Infrared Sensing for Space-Based Space Domain Awareness

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1. INTRODUCTION

The typical phenomenology Space Domain Awareness (SDA) missions rely on is designing a system that observes in the visible spectrum. Mission design in the visible bandwidth provides heritage commonality with requirements and other metrics. However, due to the reliance on reflected light for observations in the visible, issues such as eclipses, poor illumination scenarios, and smaller objects hinder an SDA mission. Using a different frequency band for SDA missions is a solution to some of the limitations present when only observing in the visible. Expanding the SDA mission into the infrared also improves threat detection sensitivity which allows a payload to see deeper, enabling threat detection monitoring of the cislunar regime.

The infrared bandwidth spans from approximately 0.7μm to 1000μm. The visible spectrum is commonly divided into categories called colors and the same can be done in the infrared. While there is no accepted common standard of the division in the infrared, the reflected infrared spectrum occurs approximately between 0.7μm to 3 μm; thermal emissions approximately span 3μm to 15μm, and it is in these two categories (reflected and emitted) that an SDA mission can be optimized to detect Resident Space Objects (RSOs). This paper focuses on how reflected and thermally emitted IR can be used in missions to observe in poor illumination scenarios and improves sensitivity. The missions discussed in this paper focus on the Earth-Moon system, but these processes can be applied to all mission types.

Modeling a mission typically starts with what objects are going to be observed. To model an Object correctly, its sources of energy need to be defined. The two sources of light an object can provide in the Visible and IR spectrums are reflected and emitted light. The Sun is the primary source of reflected energy in the Earth-Moon system. The Sun is also the primary source of passive energy that can be converted by the Object into an internal temperature. An Object's composition, orientation, and cross-section will vary the amount of reflection and absorption of the Sun's energy, but if an Object is purposefully designed to reduce its reflective surface area, then it is increasing its absorption rate, which increases temperature and can increase the re-radiation of heat. The Object's spectral signature will be a combination of reflected Sunlight and thermal emissions. At the same unit of power, more photons are generated at longer wavelengths due to the conservation of energy. Therefore man-made objects will appear brighter in the IR enabling an SDA mission to see the same target that is further away.

Observing the in the thermal infrared enables direct line of sight of the Object, and bypasses reflection's triangular relationship between the Sun, Object, and Observer. If an Object also contains an internal power source, an observer measuring in the thermal IR will be able to detect when this power source becomes powered or unpowered. Direct line of sight, internal emissions, and the Object's uniform radiation allow more photons to be detected at the Observer, improving the sensitivity. The improved sensitivity allows the Observer to detect objects that are further away. Ground-based SDA sensitivity suffers in the infrared due to the absorption of the infrared wavelengths from water vapor. Space-based SDA missions will not suffer the same degradation of performance as ground-based SDA missions and can take full advantage of detecting threats in this bandwidth.

Finally, while observing in the IR does have advantages over the Visible spectrum, there is an engineering cost. The Observer needs to be sufficiently cooled such that it is not blinded by its own thermal emissions. Modifications from the standard visible design techniques need to be incorporated into a mission design to handle unwanted thermal emissions and stray light. However, the cost does not preclude space-based detection in the infrared for SDA missions since it is a necessary update to achieve mission goals in regimes that require observing objects at greater distances or smaller objects.

2. MODELING THE TARGET'S SPECTRUM

2.1 Modeling the Sun

The main source of energy in the Solar system is the Sun. Extensive work by NASA has resulted in a very detailed breakdown of the Sun's spectrum. This work has also shown that modeling the Sun as a blackbody[1] is a good approximation for the output of the Sun.

$$B(\lambda,T) = \frac{2hc^2}{\lambda^5}\frac{1}{e^{\frac{hc}{\lambda k_b T}}-1} \tag{1}$$

Equation 1 defines the blackbody spectrum for any thermal body. Using standard S.I. units, λ is the wavelength in units of meters, T is the Temperature in units of Kelvin, h is Planck's constant, c is the speed of light, and k_b is the Boltzmann Constant. Using a temperature of 5772K [2], the Sun's spectrum can be modeled.

