A survey of COTS optical systems for space applications

Ellen Glad
Millennium Space Systems

ABSTRACT

The use of commercial off the shelf (COTS) optical systems for space applications is important for reducing system cost and schedule. While often preferable, the design, build, and testing required for a custom optical system may not meet a program's timeline or risk strategy. We present a market survey to identify COTS cameras and lenses which are potential solutions for space applications and to highlight where gaps exist. The survey was conducted across four major optical spectral bands: Visible (VIS), Shortwave Infrared (SWIR), Midwave Infrared (MWIR), and Longwave Infrared (LWIR). Data was gathered strictly from the information published online from the manufacturer of the relevant part. Environmental specifications and level of "ruggedization" of each component are included to show viability to use for space. In addition to a component's potential for the space environment, we also discuss which example mission applications the COTS optical sensor market appeals to. For example, an earth-staring optical system likely looks different than a system designed for Space Situational Awareness (SSA) detection and tracking applications. Understanding the COTS sensor market and its limitations is important as the space industry grows and as solutions are required on rapid timelines.

1. INTRODUCTION

The decision between commercial off the shelf (COTS) and custom solutions should be based upon program cost, schedule, and mission requirements. Reference [3] examines the performance characterization between a modified COTS lens and a custom lens which have similar optical parameters. The authors found the custom lens had better optical performance, but they also emphasized the amount of risk a program takes on when building a custom design for the first time. For some space missions, a COTS solution may be necessary, and this is why it is important to be informed about the current market's offerings.

The market survey, presented later in Tables 1-6, spans wavelength bands from the Visible (VIS) to the Longwave Infrared (LWIR). The decision to use a sensor and respective optic in a specific wavelength band should be made based on mission requirements. If the mission requires detection of targets with known high temperatures, then selecting a Midwave Infrared (MWIR) sensor may be appropriate based on the amount of blackbody radiance a hotter object emits. If resolution is the most important factor, then a VIS sensor is likely the best option because shorter wavelengths allow higher angular resolutions, given a constant aperture size.

Fig. 1 lists the major optical bands and their respective wavelength ranges. Specific spectral bands are often defined with slightly different cut-on and cut-off wavelengths, so the following is one example of the common ranges.

Ultraviolet (UV)	Visible (VIS)	Near Infrared (NIR)	Shortwave Infrared (SWIR)	Midwave Infrared (MWIR)	Longwave Infrared (LWIR)
0.1 – 0.4µm	**0.4 – 0.7µm**	**0.7 – 1.0µm**	**1.0 – 2.5µm**	**3.0 – 5.0µm**	**8.0 – 14.0µm**

Fig. 1. Optical Spectral Band Ranges

Keeping these spectral bands in mind, now we provide more context as to why detectors that are sensitive in specific bands are more useful for certain applications. Fig. 2 shows the solar irradiance spectrum in space. This is the Air Mass Zero (AM0) reference spectrum developed by the American Society for Testing and Materials (ASTM). The integrated solar irradiance is about 1366.1 W/m^2. For reference, this is about a 30-40% increase of total irradiance compared to what reaches through the Earth's atmosphere, which is close to 1000 W/m^2 [4].

It is noticeable that the VIS section of the spectrum includes a spike in irradiance, which is one of the main reasons why it is common to use a VIS sensor for detection of sunlit resident space objects (RSOs). Many charge-coupled device (CCD) and complementary metal oxide semiconductor (CMOS) detectors' quantum efficiency (QE) curves stretch into the Near Infrared (NIR) as well. Maybe less commonly known, the solar irradiance spectrum also includes the shortwave infrared (SWIR) band. In fact, the integrated solar irradiance in the SWIR band, as defined in Table 1, is about ~371 W/m^2, compared to ~312 W/m^2 in the NIR and ~531 W/m^2 in the VIS. The SWIR band is commonly used to observe satellites from the ground during the daytime, because much of the bright visible background is blocked out, and the solar irradiance reflected off the satellite is still detectable.

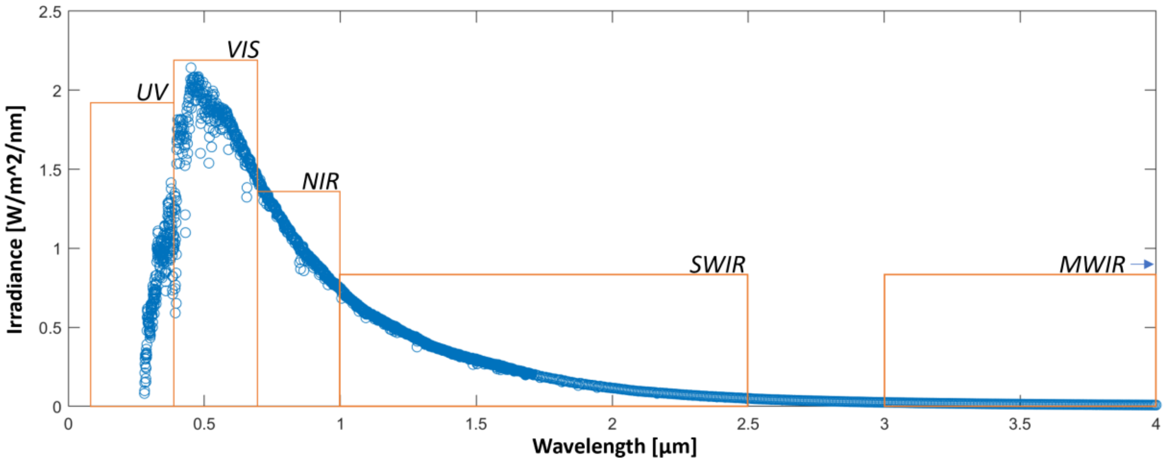

Fig. 2. AM0 Solar Irradiance Spectrum [4]

