PERFORMANCE CHALLENGES FOR HIGH RESOLUTION IMAGING SENSORS FOR SURVEILLANCE IN TROPICAL ENVIRONMENT

LEE Cheow Gim, EE Kok Tiong, HENG Yinghui Elizabeth

ABSTRACT

Electro-optical (EO) sensors offer an unambiguous means of target identification, albeit with limitations in range performance due to environmental conditions. Specific to the local tropical environment, factors affecting sensor performance include humidity, rain and clouds. Another emerging key environmental factor is the presence of haze. This article examines the physics behind these environmental factors and their impact on the performance of different sensors. It also discusses how specific EO characteristics can be leveraged to enhance sensors' performance in the local environment and highlights emerging technologies for future consideration.

Keywords: electro-optical, target identification, imaging sensor, range performance, attenuation

INTRODUCTION

In the modern battlefield, high resolution imaging sensors, typically operating in the visible or infrared (IR) electromagnetic (EM) spectrum, provide a distinct advantage by detecting targets and offering an unambiguous means of target identification. However, environmental conditions can limit the performance of such systems due to the effects of atmospheric gases and aerosols on EM waves. Specific to the local tropical environment, key factors affecting sensor performance include humidity, rain, clouds and haze. These factors, together with the basic attenuation mechanisms, are covered in detail in the following sections.

TYPES OF IMAGING SENSORS

Imaging sensors can be broadly classified into passive and active imaging sensors. A passive imaging sensor intercepts and collects surrounding EM radiation reflected off or emitted by objects found within the field-of-view of its detector to form images of its surroundings. An active imaging sensor is coupled with an illumination source to illuminate the objects to be observed. A compatible detector will then collect the reflected energy for extended surveillance range performance and better spatial resolution under low light and in dark conditions. Different detector materials are sensitive to radiation energy from different portions of the EM spectrum.

In the day, the dominant source of visible spectrum radiation is the sun, while at night, a significant amount of night glow comes from the moon and stars. Detectors that operate in the visible spectrum typically make use of either the charge coupled device or the complementary metal oxide semiconductor technologies for imaging in daytime scenarios when ample ambient light exists. Detectors using image intensifier (II) technology make use of photon amplification to generate images in low-light scenarios.

On the other hand, thermal imagers (TI) are used to detect heat or radiation emitted from hot objects in the mid wave IR (MWIR) or long wave IR (LWIR) spectrums to generate two-dimensional images, based on the black-body radiation curve and the contrast between the temperatures of these objects and their background. These imagers operate independently from ambient lighting condition and even in complete darkness. TI detectors are further classified into two types – one that relies on changes to the temperature-dependent property of its material, and another that determines the IR photon flux by measuring the electrical current due to the generation of electron-hole pairs caused by the absorption of incident photons. Common materials used to fabricate TI detectors are indium gallium arsenide (InGaAs), lead sulphide, indium antimonide, mercury cadmium telluride and vanadium pentoxide.

IR region. The window bands in the visible and IR spectrum are summarised in Table 1 and illustrated in Figure 1.

Atmospheric scattering is the process by which EM radiation is redirected by gaseous molecules and aerosol particles suspended in the atmosphere. It is governed by the relationship between the radii of the scattering molecules or particles and the wavelength of the incident radiation.

Atmospheric absorption and scattering create a two-fold effect on luminance and contrast transmittance. First, EM radiation

Window Bands in EM Spectrum	**Wavelength**
Visible	0.4μm to 0.7μm
Near IR and Short IR	1μm to 2μm
Mid IR	3μm to 5μm
Far IR	8μm to 12μm

