [4], the thermal equilibrium for a non-sunlit blackbody debris object at 1000 km altitude is given as T_{eq}=250 K, with the blackbody-equivalent temperature of a gray-body with absorptivity α given by $T_d = \alpha^{0.25} T_{eq}$. A value of α=40% (or 60% albedo) corresponds to 200 K for the blackbody equivalent temperature. Based on typical debris albedo of around 10% a temperature of around 240 K is more realistic. Using a maximum integration time of 0.1 s penalizes the λ_c=4 μm curve so that the background limit is not easily reached. This shows the benefit of using a long-wave infrared sensor.

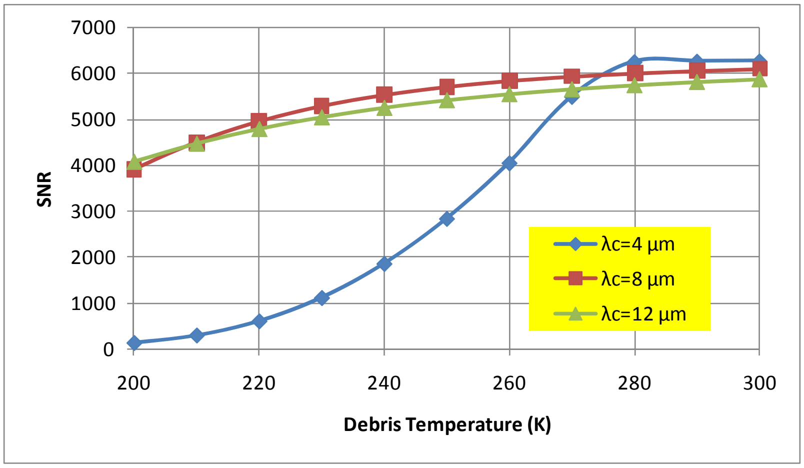

Fig. 1. SNR for Integration Time Constrained <0.1 s, Dome C in Winter, 30 cm Aperture

Before addressing the more realistic condition for the unresolved target, the accuracy of the temperature measurement is considered. Assuming that the system response is calibrated and the losses due to optics and atmosphere are known, the noise-equivalent temperature difference (NETD) estimates the thermal accuracy of the radiometric system. The value of NETD plotted in Fig. 2 for winter at Dome C using the previous example.

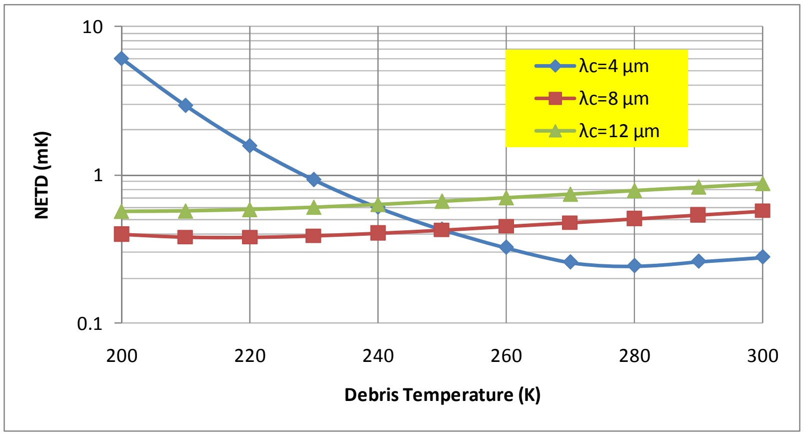

Fig. 2. NETD for Resolved Target Characterization, Dome C in Winter

For the case where both emissions from the optics and read noise can be neglected, the ideal NETD for a resolved target can be derived from the basic equation relating read-out charge to target temperature:

$$NETD_{ideal} = N_e^{-0.5}\left[1 - e^{-hc/k\lambda T_d}\right]kT_d^2 / hc \tag{3}$$

For a sufficiently cold optic that is able to resolve the object of interest, obtaining thermal accuracies less than 10 mK is physically realizable as long as dark current effects can be sufficiently reduced. This is a powerful tool for characterization albeit one that is contingent on developing an agile space-based system that views at close range.