Figs. 3 and 4 explain why the solar irradiance spectrum has the shape that is does. The figures show modeled blackbody radiation curves as functions of wavelength and temperature. This relationship is described by Planck's Law, where E is radiance in watts per steradian per meter squared per meter, λ is wavelength in meters, T is temperature in Kelvin, h is Planck's constant, and c is the speed of light.

$$E(\lambda, T) = \left(\frac{2hc^2}{\lambda^5}\right) * \left(\frac{1}{e^{hc/\lambda kT} - 1}\right) \qquad \text{Eq. (1)}$$

The sun is an "approximate" blackbody emitter, and that is why the peak in blackbody radiance for a 5778K target (Fig. 3) matches closely with the peak in solar irradiance (Fig. 2). Fig. 4 shows modeled blackbody radiance for much cooler objects than the Sun: a 300K, 400K, and 500K target. As a blackbody's temperature increases, the shift in peak of the blackbody radiance curve moves towards the visible end of the spectrum. This is exactly why a longwave infrared (LWIR) detector, which is typically sensitive in the 8-14μm range, is best for "cooler" targets which peak in radiance in the LWIR bands.

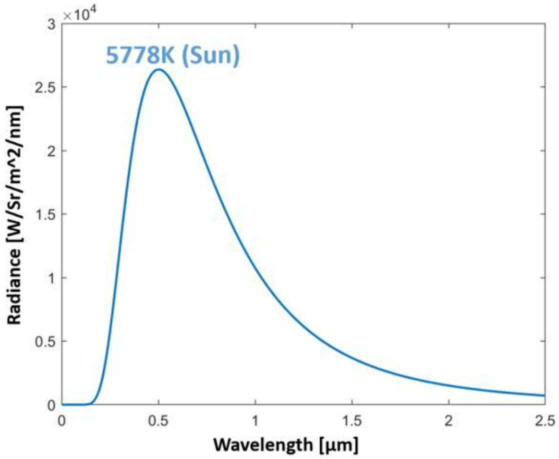

Fig. 3. Modeled Blackbody Radiance for the Sun

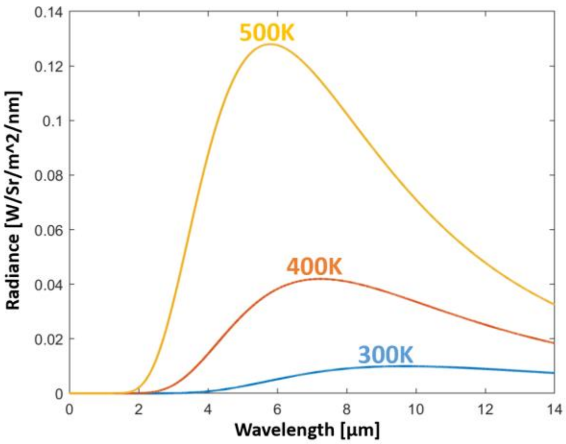

Fig. 4. Modeled Blackbody Radiance for Example Targets

Understanding how radiance is affected by blackbody temperature and wavelength provides helpful context to why several optical bands are important to maintain in any sensor trade space for space applications.

2. MARKET SURVEY

Section 2.1 lists all cameras included in the survey, divided into four tables, separated by spectral band. Section 2.2 lists all lenses included in the survey, divided into two tables, one for the VIS band and one for the IR band. Listed in the survey are camera/lens optical specifications and, when provided, notes about environmental specifications that help point to the component having potential use for space. Also of interesting note, several vendors explicitly advertise their capabilities for space. About 10 vendors were located which expressed specific space use or space heritage.

2.1 Market Survey – Cameras

The term “cameras” is purposely used to differentiate detectors sold inside a casing versus detectors that are standalone. Some exceptions are included because they are specifically advertised for space applications; therefore, they were appropriate to include in this list. The cameras listed are split by wavelength into four sections: Visible, Shortwave Infrared, Midwave Infrared, and Longwave Infrared. When specified, the wavelength range is listed, along with focal plane array (FPA) format, and pixel pitch, which is distance across one square pixel.

Table 1. Visible (VIS) Spectrum

Wavelength	Format	Pixel Pitch	Notes
VIS/NIR	5120 x 5120	4.5µm	Operating Temperature: -20C to +70C
VIS/NIR	~15 options listed on vendor website; up to 6480 x 4860	3.5-5.9µm	Operating Temperature: -20C to +65C
VIS/NIR	2152 x 1272	19µm	- Meets all MIL standards - Operating Temperature: -20C to +55C
VIS/NIR	1920 x 1080	19µm	
VIS/NIR	1944 x 1472	4.5µm	~50 total CMOS options listed on vendor site (options here show the span of formats available) -Several interface types available per format (GigE Vision w/ PoE, Camera Link Full w/ PoCL, CoaxPress, etc.) -MIL-STD-810G
VIS/NIR	2464 x 2056	3.45µm	
VIS/NIR	3216 x 2208	4.5µm	
VIS/NIR	4432 x 4436	3.45µm	
VIS/NIR	5328 x 4608	2.74µm	
VIS/NIR	6480 x 4860	3.45µm	
VIS/NIR	9344 x 7000	3.2µm	
VIS/NIR	2048 x 2048	10µm	- Image detector package - Designed for use in space
VIS/NIR	2048 x 2048	10µm	