Table 1. Window bands in the visible and IR spectrum

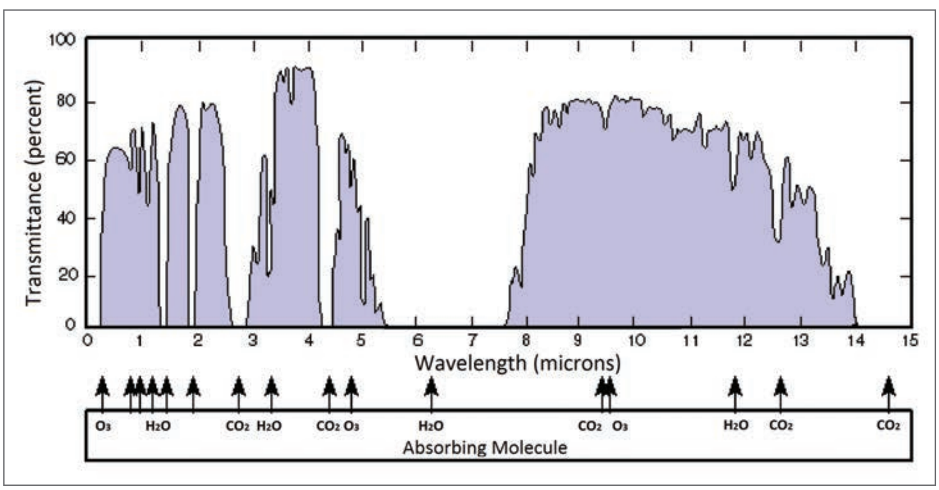

Figure 1. Atmospheric windows in the visible and IR regions

BASIC ATTENUATION MECHANISMS

Atmospheric attenuation is caused by both the absorption and scattering of EM radiation from aerosol particles or moisture droplets suspended in the atmosphere. EM radiation is mainly absorbed by gaseous agents such as water vapour, carbon dioxide, nitrous oxide, ozone, molecular and atomic oxygen, and nitrogen. The absorption is generally negligible in the visible region and at a minimum in a few atmospheric windows in the

from a target and its immediate background is progressively scattered out of the viewing path. Some will be absorbed and will not reach the sensor. The attenuation of EM radiation follows an exponential law in homogeneous air. A beam of EM radiation containing a flux F_o at the target of range R from the sensor will have a residual flux F received by the sensor in homogeneous air, given by:

$$F = F_o \exp[-(b+k)R] = F_o \exp(-\sigma_e R)$$

where *b* and *k* are the scattering coefficient and absorption coefficient respectively, and σ_e is the extinction coefficient of the atmosphere. Second, EM radiation, which does not come directly from the target or its immediate background, is scattered into the viewing path. This additional radiation is called air-light or path radiance, and varies with the scattering angle.

ATMOSPHERIC ATTENUATION IN THE LOCAL ENVIRONMENT

The key atmospheric elements in the local environment which attenuate the sensors' performance in the visible and IR spectrum are rain, clouds, fog and haze. The first three elements are related to the presence of water vapour, which is the most influential absorbing gas as well as the most variable. Relative humidity and absolute humidity are the two environmental parameters associated with water vapour content.

Rain Attenuation

Rain effects are difficult to estimate because of the variation in droplet size, density, drop size distribution, phase function, raindrop shape and the different effects that the water refractive index has on different waveband portions of the EM spectrum. Rain attenuates EM radiation through absorption and scattering, with the relative amounts dependant on the ratio of raindrop radius to wavelength. In the visible and IR spectrums, attenuation by rain is independent from wavelength because the raindrop radius (typically from 0.5mm to 5mm) is much larger than the wavelength. The extinction coefficient, which measures how strongly the EM radiation is absorbed by the medium (rain), indicates that the greater the rainfall rate, the higher the absorption.

Rainfall is the most significant atmospheric element affecting sensors operating in the visible and IR portions of the EM spectrum in Singapore, where rainfall occurs every month of the year. The two main wet seasons are the Northeast monsoon season from late November to March, and the Southwest monsoon season from late May to September, which account for 48% and 36% of the annual rainfall respectively. The type of rainfall varies from drizzle, which has a rain rate of up to 1mm/hr, to thunderstorms with rain rates exceeding 50mm/hr. Thunderstorms are observed during 78% of those days with rainfall. To illustrate the impact of rain on visible or IR sensors, a moderate rain rate of 10mm/hr would allow only approximately 6.7% of the EM radiation to pass through a 1.8km path. Along a 10km path, the transmittance even through a light rain with rain rate of 2.5mm/hr would be only 0.1%. This means that visible and IR sensors are rendered almost useless in either case. Table 2 shows the various rainfall statistics for different input parameters (Bernard et al, 2013).