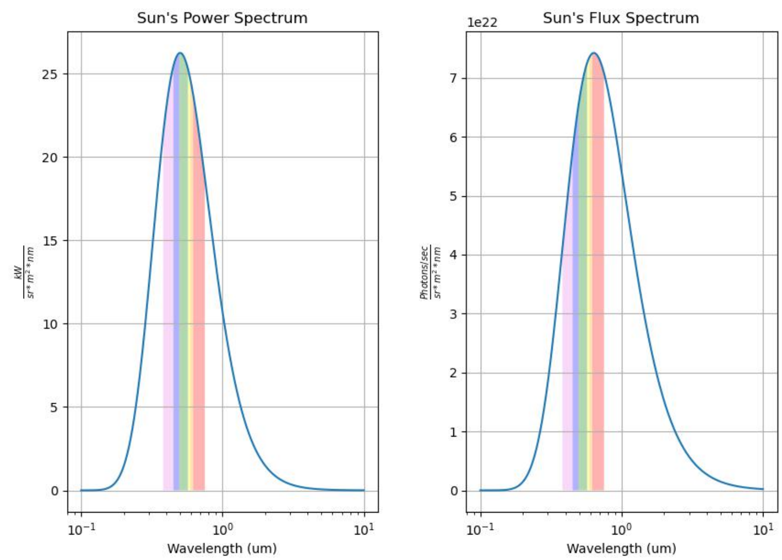


Fig. 1: The Sun's spectrum. The left plot is in units of power and the right in units of flux. The Sun's peak power occurs at $\lambda_{peak} \approx 0.502\mu$m and the peak flux output occurs at $\lambda_{peak} \approx 0.635\mu$m.

Fig 1 demonstrates important considerations when designing an SDA mission. Both peak power and peak flux achieve maximum values in the visible spectrum, but do not occur at the same wavelength. More flux is generated at a redder wavelength than power. While the Sun's output power and flux quickly diminishes in the ultraviolet and infrared, there still is an excess of signal which can be captured in these regimes. Finally, many celestial source intensities fade quickly like the Sun in the infrared. An IR SDA mission can be tuned to minimize unwanted background thermal emissions and celestial sources.

2.2 Modeling the Object

An advantage of designing an SDA mission in the IR is that the mission can take advantage of detecting both reflected and emitted light. To illustrate this point, we propose a thought experiment with the following assumptions:

1. The Object is a gray body with realistic conservative estimate of 20% reflection [over all wavelengths] and 80% absorption/emission [over all wavelengths]. A gray body has elements of a blackbody (purely absorption/emissions) and white body (purely reflective).

2. The object resides 1 Astronomical Unit (AU) away from the Sun.

3. The reflection is Lambertian with the best phase angle.
4. The object has achieved a steady state temperature.
5. An observer is situated 60,000km away from the object and the object completely fills the observer's field of view (FOV). NOTE: In a typical SDA mission, the object will not fill the FOV and may only cover up to a few pixels, however, the radiometry of the object is not affected, and the results will be similar.

Unless blocked by the Earth or Moon, the object will always have direct line of sight to the Sun. Its relationship of area, distance, and Solid Angle (Ω), determine the amount of power from the Sun interacting with the object. Once the power from the Sun reaches the object, three things can happen:

1. Reflection of the sunlight. This is a geometric interaction where the incoming light at some angle of incidence will bounce off the object at an angle of reflection.
2. Absorption of the sunlight. This is a heat transfer interaction where the incoming light will enter the object then be stopped within, transferring its energy via heat [increasing the object's temperature].
3. Transmission of the sunlight. This is an energy interaction where the light that is not absorbed or reflected, will pass through the object (potentially bend the trajectory of the light) and impart little to no energy into the object.

For this discussion within this paper, it is assumed that the sunlight will either be absorbed[3] and/or reflected.

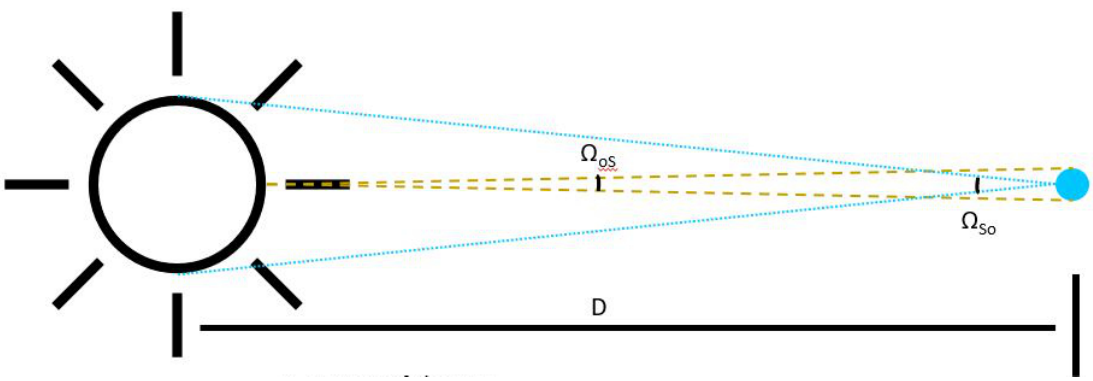


Fig. 2: Radiometric relationship between the Sun and the Object

The object receives the Sun's entire output spectrum, but the intensity of the object is reduced by the Area and Solid Angle relationship.