For the ground-based scenario, realistic aperture limitations must be considered. As previously mentioned, the IRAIT project is deploying a small system at Dome C in Antarctica at the Concordia Station [10]. The system features an 80 cm aperture and two FPAs, an InSb 256x256 FPA from Raytheon and an Si:As 128x128 FPA from DRS. Even this small system has been many years coming to fruition due to the challenges of the environment and robotic operation. Such a small aperture is incapable of making space debris measurements under fully resolved conditions as considered by the preceding analysis. Resolved measurements would require basing in space and precise maneuvers. However, unresolved measurements of low-altitude debris using a medium aperture system in a cold environment are feasible. Instead of making a direct measurement of the target radiance (and hence its blackbody-equivalent temperature), the target intensity is measured instead, which requires that the viewing range is known. If the projected area is also known, then the target radiance can be determined from intensity, allowing thermal characterization.

The well fill under unresolved conditions is not dependent on the target emissions but rather on the optical emissions and dark current. As was previously done, dark current will be not be included in the calculations, which yields an optimistic solution but serves to show the potential benefits to be derived from the colder optics temperatures if sufficient cooling or detector quality is obtained to limit dark current effects. If the well fill is determined by the optical emissions, then the integration time for background-limited imaging is computed using Eq. 4 below, which was used to compute the values given in Table 1.

$$\tau_{\text{int}} = \frac{N_e \lambda^4 \left(1 + 4F^2\right)\left[\exp\left(\frac{hc}{kT_o \lambda}\right) - 1\right]}{2\eta_q A_d \Delta\lambda \pi c \left(1 - \tau_o\right)} \tag{4}$$

Table 1. Integration Time and Blurring for Non-Resolved Detection, Dome C Winter

Center Wavelength	Integration Time for Dome C Winter	Integration Time for Dome C Summer	Blur Circle Efficiency
4 μm	1.5E+01 s	1.0E+00 s	88%
8 μm	4.4E-02 s	1.1E-02 s	42%
12 μm	1.2E-02 s	4.9E-03 s	22%

For an unresolved target, there are two additional losses in signal. The measurement of a resolved target consists of determining the effect that a part of the target has on a single pixel that sees nothing but target. In contrast, for an unresolved target, the measurement consists of determining the effect that the whole target has on a group of pixels that is influenced not only by the target but also by the surrounding background. Further, the long integration times for the medium-wave infrared would prevent use of high frame rates, so performance estimates should consider a minimum frame rate. Using 10 fps as was done earlier imposes further signal loss for the medium-wavelength case. Using this constraint and modeling the aforementioned losses, the SNR is computed for viewing 10 cm debris at a distance of 250 km under Dome C winter conditions. Atmospheric losses have not been included. The results are plotted in Fig. 3, which indicates that the best performance would be obtained using the 8 µm wavelength.

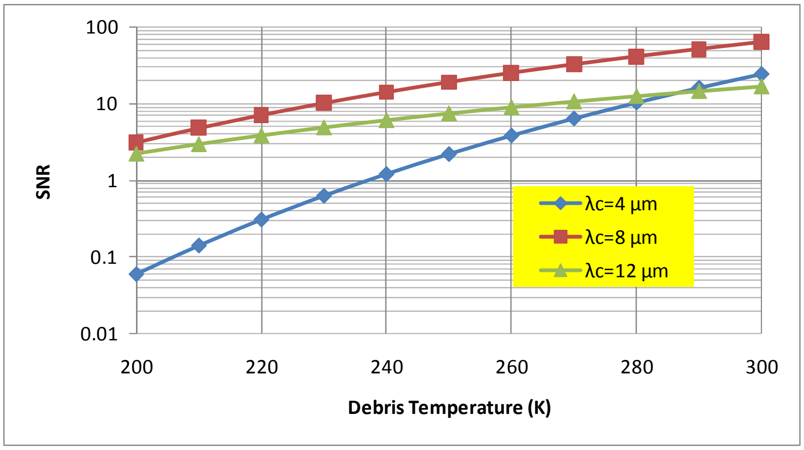

Fig. 3. SNR Versus Temperature for Space Debris At 250 km Range

Just as was the case when the resolved target was considered, the accuracy of the thermal measurements can be considered when the target is unresolved. The NETD for the unresolved case was computed analytically and is shown plotted in Fig. 4 for the same example used for Fig. 3. It is assumed that both the range and the size of the debris object are known accurately. The result assumes sufficient SNR for detection, which in this case is limited to use of the 8 µm wavelength for debris temperature above 230 K.