VIS/NIR	2048 x 2048	10µm	
VIS/NIR	16000 x 4	5µm	- Image detector package - CMOS Time delay integration (TDI) Sensor
VIS/NIR	12288 x 2	7µm	- Image detector package - Time delay integration (TDI) Sensor
VIS/NIR	12288 x 2	7µm	
VIS/NIR	12288 x 2	7µm	
UV/VIS/NIR	1280 x 1024	5.3µm	-Image detector package
UV/VIS/NIR	1280 x 1024	5.3µm	

Even though the SWIR band is commonly specified as stretching from 1.0 to 2.5 microns, most SWIR-only cameras we found are sensitive from 0.9-1.7 microns. Several options stretch further into the VIS spectrum, creating many VIS-SWIR camera options which are included below.

Table 2. Shortwave Infrared (SWIR) Spectrum Cameras

Wavelength	Format	Pixel Pitch	Notes
0.4 – 1.7µm	656 x 520	5µm	-Industrial -Operating Temperature: -20 to +55C -Frame Rate 234 fps
0.4 – 1.7µm	1280 x 1024	5µm	-Industrial -Frame Rate 94 fps -Operating Temperature: -20 to +55C
0.9 – 1.7µm	2048 x 1	7.5µm	-Operating Temperature: 0 to +65C -Line-Scan Array Camera
0.9 – 1.7µm	1280 x 1024	10µm	Operating Temperature: -40C to +71C
0.9 – 1.7µm	320 x 256	15µm	Operating Temperature: -40C to +65C
0.9 – 1.7µm	640 x 512	15µm	Operating Temperature: -40C to +65C
0.9 – 1.7µm	320 x 256	25µm	-Operating Temperature: -40C to +70C -Vibration & shock tested
0.9 – 1.7µm	640 x 512	15µm	-Operating Temperature: -40C to +71C -Vibration & shock tested
0.9 – 1.7µm	640 x 512	15µm	Operating Temperature: 0 to +65C
0.6 – 1.7µm	320 x 256	30µm	-Operating Temperature: -20C to +55C -350Hz full res. frame rate
0.6 – 1.7µm	640 x 512	15µm	Operating Temperature: -20C to +55C
0.6 – 1.7µm	640 x 512	15µm	-Operating Temperature: -20C to +55C
0.6 – 1.7µm	640 x 512	10µm	Operating Temperature: -20C to +55C
0.6 – 1.7µm	640 x 512	15µm	Operating Temperature: -20C to +55C -TEC-less
0.6 – 1.7µm	640 x 512	15µm	Operating Temperature: -20C to +55C -Analog output version of series

0.9 – 1.7µm	640 x 512	15µm	-Operating Temperature: -20C to +55C -300Hz full resolution frame rate
0.6 – 1.7µm	1280 x 1024	10µm	Operating Temperature: -20C to +55C
0.6 – 1.7µm	640 x 512	15µm	-Operating Temperature: -20C to +55C -Dark current <750e-/p/s at -15C
0.9 – 1.7µm	640 x 512	15µm	-Operating Temperature: -20C to +55C -Vacuum cooled to -80C
0.6 – 1.7µm	1280 x 1024	10µm	-Operating Temperature: -20C to +55C -Cooled
0.6 – 1.7µm	1280 x 1024	10µm	-Operating Temperature: -30C to +55C (Full performance) -Operating Temperature: -40C to +70C (Degraded performance – Random noise)
0.6 – 1.7µm	640 x 512	10µm	Operating Temperature: -40C to +85C
0.6 – 1.7µm	640 x 512	15µm	-Operating Temperature: 30C to +60C (Full performance) -Operating Temperature: 40C to +70C (Degraded performance - Random noise)
0.6 – 1.7µm	640 x 512	15µm	Operating Temperature: -40C to +71C
0.4 – 1.7µm	640 x 512	15µm	-Operating Temperature: 30C to +60C (Full performance) -Operating Temperature: 40C to +70C (Degraded performance - Random noise)
0.9 – 1.7µm Optional: 0.7 – 1.7µm 0.5 – 1.7µm	1280 x 1024	12.5µm	-Operating Temperature: -40C to +70C -Functional shock, vibration, thermal shock: MIL-STD-810G compliant
0.9 – 1.7µm Optional: 0.7 – 1.7µm	640 x 512	12.5µm	-Operating Temperature: -40C to +70C -Functional shock, vibration, thermal shock: MIL-STD-810G compliant
0.9 – 1.7µm	320 x 256	12.5µm	-Operating Temperature: -5C to +60C -Functional shock, vibration, thermal shock: MIL-STD-810G compliant
0.7 – 1.7µm	640 x 512	15µm	-Operating Temperature: -40C to +70C -Functional shock, vibration: MIL-STD-810G compliant
0.4 – 1.7µm	640 x 512	15µm	Operating Temperature: -20C to +55C
0.4 – 1.7µm	1280 x 1024	15µm	Operating Temperature: -20C to +55C
0.4 – 1.7µm	1920 x 1080	15µm	Operating Temperature: -20C to +55C
0.4 – 2.0µm	640 x 512	15µm	-Operating Temperature: -20C to +55C -Extended wavelengths
0.4 – 2.0µm	1280 x 1024	15µm	-Operating Temperature: -20C to +55C -Extended wavelengths
0.4 – 2.0µm	1920 x 1080	15µm	-Operating Temperature: -20C to +55C -Extended wavelengths