$\Omega_{oS} = \frac{A_o}{D^2}$	$\Omega_{So} = \frac{A_S}{D^2}$	$A_S\Omega_{oS} = A_o\Omega_{So}$

Table 1: Radiometric equation relationship between the Sun and the Object

A_o is the area of the object, A_S is the area of the Sun, Ω_{oS} is the projected solid angle of the object as seen by the Sun, and Ω_{So} is the projected solid angle of the Sun as seen by the object. Using the Sun's modeled spectrum from Section 2.1, and the assumptions in this section, the spectrum at the object is shown in Figure 3.

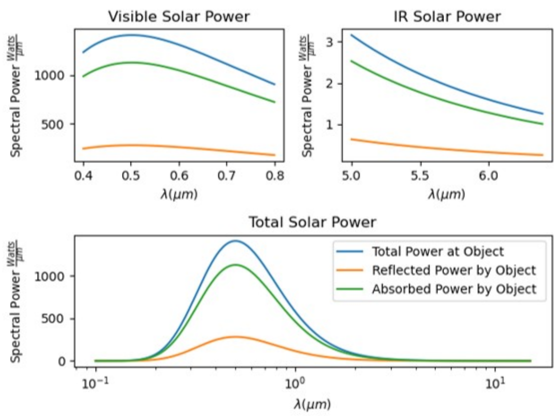


Fig. 3: Sun's output spectrum at the location of the Object. The top two plots are in a linear scale. The bottom plot x-axis in in log scale.

The spectrum at the object is broken into three categories, total power, reflected power, and power absorbed by the object.

Power Type	Visible Power[0.4-0.8]μm	IR Power[5.0-6.4]μm	Total Power[0.1 - 15]μm	Units
Total Power	494.23	2.82	107.36	Watts
Absorbed Power	395.38	2.26	859.49	Watts
Reflected Power	98.85	0.56	214.87	Watts

Table 2: Integrated power at the object for various bandwidth and interaction types. The IR spectrum chosen in the table is a small subset of the entire available IR spectrum.

Figure 3 and Table 2 demonstrate that an object reflects and absorbs the sunlight. For this object, 80 percent of the sunlight is actually absorbed which turns into heat. Using the assumption that the object is at steady state, the object will have reached a temperature which can easily be calculated.

$$T_{obj} = \left(\frac{\int B(\lambda, T)_{Sun} \times \Omega_{So}}{4k_b} \right)^{0.25} \tag{2}$$

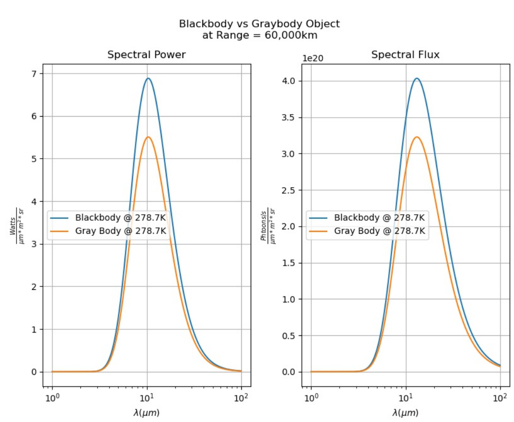


Fig. 4: Two spectral curves representing a perfect blackbody and the modeled gray body.

The object's peak power occurs around $\lambda_{peak} \approx 10.4\mu$m, and peak flux occurs $\lambda_{peak} \approx 13.2\mu$m. All observable light generated by the object is in the infrared. Both the blackbody and gray body achieve the same steady state temperature, but the gray body's intensity profile is less than the blackbody due to its reflective properties.

An object's observable spectrum is a makeup of reflected and emitted light. When adding an observer, the geometric relationship between the Sun, Object, and Observer becomes a key design driver. Reflection is the primary propagation method for the Visible spectrum and viewing reflected light has a dependency on geometry.

3. MODELING GEOMETRIC RELATIONSHIPS

When modeling the system, the Object has direct line of sight interactions with the Sun and the Observer has a direct line of sight interaction with the Object. However, the interactions between the Sun, Object, and Observer becomes more complicated as the system is now dependent on the angular position of all three entities. Thermal emission from the Object is not constrained by a geometric relationship to the Sun. For this discussion, it is assumed that the Sun/Object/Observer relationship is in the BEST geometric relationship to MAXIMIZE the reflected light.