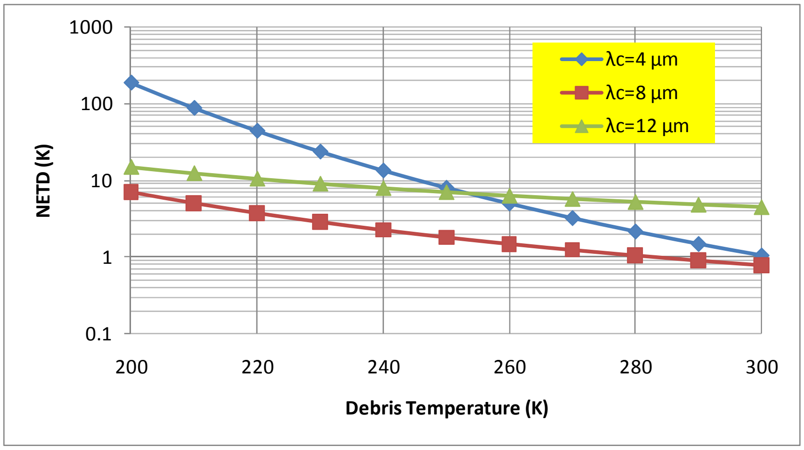

Fig. 4. NETD Versus Temperature for Space Debris At 250 km Range

4. Orbital Propagation of Simplified Break-Up Event

Although space debris is prolific, a space-based thermal imager would only rarely pass near debris objects because they are distributed among dissimilar orbits. However, following a breakup event, there are numerous debris objects with similar orbits. To show the potential for frequent viewing encounters in this situation, a controlled breakup event was simulated. The simulation computed position data for a period of 92 days for a postulated thermal imager and 1000 debris objects. A simple circular orbit was used for the thermal imager. The debris orbits were created by applying delta v offsets to the orbit for the imager. The debris objects initially appear as an exploding cube with debris particles having differential velocity magnitudes relative that of the imager of from 9 m/s to 78 m/s.

Using the previously described analytical modeling, it was determined that a small aperture of 30 cm would suffice for detecting objects with area 25 cm^2 from a range of 50 km. This assumes debris temperature of at least 230 K and the optics temperature of -65 C. Given this range limitation, the number of viewing opportunities was assessed by determining how often there was at least one debris object within 50 km of the thermal imager.

Within the first 1.3 hours of the breakup event, the debris particles with the smallest differential velocities are within range continuously of the thermal imager. After this initial period, the viewing opportunities recur separated by intervals during which none of the debris particles is within range. The first recurring viewing opportunity occurs just 2 hours after the initial breakup. On average over the 92-day period, debris particles are within range 9% of the time. The average value of the minimum range calculated over all debris objects for hour-long intervals is shown plotted in Fig. 5. Although the hour-long averaging suppresses many brief periods for which the minimum falls below 50 km, it shows there are long periods for which the nearest object lies far beyond the maximum range of the sensor.