0.9 – 1.7µm	640 x 512	20µm	Operating Temperature: 0C to +30C
0.85 – 1.55µm	640 x 512	20µm	Operating Temperature: 0C to +30C
0.9 – 1.7µm	640 x 512	20µm	-Operating Temperature: -40C to +70C -Shock, Vibration: MIL-STD-810G -TE Cooler
0.4 – 1.7µm	1280 x 1024	5µm	-Operating Temperature: -40C to +70C -Shock, Vibration: MIL-STD-810G - TE Cooler
0.9 – 1.7µm	320 x 256	20µm	-Operating Temperature: -40C to +70C -Shock: IEC60068-2-27 Ed4.0 -Vibration (Random): IEC60068-2-64 Ed2.0
0.5 – 1.7µm	320 x 256	20µm	-Operating Temperature: -40C to +70C -Shock: IEC60068-2-27 Ed4.0 -Vibration (Random): IEC60068-2-64 Ed2.0
0.9 – 1.7µm	640 x 512	20µm	TE cooler

Table 3. Midwave Infrared (MWIR) Spectrum Cameras

Wavelength	Format	Pixel Pitch	Notes
MWIR	640 x 512	15µm	Operating Temperature: -40C to +70C
MWIR	640 x 512	15µm	Operating Temperature: -40C to +70C
MWIR	1280 x 720	8µm	Operating Temperature: -40C to +70C
MWIR	1280 x 720	8µm	Operating Temperature: -32C to +70C
3.6 – 4.2µm (XBn)	640 x 512	10µm	-Operating Temperature: -40C to +71C -Integrated Detector and Lens (Focal length options: 135mm, 180mm, 225mm)
3.6 – 4.2µm (XBn)	1280 x 1024	10µm	-Operating Temperature: -40C to +70C -Integrated Detector and Lens (Focal length options: 225mm, 300mm)
3.6 – 4.9µm (InSb)	1280 x 1024	10µm	-Operating Temperature: -40C to +71C -Integrated Detector and Lens (Focal length options: 420mm, 690mm, 900mm)
3.6 – 4.9µm (InSb)	1280 x 1024	15µm	-Operating Temperature: -40C to +71C -Integrated Detector and Lens (Focal length options: 850mm, 1350mm)
3.4 – 5.1µm	640 x 512	15µm	-Operating Temperature: -40C to +71C -Shock and vibration specifications listed

Table 4. Longwave Infrared (LWIR) Spectrum Cameras

Wavelength	Format	Pixel Pitch	Notes
8.0 – 14.0µm	640 x 480	17µm	- Operating Temperature: -40C to +71C -Shock specifications listed
3.0 – 14.0µm	640 x 480	17µm	-Operating Temperature: -40C to +71C -Extended wavelength

			-Shock specifications listed
8.0 – 14.0µm	320 x 240	17µm	Operating Temperature: -40C to +65C
8.0 – 14.0µm	640 x 480	17µm	
8.0 – 14.0µm	320 x 240	12µm	-Operating Temperature: -40C to +80C -Shock specifications listed
8.0 – 14.0µm	640 x 480	12µm	
8.0 – 14.0µm	320 x 240	12µm	-Operating Temperature: -40C to +70C -Shock, vibration: MIL-STD-810G -Shutterless microbolometer family
8.0 – 14.0µm	1024 x 786	12µm	
8.0 – 14.0µm	1024 x 786	12µm	
8.0 – 14.0µm	640 x 480	12µm	-Operating Temperature: -40C/-30C to +70C; Lower limit depends on output type selection -Shock, vibration: MIL-STD-810G -Shutterless microbolometer family
8.0 – 14.0µm	640 x 480	12µm	
8.0 – 14.0µm	1280 x 1024	12µm	
8.0 – 14.0µm	1280 x 1024	12µm	
8.0 – 14.0µm	640 x 480	12µm	-Operating Temperature: -40C to +70C -Shock, vibration: MIL-STD-810G -Shuttered microbolometer family
8.0 – 14.0µm	1280 x 1024	12µm	
8.0 – 14.0µm	640 x 480	17µm	-Operating Temperature: -40C to +80C -Shock, vibration: MIL-STD-810G

2.2 Lenses

The following Tables 5 and 6 detail the industrial and ruggedized lenses found in the survey, split into visible lenses and infrared lenses (fewer IR lenses were found, so Table 6 is a compilation of the SWIR, MWIR, and LWIR bands). The lens focal length and the focal ratio (or F/#) are listed. In the notes column, environmental specifications, ruggedization levels, and/or Ingress Protection (IP) levels are described. Several vendors quantify the amount of ruggedization for shock levels; when available, those values are included below. It should be noted that one vendor included was not explicitly COTS; however, because their lens options are quantified with a radiation resistance which is extremely important for space, those lens options are included in the survey.