First, it is important to understand how reflections and emissions differ between two-dimensional and three-dimensional shapes. Currently, a driving assumption in this paper is that the object to be observed is spherical in shape.

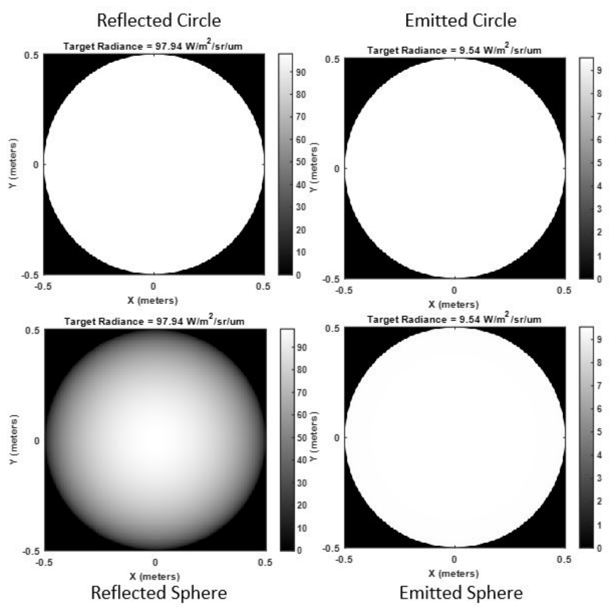


Fig. 5: *2-D* and *3-D* reflection and emission profiles

It is immediately apparent that reflection and emission of a *2-D* shape is equivalent spatially. However, moving to a *3-D* shape there is an immediate difference. The light reflected sphere has a geometric dependence on the viewing angle where the peak target radiance occurs at point (0, 0) with the radiance rolling off toward the edge of the sphere. The emissions profile of a *3-D* sphere matches that of an emitted and reflected circle where the thermal emissions is uniform i.e not spatially dependent. Object features such as solar panels will act like a reflected circle, whereas an MLI wrapped object will have a profile similar to a reflective sphere.

Continuing with the geometric impacts, Figure 6 looks at the system geometric relationship.

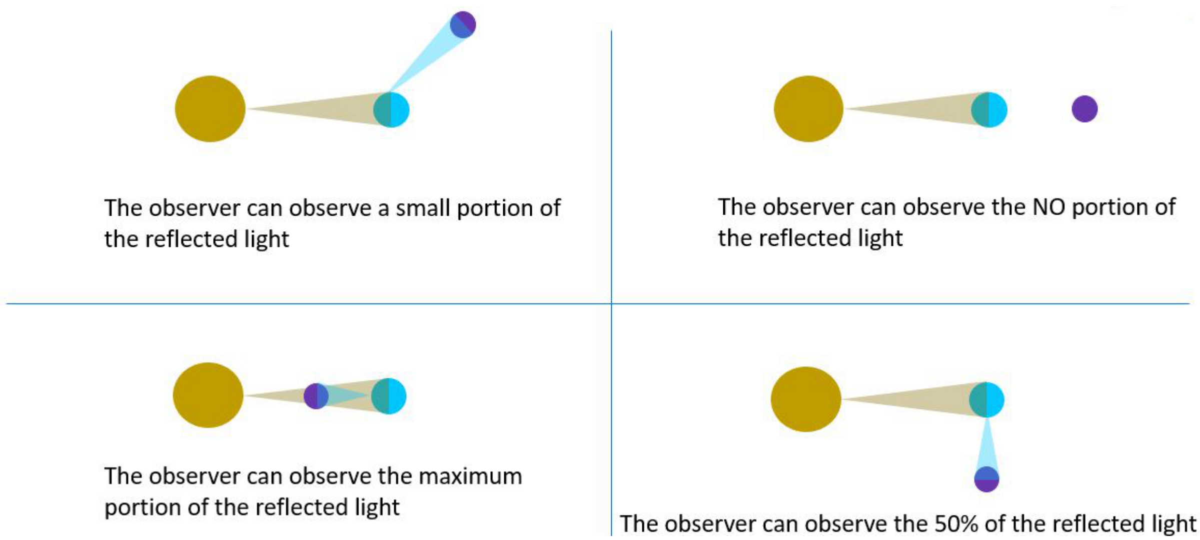
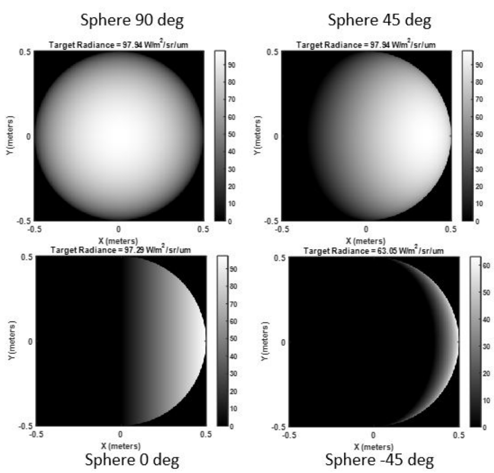
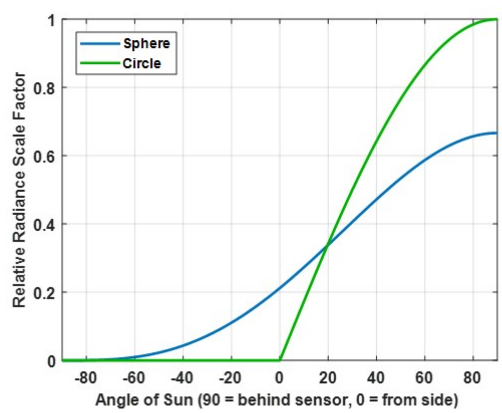