Rain rate	**5mm/h (light rain)**	**10mm/h (moderate rain)**	**20mm/h (heavy rain)**
Extinction	0.5km^{-1}	0.7km^{-1}	~1.2km^{-1}
Water Volume / Rain Volume	320mm^{3}m^{-3}	588mm^{3}m^{-3}	1070mm^{3}m^{-3}
Number of raindrop	3600m^{-3}	4800m^{-3}	6400m^{-3}

Table 2. Various rainfall statistics for different input parameters, computed using Marshall-Palmer distribution

Cloud Attenuation

Similar to rain, cloud effects are difficult to forecast because of the variation in particle size. Attenuation is dependent on the cloud type and water vapour content. Within the cloud, the attenuation of EM radiation by water droplets is due to both absorption and scattering.

Clouds in Singapore tend to have higher water content because warmer air holds more moisture than colder air. The median cloud cover in Singapore is 90% (mostly cloudy) and does not vary significantly. The typical cloud forms in Singapore are cirrus clouds (high clouds with bases above 20,000ft), altocumulus clouds (medium clouds with bases between 7,000ft to 20,000ft) as well as cumulus and cumulonimbus clouds (low clouds with bases below 7,000ft). The typical cloud thickness ranges from 1km to 6km with the radii of the cloud water droplets ranging from about 0.5μm to 80μm. The extinction coefficient increases by an order of 10 for every kilometre of cloud thickness. Hence, the vertical transmittance through such clouds would be less than 0.005%, and the clouds would be opaque to visible and IR radiation.

Fog Attenuation

Water vapour in the air usually condenses high in the atmosphere to form clouds but it can also condense close to the ground to form fog. Fog forms when the difference between atmospheric temperature and dew point is less than 2.5°C and occurs at relative humidity near 100%, which means that the air will become supersaturated if additional moisture is added. When the air is almost saturated with water vapour at relative humidity of close to 100%, fog can form in the presence of a sufficient number of condensation nuclei which can be smoke or dust particles. The reason for degradation of visibility in a foggy atmosphere is the absorption and scattering of EM radiation by fog particles. The degradation is dependent on the droplet size and its distribution. Fog has similar effects to that of clouds.

In Singapore, fog is most likely to occur during the inter-monsoon periods, at times when winds are light and on cloud-free nights with high humidity. On the average, the dew point for Singapore varies from 22°C to 27°C, while the atmospheric temperature varies from a low 25°C to 27°C during the monsoon seasons and inter-monsoon periods respectively. The fog observed in Singapore is mainly due to radiative cooling of the land, which causes the temperature of the air near ground level to fall within 2.5°C of the dew point, resulting in the condensation of water droplets. It can be observed that attenuation due to an evolving fog decreases rapidly with increasing wavelength. Hence, IR sensors perform better than visible sensors in foggy conditions. The same is not true for transmission through stable fog, where IR attenuation is so severe that IR sensors have little advantage over visible sensors.

Determining Visible and Infrared Sensor Performance Using Transmittance

Visual range is a measure of visibility (Malm, 1999). The larger the visual range, the better the visibility. Visibility is calculated from a measurement of EM radiation extinction which includes the scattering and absorption of light by particles and gases.

In natural weather scenarios, transmittance along the line-of-sight between the sensor and its target is degraded uniformly. This degradation is characterised by an extinction coefficient α km^{-1}. The extinction coefficient quantifies how the passage of light from a scene to an observer is affected by air particles (Malm, 1999). The extinction is dependent on particle mass and chemical composition. To estimate the performance of sensors in man-made induced obscurants, transmittance degradation in the form of a mass extinction coefficient α' m^2/g for the obscurant is added to natural weather degradation. Hence, to determine the sensor performance, its transmittance can be calculated using the equation:

Transmittance, $T = \exp^{(-\alpha R - \alpha' CL)}$

Where α = ambient atmosphere extinction coefficient (km^{-1})
R = range (km) from target to sensor
α' = induced obscurant mass extinction coefficient (m^2/g)
CL = induced obscurant concentration pathlength (g/m^2)

In other words, range can be calculated as:

$R = -[\ln(T) + \alpha' CL]/\alpha$

The range equation shows a negative logarithmic relationship to transmittance. However, the equation does not show a direct relationship to wavelength as it is affected to varying degrees by ambient atmosphere and obscurant.