The term "ruggedization" should be discussed, as there are several forms of ruggedization and methods to design a lens for space. A lens system for space will be exposed to shock, vibration, and extreme thermal environments. A ruggedized lens uses fewer moving parts than a typical lens to withstand these harsh conditions. A typical lens usually has an adjustable aperture, i.e., options to use various f-numbers to adjust the depth of focus. For space, oftentimes the lens has a fixed iris which limits the aperture stop but provides a more rugged design. A SPIE article about ruggedized optics talks about different categories of ruggedization. "Industrial" ruggedization describes the optic being manufactured with few moving parts as already discussed, and "stability" ruggedization does this as well, but also includes gluing the lens elements together to preserve optical pointing. Ingress Protection ruggedization is quantified by an IP level which is standardized by IEC 60529; hence, there is often a reference to "IP67," for example, as seen in the market survey tables below. Ruggedization is an important quality to understand for any optical system, and it is extremely helpful when a vendor quantifies this value [1].

Table 5. Visible (VIS) Spectrum Lenses

Focal Length	F-Number	Notes
~10 options between 2mm to 25mm	Options: f/2.5 to f/8	-Stabilized Ruggedization -Ruggedized to withstand shock @50g
~10 options between 3.5mm to 50mm	Options: f/2 to f/16	-Stabilized Ruggedization -Ruggedized to withstand shock @50g
8.5mm	Options: f/1.4 to f/8	-Stabilized Ruggedization -Ruggedized to withstand shock @50g
12mm	Options: f/2.8 to f/11	-Stabilized Ruggedization -Ruggedized to withstand shock @50g
100mm	Options: f/4, f/5.6, f/8	-Operating Temperature: -10 to +50C -Ruggedized for shock and vibration -Passive Athermalization
150mm	Options: f/4, f/5.6, f/8	- Operating Temperature: -10 to +50C -Ruggedized for shock and vibration -Passive Athermalization
5mm	All options have adjustable F-Number f/1.4-f/16	Operating Temperature: -10C to -50C
8mm		
12.5mm		
16mm		
25mm		
35mm		
50mm		
8mm	All options have adjustable F-Number f/1.4-f/16	Operating Temperature: -10C to +50C
12.5mm		
16mm		
25mm		
35mm		
50mm		
4.8mm	f/1.8-11	Ruggedized to withstand shock @100g
8mm	f/1.4-11	Ruggedized to withstand shock @100g
12mm	f/1.4-11	Ruggedized to withstand shock @100g
17mm	f/1.4-11	Ruggedized to withstand shock @100g
23mm	f/1.4-11	Ruggedized to withstand shock @100g
35mm	f/1.9-16	Ruggedized to withstand shock @100g
50mm	f/2.8-32	Ruggedized to withstand shock @100g
28mm	f/2.0-16	Ruggedized to withstand shock @100g
10mm	f/1.6-16	Ruggedized to withstand shock @100g
16m	f/1.8-11	Ruggedized to withstand shock @100g
70mm	f/2.2-32	Ruggedized to withstand shock @100g

6.5-65mm	f/1.8	-Radiation resistant up to 100,000,000 rad -Operating Temperature: Up to +55C
12-120m	f/3.6	-Radiation resistant up to 100,000,000 rad -Operating Temperature: Up to +55C
6.5-65mm	f/1.8	-Radiation resistant up to 100,000,000 rad -Operating Temperature: Up to +55C
6.5-65mm	f/1.8	-Radiation resistant up to 100,000,000 rad -Operating Temperature: Up to +55C
8-24mm	f/2.8	-Radiation resistant up to 100,000,000 rad -Operating Temperature: Up to +55C
8-24mm	f/2.8	-Radiation resistant up to 100,000,000 rad -Operating Temperature: Up to +55C
12-72mm	f/1.8	-Radiation resistant up to 100,000,000 rad -Operating Temperature: Up to +55C
12-72mm	f/1.8	-Radiation resistant up to 100,000,000 rad -Operating Temperature: Up to +55C
24-144mm	f/3.6	-Radiation resistant up to 100,000,000 rad -Operating Temperature: Up to +55C
23mm	f/2	-Radiation resistant up to 100,000,000 rad -Operating Temperature: Up to +55C
5mm	-	-Radiation resistant up to 100,000,000 rad -Operating Temperature: Up to +55C
6mm	f/1.4	-Radiation resistant up to 100,000,000 rad -Operating Temperature: Up to +55C
25mm	f/1.4	-Radiation resistant up to 100,000,000 rad -Operating Temperature: Up to +55C
9mm	f/2	-Radiation resistant up to 100,000,000 rad -Operating Temperature: Up to +55C

Table 6. Infrared (IR) Lenses

Spectral Band	Focal Length	F-Number	Notes
SWIR (0.9-1.7µm)	40-400mm	f/5.6	-Operating Temperature: -30 to +80C -Shock/vibration per applicable spec
MWIR (3.2-3.7µm)	25mm	f/1.5	Ruggedized
MWIR (3.2-3.7µm)	50mm	f/1.5	Ruggedized