Fig. 6: Geometric impacts of adding an observer

The location of the observer directly impacts the amount of reflected light it can detect from an object. Now, the system and shape geometric relationships can be combined and modeled (Figure 7).



(a) Observer's view of the object showcasing the illumination profile could see with different positions of the Sun



(b) Plot detailing the how the Observer's location impacts the percentage of light it can detect between a *2-D* and *3-D* object

Fig. 7: Relative reflectance curves for *2-D* and *3-D* objects

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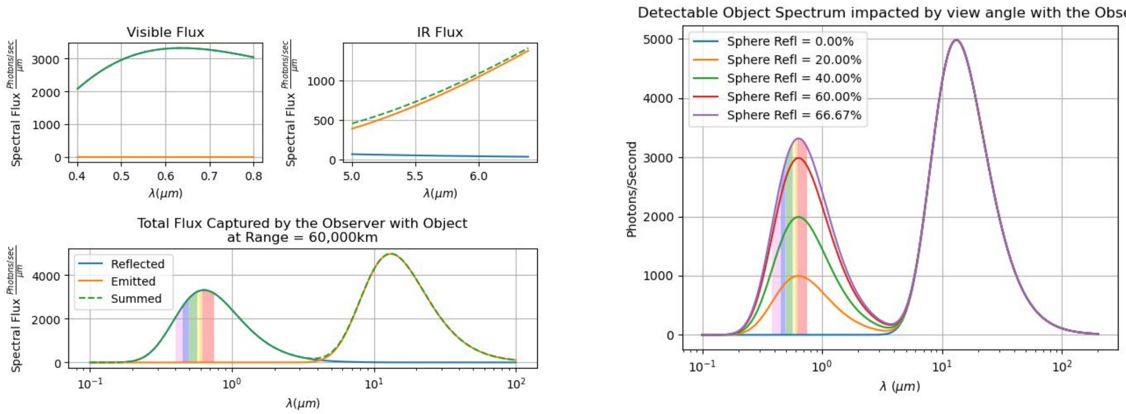
4. DETECTING THE OBJECT

4.1 The Object's Complete Spectrum

The total detectable flux of an object is the combination of reflected and absorbed sunlight, the geometric interaction of the reflection and emissions with a *3-D* object, and the observer's view of the object with respect to the position of the Sun. Modeling these interactions with a 1-meter object that is 60,000km away from the observer creates the following spectrum:



(a) Total detectable flux of the object by the Observer

(b) Impacts to the visible spectrum as the geometry changes between the Sun, Object, and Observer (see fig. 6 and 7)

Fig. 8: Detectable flux at the Observer and the impacts of geometry

Flux Type	Visible Flux[0.4-0.8]μm	IR Flux[5.0-6.4]μm	Total Flux	Units
Reflected Flux	1218	66	4386	$\frac{Photons}{Sec}$
Absorbed Flux	2.3×10^{-20}	1162	123209	$\frac{Photons}{Sec}$
Total Flux	1218	1228	127595	$\frac{Photons}{Sec}$

Table 3: Observable integrated flux at the observer (for Figure 8a). The IR bandwidth chosen in the table is a small subset of the entire available IR spectrum.