While the above equations provide a general guide on predicting sensor performance, it must be noted that the industry employs more complex simulation software such as the TACOM Thermal Image Model, NVThermIP with MODTRAN, NVESD

Time Dependent Search Parameter search model for search and detection predictions, and most recently NVLabCap for detailed analysis and prediction of sensor performance under different environmental conditions. These software are able to evaluate imaging sensor system performance comprehensively based on multiple factors including system design and tolerances which cannot be adequately represented in the equations mentioned. The NVESD Time Dependent Search Parameter search model, NVThermIP and NVLabCap are authoritative simulation systems developed by the US Army Night Vision and Electronic Sensors Directorate over the years to improve the accuracy and repeatability of measurement techniques, in their effort to characterise and evaluate a variety of EO imaging systems for the US Army.

Impact of Haze on Sensor Performance

Haze refers to small particles dispersed throughout the atmospheric aerosol (Chen, 1975). Biomass burning is a global phenomenon that releases large quantities of gases and aerosol particles into the atmosphere, affecting the atmospheric chemistry and climate on a large scale via the scattering and absorption of solar radiation (Li, Shao, & Buseck, 2010). Aerosols in regional hazes are contributed largely by anthropogenic sources such as industrial emissions, coal power plant operations, vehicular fossil fuel combustion, and agricultural biomass burning (ABB). Academic researchers in China who conducted studies about the severe haze situation in Beijing and northern China, have defined seven major fine aerosol particles commonly found in haze – namely mineral, soot, organic matter, fly ash, K-rich, S-rich and metal particles (Li et al, 2010). Notably, their studies indicated that the ageing of soot particles from ABB in a high relative humidity environment increased the absorption of visible solar radiation as compared to soot alone.

Attenuation due to haze is very complex because of diversity in the particle type, size, shape and size distribution in a hazy atmosphere. In general, haze attenuates visible radiation more than it attenuates IR radiation due to the small size of haze particles. This is because the small diameter of the particles typically coincides with the short wavelengths found in the visible portion of the EM spectrum. Scattering is the dominant attenuation factor. However, in regions with high relative humidity, aerosol liquid water absorption can increase as moisture can condense on the particles. Experimental studies have shown that attenuation at longer wavelengths is less than that at shorter wavelengths. Hence, IR sensors can penetrate further through haze than visible optical sensors. Figure 2 shows the photographs taken in Singapore on a clear day and on a hazy day in 2013.

Specific to Southeast Asia (SEA) is the recurring biomass burning-induced smoke haze. The particles in the SEA haze are contributed primarily by forest fires burning in Indonesia. This is different from the particles contributed by an amalgamation of sources, including industrial emissions, coal power plant operations and vehicular fossil fuel combustion on top of

Figure 2. Daytime photograph showing Bedok South Ave 1, looking west towards Marine Parade at 12:04pm on 24 June 2013 (left) (© Wolcott / File:Marine Parade Road (2).jpg / Wikimedia Commons / CC BY 3.0) and view from the same vantage point on 21 June 2013 at 10:35am, when the haze was at hazardous levels (right) (© Wolcott / File:Haze obscuring Marine Parade.jpg / Wikimedia Commons / CC BY 3.0).

ABB in northern China that resulted in the persistent haze in Beijing. One of the SEA's worst air pollution events took place in June 2013 when the three-hour Pollution Standards Index (PSI) in Singapore reached a record high of 401 on 21 June 2013. Figure 3 illustrates the severity of the haze's impact on visibility when the PSI reached 312.

In summary, the increase in particles, particularly those with diameter similar to the wavelength of light, is thought to be responsible for visibility impairment on hazy days. Since visible light would be more strongly attenuated, IR sensors would perform better under such conditions. However, the scattering and absorption coefficients of haze particles increase as their concentrations increase. This could reduce the performance of even IR sensors, as the wavelengths at which they are operating could also be severely attenuated.