MWIR (3.4-5µm)	16.5mm-330mm	f/4, f/5.5	-Operating Temperature: -25C to +80C -Shock/vibration per applicable spec -Sealing: IP67, Front Element -Controller provides active athermalization
MWIR (3.4-5µm)	18-430mm	f/5.5	
MWIR (3.4-5µm)	21-420mm	f/4	
MWIR (3.4-5µm)	33-660mm	f/4	
MWIR (3.4-5µm)	42-850mm	f/4	
MWIR (3.4-5µm)	100-1000mm	f/4	
MWIR (3.4-5µm)	75mm	f/1.2	-Operating Temperature: -20C to +55C -Sealing: IP 67, Front Element -Passive Athermalization
LWIR (8-14µm)	~40 options ranging from 2.4mm to 100mm	All options fixed F/#, ranging from f/0.85 to f/1.6	-Operating Temperature: Depending on config., ranges from -30C to +70C, to -40C to +80C -Sealing: IP 67, Front Element (*most options)* -Passive Athermalization

3. SPACE APPLICATIONS

Next, we include in our survey a discussion on which space mission applications the COTS optical sensor market accomplishes. For example, an earth-staring optical system likely looks different than a system designed for space situational awareness (SSA)/resident space object (RSO) tracking applications. Specific optical bands will be more useful for certain applications than others, e.g., a VIS lens being chosen for general SSA applications because a small VIS lens will result in longer maximum detection distance when compared to an IR lens of the same size. In this discussion, we use sensor modeling calculations to show effectiveness of COTS sensors for example mission objectives.

First, maximum detection distance is important for SSA and detection and tracking applications. Figs. 5-8 show maximum detection range versus solar phase angle for three different lens aperture diameter sizes, for each of the major bands surveyed. These aperture diameters were selected based on sample aperture sizes calculated from the known focal lengths and focal ratios noted in the lenses surveyed. Table 7 lists the model input values used to calculate the detection ranges below. Following, we explain the model used to obtain the results presented. As shown in the plots, VIS detectors generally allow the potential for higher detection ranges with smaller aperture sizes when compared to equivalently sized apertures in the IR bands. The LWIR results show no variation across solar phase angle because there is no solar irradiance past about ~4um modeled, based on ASTM E-490 data [4]. The MWIR results' slight variation over changing solar phase angle is because the total radiance is combination of blackbody radiation and reflected solar irradiance. The results here are for a 300K target; if a 500K target is assumed, the MWIR results would show much less variation across solar phase angle because the dominant radiance term would be from blackbody radiation.