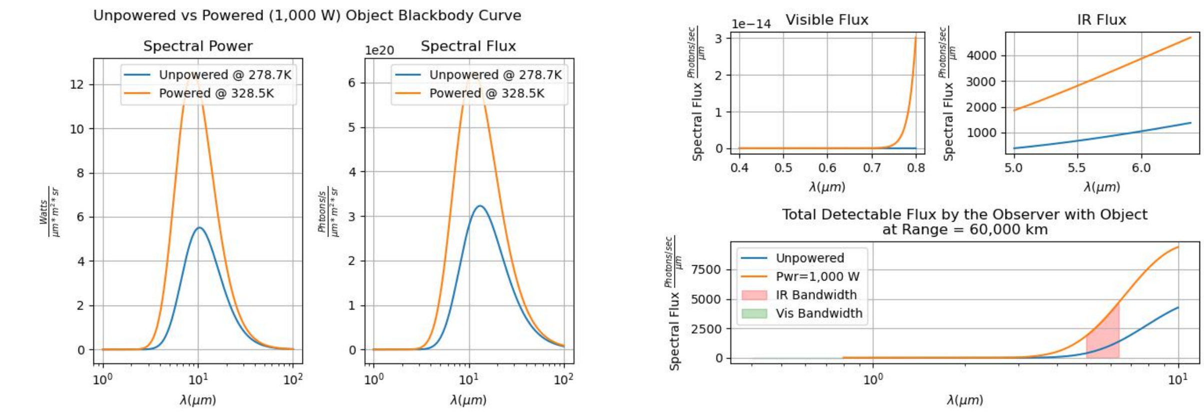
An IR detector that can observe between 5-6.39μm will capture approximately the same number of photons as the visible bandwidth 0.4-0.8μm. In the Visible bandwidth, there is no signal contribution from emissions out of the object, it is all reflective. While Table 2 and Figure 8a are assuming the BEST phase angle, Figure 8b highlights how the visible flux is significantly impacted by phase angles. Should the object be in a phase such that it has no reflected light, the IR detector still receives 99% of its light from emissions. The dashed green line in Figure 8a will trend towards the emission profile as the visible flux trends towards zero.

4.2 The Impact of Power

Thus far, the object has been assumed to reach a steady state temperature from the Sun's radiation. What happens if the object also has an internal power source? Equation 3 can be further modified to account for power.

$$T_{obj} = \left(\frac{\int B(\lambda, T)_{Sun} \times \Omega_{So} + \frac{Power_{object}}{A_{radiated}}}{4k_b} \right)^{0.25} \tag{3}$$

Typical radiators dissipate between 100 - 350 Watts of power per square meter. For this example, assume the object is now dissipating an additional 1kW or heat at the same distance from the Sun and observer. The object's temperature will increase approximately 50K.



(a) The object's temperature and intensity increase as expected (b) The generated flux in the 5-6.4μm increases.

Fig. 9: Impacts to the Object's spectrum as power increases

Flux Type	Visible Flux[0.4-0.8]μm	IR Flux[5.0-6.4]μm	Total Flux	Units
Absorbed Flux	2.3×10^{-20}	1162	123209	$\frac{Photons}{Sec}$
Absorbed Flux	4.7×10^{-16}	4497	204375	$\frac{Photons}{Sec}$

Table 4: An increase in power increases the emission spectrum.

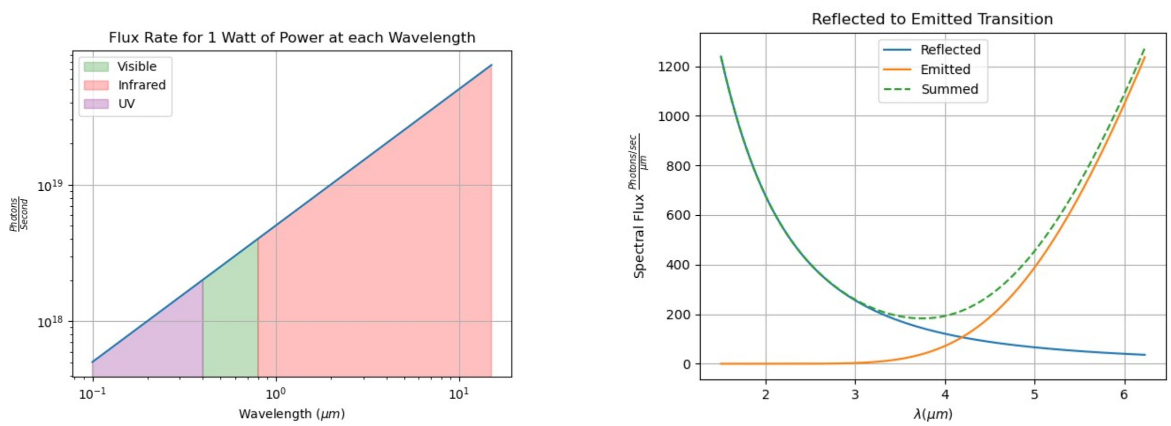
Figure 10 is only describing the impacts to emitted spectra. The peak wavelengths move slightly towards the visible spectrum, while the bandwidth between 5-6.4μm increased approximately 4 times. An interesting use case is presented here, assuming an object is normally observed un-powered or in a low powered state, it will present a certain spectrum like the blue line in Figure 9b. When an object is powered or using a lot more power, its spectrum will change (orange line). The spectra change (color change) is a characteristic of something happening that can be monitored. As technology continues to improve IR systems will be able to detect smaller and smaller thermal fluctuations.