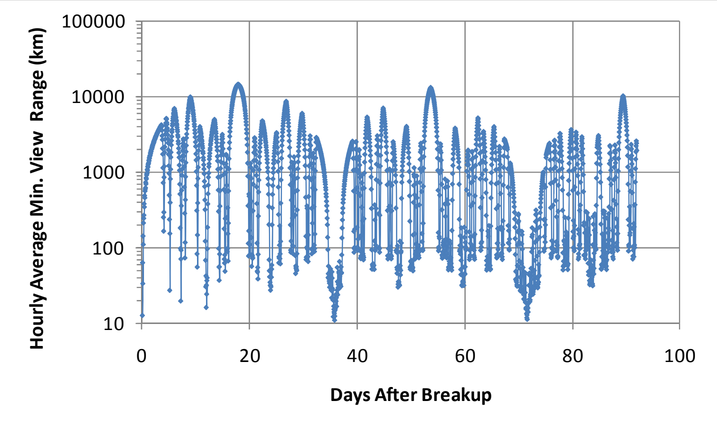

Fig. 5. Minimum Viewing Range During Notional 92-Day Debris Viewing Experiment

The simulation of the debris dispersion from such a notional breakup event demonstrates that even though the smallness of debris makes thermal characterization challenging, it is conceivable that a space-based sensor placed in a suitable orbit could view post-breakup debris on a relatively frequent basis. A controlled space experiment such as the one simulated could provide a means of demonstrating this concept and correlating the thermal observations with known particle characteristics (such as mass and albedo). However, this would require careful planning to avoid unintended collisions which may preclude any real-world implementation. A more realistic scenario might be a future unintended satellite breakup leading to a quick-response sensor mission to obtain thermal data on resulting debris. In either case, the detailed planning would not only have to consider the use of the sensor for viewing debris (including details such as attitude control and data dissemination) but also implications for safety given the possibility some debris encounters might be too close for comfort.

5. Space-Based Payload for Debris Characterization

Given that the foregoing analysis based on a controlled release of debris particles, a basic concept for a space-based debris characterization has been formulated. The concept consists of two primary components. The first component is a staring long-wave infrared camera utilizing a HgCdTe FPA with high quantum efficiency, fill factor and pixel operability and with low dark current. Second, it should utilize a fast, compact optical design with focal ratio about F/2 and collecting aperture with diameter of 30 cm. The total weight including the on-board computer and power supply should be about 50 kg.

As discussed in [4], the temperature of a space object depends on the solar illumination. For an altitude of 1000 km, the maximum theoretical equilibrium temperature is 315 K for sunlit and 255 K for non-sunlit conditions. Given thermal shielding from both the sun and earth, an optical temperature near the -65 C (208 K) winter condition at Dome C should be possible. This should allow achieving the 50 km detection range against debris necessary for achieving frequent (~10% occurrence rate) viewing of particles from the controlled debris release.

Further work is necessary to refine the attitude control and measurement capabilities for the concept. However, some basic calculations are provided. Given the velocity difference is no more than 100 m/s, the rotation rate required to track through a tangent point with viewing distance of 50 km is less than 2 mrad/sec. If the tangent point is within 10 km of the sensor, the sensor requires a rotation rate of less than 10 mrad/sec. Given a field of view of 1 deg, the pointing accuracy should be at least 0.05°. Tracking data with which to cue the sensor to the approaching debris should be accurate to ±100 m assuming that the object is acquired at the maximum range of 50 km.

The primary benefit resulting from thermal characterization of space debris is an increased understanding of the mass and optical properties of debris objects. Since debris objects present a significant hazard to all spacecraft including manned missions, the knowledge gained would result in significant safety enhancements for space operations. The use of space-based thermal imaging provides advantages since ground-based thermal imagers are limited by emissions from warm optics and atmosphere. Even telescopes in a very cold environment such Dome C in winter have a very limited means of detecting small debris at altitudes above 500 km. In contrast, a space-borne thermal imager has the potential to obtain unique data on debris objects that would help improve the accuracy of tracking predictions for debris at altitudes above 500 km. Debris at this altitude tends to decay very slowly and hence gaining a better understanding of characteristics such as mass would provide tracking benefits long into the future.

6. Summary

Maturing thermal imaging technologies enable new options for conducting space surveillance. Thermal imagers in particular provide well known benefits such as being able to operate through periods when solar illumination is not available. Lesser known advantages include the ability to perform thermal characterization. Using this capability for characterizing debris objects could benefit efforts to mitigate debris and enhance safety of space operations. This paper has applied analytical modeling to demonstrate that obtaining sufficient sensitivity to view space debris requires cool optics to reduce the effects of background. One possibility for achieving this is to base a medium aperture optic in Antarctica at a site such as Dome C. In addition to low temperatures this site features excellent atmospheric conditions. Even with these advantages, viewing debris at higher orbits requires a space-based thermal imager. A small-aperture system provides sufficient capability to view debris resulting from a breakup event. If such a system were inserted into a suitable orbit following a breakup event, valuable information on the thermal characteristics of the debris could be obtained and used to benefit efforts to mitigate debris effects in the future.

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