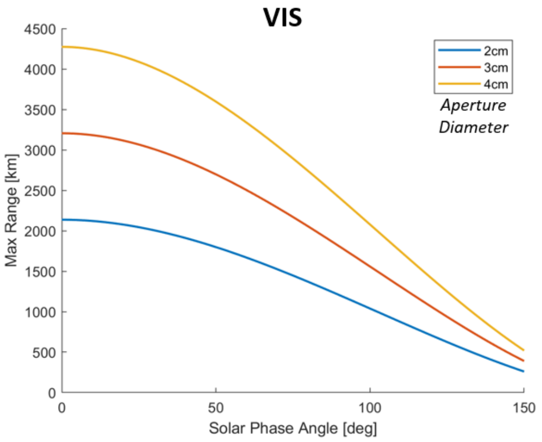

Fig. 5. VIS – Max Detection Range vs Solar Phase Angle

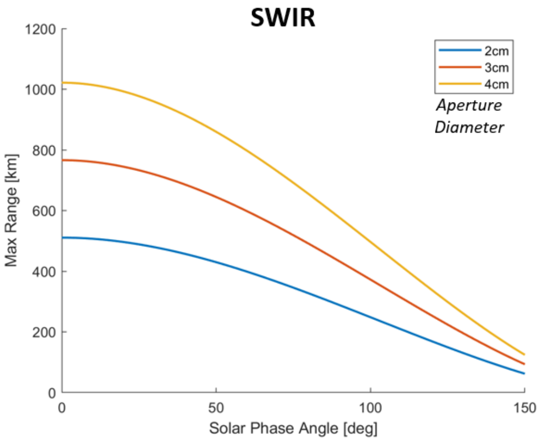

Fig. 6. SWIR – Max Detection Range vs Solar Phase Angle

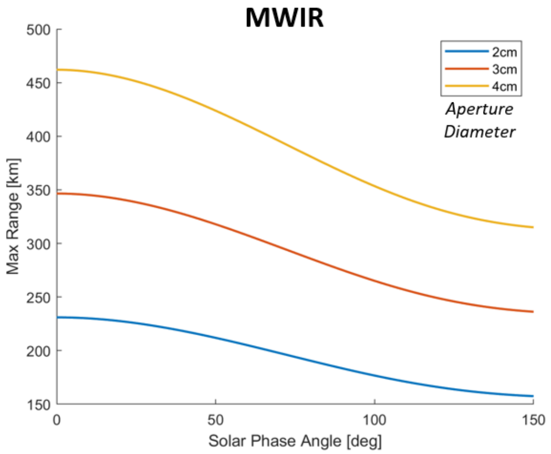

Fig. 7. MWIR – Max Detection Range vs Solar Phase Angle

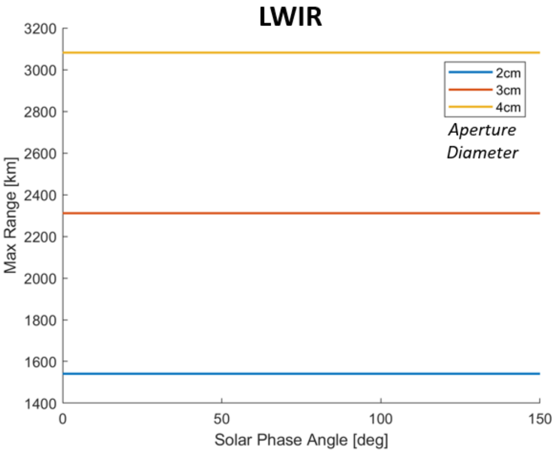

Fig. 8. LWIR – Max Detection Range vs Solar Phase Angle

Table 7. Signal to Noise Model Assumptions

Parameter	**Value**
Signal to Noise Threshold ***SNR***	10:1
Integration Time ***t*** [s]	0.1
Optical Transmission ***OT***	90%
Quantum Efficiency ***QE***	Peak 60%, Estimated curve for each band (VIS, SWIR, MWIR, LWIR)
Energy on Detector ***EOD***	25%
Read Noise ***RN*** [e-]	10e- (VIS) 100e- (SWIR, MWIR, LWIR)
Dark Current ***DC*** [e-/p/s]	50e-/p/s (VIS) 50ke-/p/s (SWIR, MWIR, LWIR)
Target Temperature ***T*** [K]	300K
Target Reflectivity ***a***	50%
Target Emissivity ***E***	50%
Target Diameter [m]	1m

Now we describe how the signal to noise model was developed. Using the optical parameter inputs above, signal to noise can be computed for an unresolved point target. To create Figs. 5-8, a signal to noise threshold of 10:1 was assumed, and the following equations were rearranged to output maximum range versus solar phase angle.

To calculate the radiance of a point target due to sunlight reflection, first the relationship between solar phase angle and the relative amount of radiance fall-off is established. Hejduk describes a phase function model for a diffuse sphere, shown in Eq. (2) [2]. At a zero-degree solar phase angle, reflected solar radiance is highest, and this reflected radiance goes to zero at a 180-degree solar phase angle when the target is in the sun's shadow.

$$F(\theta) = \left(\frac{2}{3\pi^2}\right) * ((\pi - \theta)cos\theta + sin\theta) \; [2] \qquad \textbf{Eq. (2)}$$

Using the phase angle factor from Eq. (2), radiance of the target due to sun reflection is computed in Eq. (3), where I_{Sun} represents the irradiance of the sun, and a is the target's reflectivity.

$$E_{Sun}[W/Sr/m^2/nm] = I_{Sun} * a * F(\theta) \qquad \textbf{Eq. (3)}$$

Next, the total radiance of the target E_{Target} is calculated in Eq. (4), using the sum of the radiance due to the sun and the radiance due to blackbody emissivity. The equation for $E_{Blackbody}$ is shown in Eq. (1).

$$E_{Target}[W/Sr/m^2/nm] = E_{Sun} + E_{Blackbody} \qquad \textbf{Eq. (4)}$$

Irradiance of the target I_{Target}, at the front of the observer's aperture, is calculated knowing the target's radiance, area A, and range R from the observer.

$$I_{Target} \; [W/m^2/nm] = E_{Target} * A_{Target}/R^2 \qquad \textbf{Eq. (5)}$$

Target irradiance is converted to signal on the focal plane array through Eq. (6).

$$Sig \; [e-] = (I_{Target} * \lambda * QE * d_{Lambda} * A_{Aper} * OT * EOD * t)/(h * c) \qquad \textbf{Eq. (6)}$$

Last, the signal to noise ratio SNR can be computed, where an estimate of noise is calculated using the square root of the Signal in electrons, the dark current DC in electrons per pixel per second, and the read noise RN in electrons.

$$SNR = \frac{Sig}{sqrt(Sig + DC + RN^2))} \qquad \textbf{Eq. (7)}$$

Besides detection distance, resolution of a target is another interesting metric to test against the COTS-sized sensors. Fig. 9 shows an example target's size in pixels if it were imaged on a focal plane, for both an example VIS sensor and an example LWIR sensor. For the example sensor parameters, we used the smallest pixel pitches found for both the VIS and LWIR bands, as well as the longest focal length lens found to provide an idea of the resolution limitations in the COTS market. Therefore, the VIS sensor modeled has a pixel pitch of 3.5um and a focal length of 100mm. And the LWIR sensor modeled has a pixel pitch of 12um and a focal length of 100mm.