5. OBSERVING IN THE INFRARED

At constant power, more photons are generated at longer wavelengths to maintain the conservation of energy. One causality of energy conservation is the Planck-Einstein[4][5] relation:

$$E = \frac{hc}{\lambda} \qquad Flux = \frac{P}{E} \tag{4}$$

Shorter wavelengths (Visible, UV, X-ray, etc.) produce less photons with more energy. Longer wavelengths (IR, Radar, FM) produce more photons with less energy.



(a) Signal Generation vs λ for 1 Watt of Power

(b) Transition Point between reflected IR and Thermal IR

Fig. 10: Flux generation in the IR

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While black and gray bodies do not emit at a constant power wavelength (like a laser), the reduction of reflected light due to distance and area combined with the the absorption/emissions of the sunlight enables these bodies to produce more photons in the infrared than visible. An SDA's ideal bandwidth is mission dependent. While there is more flux generated in the IR, there is a transition point between reflected and emitted IR. With today's technologies, an SDA mission can focus on a narrow region of the IR (reflected, emitted, etc) or a much broader region that encompasses both reflected and emitted IR.

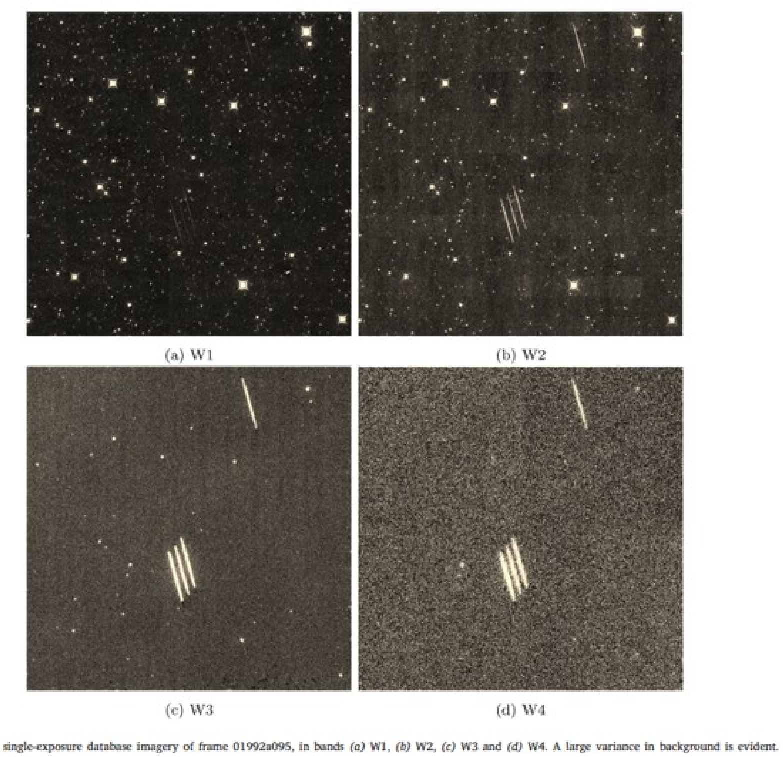

Fig. 11: Sample WISE data[6] detecting Resident Space Objects (RSOs) at various wavelengths.

The NASA Wide Field Infrared Explorer (WISE)[7] mission surveyed the celestial sky in the infrared. During its mission, it unintentionally captured man-made objects that passed through its field of view. WISE was able to take four images simultaneously in four different bands before its coolant ran out. Each channel collected a specific region within the IR spectrum:

1. Channel 1 (W1) - Centered at 3.4μm (Reflected IR)
2. Channel 2 (W2) - Centered at 4.6μm (Reflected/Emitted IR)
3. Channel 3 (W3) - Centered at 12μm (Thermally emitted IR)
4. Channel 4 (W4) - Centered at 20μm (Thermally emitted IR)

As the wavelength increases, fewer celestial objects are observed, matching figure 1. However, the RSOs become brighter, matching figures 4 and 8, where the RSOs spectrum is dominated by its thermal emissions. Overall system sensitivity is improved at longer wavelengths as the objects become brighter allowing for shorter integration times and enables an SDA mission to detect objects that are further away than their visible mission counterparts.