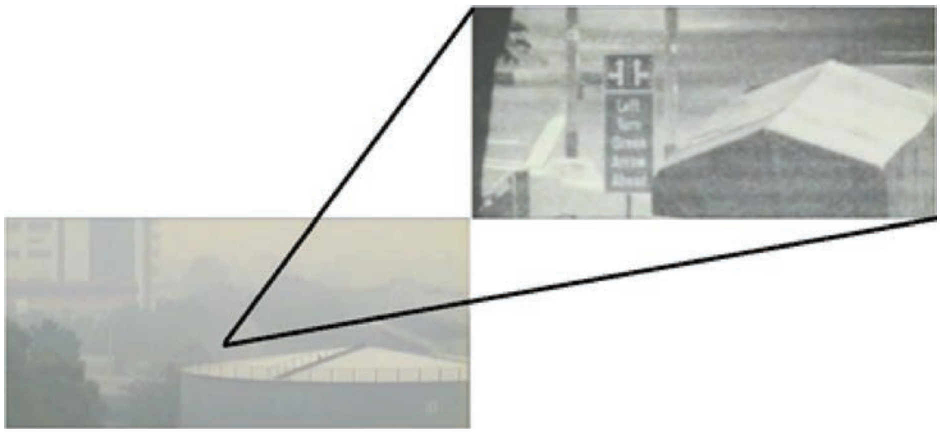

Figure 3. Daytime photograph of a traffic junction taken from 1km (left) and close range of 50m (right) when the PSI reached 312 in June 2013.

Studies by local academic researchers noted that the concentrations of particulate matter of 2.5µm size ($PM_{2.5}$) increased more than 15 times during the haze in June 2013 as compared with non-haze periods. To explore the particles' interaction with light, the optical properties of ambient aerosols were examined in terms of b_{ap}, the light absorption coefficient of particles, as well as b_{sp}, the light scattering coefficient of particles. It was found that $PM_{2.5}$ was more correlated with b_{sp} than b_{ap}. This implied that attenuation by $PM_{2.5}$ was mainly due to the scattering of light by the particles (See, Balasuhramanian, & Wong, 2006).

The studies also reported that fine particles were generally found in greater mass concentration than coarse particles in our local environment. An interesting observation made during hazy days was that while the mass concentration increased across the entire size range, the increase in coarse particles was larger than in fine particles. A possible reason for this could be that while biomass burning in Indonesia emitted more fine particles than coarse particles, some of the fine particles amalgamated to form coarse particles during the long range transport to Singapore.

EMERGING TECHNOLOGIES FOR FURTHER CONSIDERATION

Local environmental effects affect sensor performance, albeit to different extents on different wavelengths. Multispectral or hyperspectral detection technologies could potentially reduce sensor performance degradation by applying spectral signature analysis across multiple wavelengths. In addition, sensing in the shortwave IR (SWIR) portion of the EM spectrum (wavelengths from 0.9 to 1.7 microns) has recently been made viable with the maturity of InGaAs sensors. Image fusion and enhancement techniques are examined in the following sections.

Multispectral and Hyperspectral Sensors

Multispectral sensors detect the wavelengths across different bands in the EM spectrum. The spectral signature of the detected target is then compared to those of known targets to determine if there is a match. Similarly, hyperspectral sensors create a larger number of images from contiguous, rather than disjointed regions of the EM spectrum, typically with much finer resolution. The finer resolution provides additional information for the spectral signature analysis (Renhorn et al, 2013). Studies have shown that such sensors could provide significant improvement in target detection performance as well as improve false alarm performance over single-band sensors. The challenge, however, is the requirement to build a comprehensive database of the targets' spectral signatures for comparison during the analysis. One development that has potentially sped up the development of viable multispectral and hyperspectral sensors is the Quantum Well IR Photodetector (QWIP).