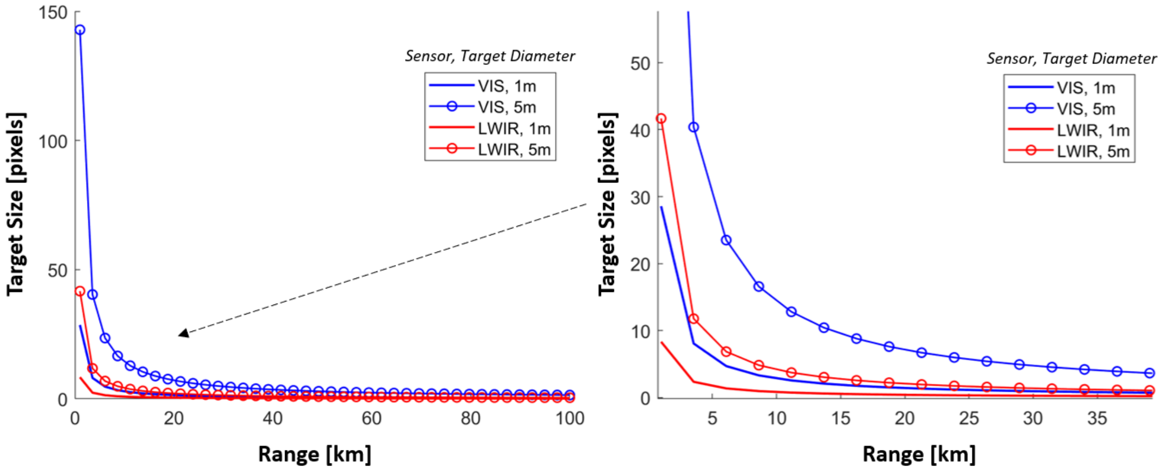

Fig. 9. Target Size vs Range for COTS-sized Optics

Next, we provide a few more data points to provide extra context to the capabilities of small optics. Fig. 10 shows the relationship between focal ratio (or F/#) versus FOV for a 2cm and 4cm aperture diameter, given a square detector with dimensions of 5x5 millimeters. Few lenses are found with a lower F/# than 1.0, and even an F/# between 1.0 and 2.0 is difficult to manufacture as aperture size grows larger. For these relatively small aperture sizes however, the low F/#s are realistic. The maximum FOV calculated for a 4cm aperture F/1 system, given the 5x5mm sensor, is about 10 degrees. The maximum FOV calculated for the smaller aperture of 2cm is about 20 deg. Fig. 11 speaks directly to Earth-staring and surveying missions. Shown is the distance on the ground that correlates to the angular size of one pixel, for various ranges representing common Low Earth Orbit (LEO) altitudes. This calculation is done for both an example VIS sensor and example LWIR sensor, and the sensor parameters were described above and used for Fig. 9.

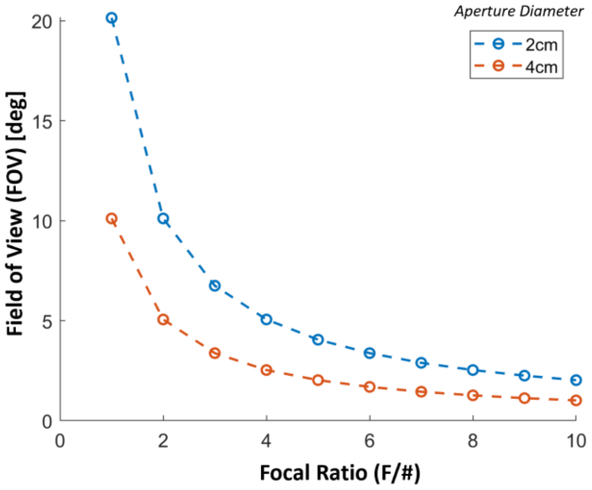

Fig. 10. F/# vs FOV for Given Aperture Sizes

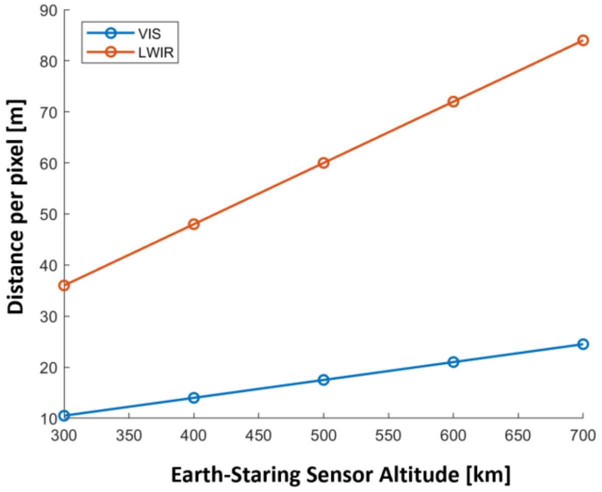

Fig. 11. Resolution per Pixel for Earth-Sensing COTS-sized Optics

4. CONCLUSION

Staying relevant to the current offerings in the COTS sensor market is important for selecting the right components for space missions. About 15 vendors were surveyed, and over 50 cameras and lenses were found. We found that with industrial COTS cameras, most vendors post operating temperatures, but less post references to shock and vibration capabilities. And with industrial lenses, many vendors are specific about the lens's ruggedization qualities.

Few vendors quantify the radiation tolerance for both cameras and lenses, which is another useful metric to know. In general, we were pleasantly surprised by the diversity of viable options across spectral bands for both cameras and lenses.

Some of the key findings included:

- Level of “ruggedization” mostly discussed in the context of lenses, but not for cameras
- Shock and vibration resistance sometimes mentioned, for both cameras and lenses
    - About 50-75% of the time, shock/vibration resistance quantified
- If a standard is provided for shock/vibration/thermal levels, MIL-STD-810G is common
- MWIR cameras and lenses were lowest in quantity compared to the parts found for other wavelengths
- Larger amount of SWIR cameras available than expected
- IR lenses are less common that VIS lenses
- Largest variety in sensor size and pixel pitch is offered in the VIS

Overall, efforts to increase the availability of fully space qualified components can enable industry’s ability to deliver rapidly. Understanding the COTS sensor market and its limitations is important as the space industry, and Aerospace and Defense in particular, requires better technical solutions and shorter timelines to delivery.

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