6. ENGINEERING COST

Choosing between a visible or infrared mission will inevitably lead to many engineering trades. One common trade when dealing with the choice between visible and IR is payload temperature. The payload temperature is just as important as the temperature of the object when observing in the IR.

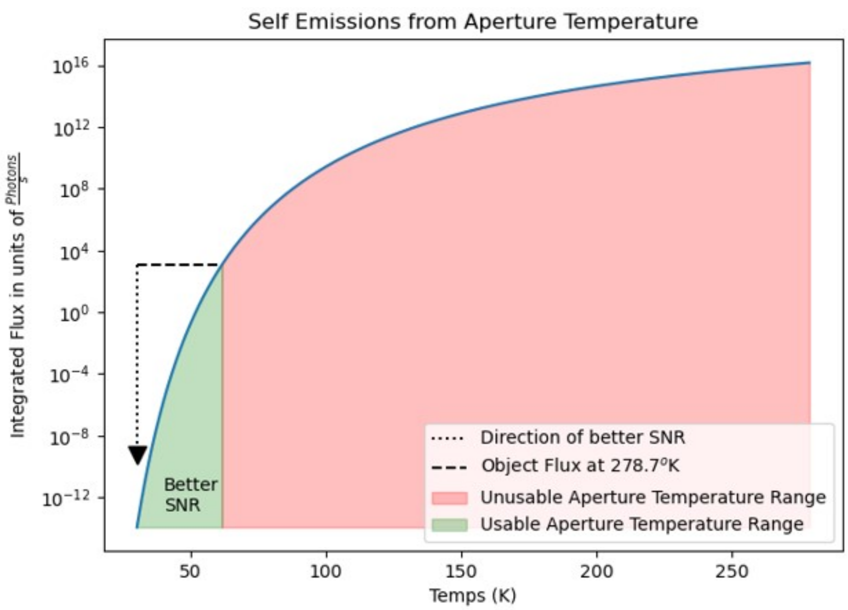

Fig. 12: A simple example of the impacts of self-emissions.

For the example in Figure 12, an aperture's temperature within the payload was allowed to vary. Then the integrated flux was calculated and compared to the signal values in Table 3. When the aperture is above 61K, the self-emissions matches or exceeds that of the target. There are a variety of ways to deal with the near field emissions from unwanted temperature sources. One way is designing a heat rejection system such as active and/or passive cooling. Passive cooling is designed to use unpowered means of removing heat from a system. Active cooling requires power to actively remove heat from a system. Both systems are actively used in space missions.

Recent trade studies performed at Ball looked at various aspects of the payload design. With a goal of achieving the same performance between a visible and infrared system of the outcomes are:

1. The visible system payload becomes larger (volume) and more massive than the IR payload
2. The size increase is due to the need to capture more photons with a larger collecting area
3. The IR payload needs to be much cooler than the visible system (either using a larger passive cooling system or an active cooling system)

4. IR technology costs, such as detectors, are decreasing as they become ”state-of-the-now”

At the Space Vehicle level, mass and volume are controlled by the launch vehicle, constraining the Space Vehicle volume. At Mission Level, assuming a goal of reducing/eliminating performance outages, more space vehicles with visible payloads are needed to meet the same performance of the IR payloads. The cost to have equivalent performance greatly depends on where one looks. IR may be somewhat more expensive at the payload level, but a cheaper option at the mission level.

7. SUMMARY

Heritage Space Domain Awareness (SDA) missions have relied on the visible bandwidth to achieve mission goals. The visible bandwidth can suffer from low illumination gaps which hinders sensitivity and detection. To avoid these gaps, new missions should expand their detection capabilities into the infrared wavelengths. Unlike ground-based SDA missions which experience performance degradation due to atmospheric effects, space-based missions will see improved sensitivity in the infrared due to the increase in signal this bandwidth provides. The visible spectrum relies on reflected sunlight to detect the threat. However, all objects, benign or threat, are actually detectable in the visible and infrared wavelengths. All object spectrums contain a combination of reflected and emitted light. The emitted light is a combination of the absorption of the sunlight and any internal power source. These sources create a temperature, and any object that has a temperature generated heat which is emitted out a thermal radiation. The thermal infrared emissions also breaks the geometric relationship required by reflection. With Objects able to be directly imaged, and the increased number of photons generated by the longer wavelengths, the sensitivity is improved, allowing an SDA mission to see further. Expanding in the thermal infrared wavelengths creates a natural update to the SDA mission area. As threats continue to advance, SDA missions that take advantage of the thermal infrared make it harder for threats to hide.

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