The QWIP typically consists of multiple quantum wells sandwiched between its emitter and collector contacts (Ting et al, 2014). By adjusting the width and depth of the well, the sub-band transition energy and absorption wavelength can be adjusted. The gallium arsenide-based or aluminium gallium arsenide-based QWIP stands out as a prime candidate for the development of Focal Plane Arrays (FPA) due to its favourable inherent properties. These include its ease of fabrication, ruggedness, pixel-to-pixel uniformity, high pixel operability, temporal stability and its ability to be tailored to the selected wavelengths. To date, the industry has demonstrated the megapixel single band LWIR QWIP FPA, simultaneous dual-band megapixel QWIP FPA, 640 x 512 format spatially separated four-band FPA, as well as the development of a super-pixel QWIP FPA for an imaging multiple wave band temperature sensor. The next bound of development is expected to focus on harnessing the QWIP FPA technology for a compact 7.5μm to 12μm hyperspectral IR imager.

Shortwave Infrared Sensors

In recent years, SWIR has grown to become a viable low light imaging option to overcome environmental effects such as haze, fog and dust for mission scenarios, where target details are highly valued but do not show up on MWIR or LWIR sensors due to non-representation by temperature differences. A SWIR system can typically provide better spatial resolution than a similar class MWIR or LWIR system, enhancing target recognition and identification which are critical functions on the battlefield to minimise collateral damage. When operated at night, SWIR can also take advantage of an atmospheric phenomenon called night sky radiance or night glow, which emits five to seven times more illumination than starlight, and nearly all in the SWIR wavelengths. These wavelengths are relatively covert as they are undetectable by visible spectrum cameras, II-based night vision devices as well as MWIR and LWIR cameras. In addition, SWIR also allows surveillance through glass windows which MWIR and LWIR cameras are unable to penetrate.

Image Fusion and Enhancement Techniques

Recent global geo-political activities have escalated the urgent need to deploy multiple imaging sensors operating across different spectral bands to provide timely anomaly detection. Surveillance agencies now require situation pictures from multiple sensors to reach their command centres simultaneously. The use of effective image fusion techniques would: (a) maximise the amount of relevant information that is delivered to the operator; (b) cut down the time spent on irrelevant details (e.g. false alarms), uncertainty and redundancy in the output; (c) prevent the occurrence of artefacts or inconsistencies in the fused image; and (d) suppress irrelevant features such as distortion caused by noise found in the source images. In addition, fused imagery that optimally agrees with human cognition processes allows the human operator to grasp the gist of the displayed information quickly and execute efficient and effective responses for time-critical surveillance missions. Over the years, multiple smart processing and target tracking algorithms, including edge detection, autonomous video motion detection and tracking, have been developed and integrated with the central display interface of multiple sensor feeds. This has greatly enhanced collective surveillance efforts.

Fused imagery has traditionally been represented in grey or monochromatic tones, due partly to the output displays of the IR imaging sensors. While the human eye can only distinguish about 100 shades of grey at any instant, IR imaging sensors produced in the industry today can discriminate between several thousands of colours. The use of colour images may improve feature contrast and reduce visual clutter, enabling better scene segmentation, object detection and depth perception. This will also yield a more complete mental representation of the perceived scene for enhanced situational awareness.

Research in this field is ongoing. In time, these developments will mature and systems could be deployed in the field for improved wide area situation awareness. The higher probability of target detection, recognition and identification would also drive the optimisation of automatic surveillance systems and alleviate manpower constraints faced by national security and defence entities regionally and globally.

CONCLUSION

EO sensors play a critical role in detecting and identifying targets in modern day battlefields. However, they can be affected by environmental conditions. In our local environment, the presence of water vapour due to high humidity, rainfall, clouds or fog, can severely impact the sensors' performance. It is thus useful to understand the operational requirements of the sensors and the environmental conditions in which they operate, in order to select the most optimum sensor for the situation.

REFERENCES

Anon. (1993). *Protecting visibility in national parks and wilderness areas*. National Research Council, Washington, DC.

Bernard, E., Riviere, N., Renaudat, M., Guiset, P., Pealat, M., & Zenou, E. (2013). Experiments and models of active and thermal imaging under bad weather conditions. *Proceedings of SPIE, Electro-Optical Remote Sensing, Photonic Technologies, and Applications VII; and Military Applications in Hyperspectral Imaging and High Spatial Resolution Sensing, 8897*. doi: 10.1117/12.2028978

Chen, C. C. (1975). *Attenuation of electromagnetic radiation by haze, fog, clouds, and rain*. (RAND Report No. R-1694-PR) Retrieved from http://www.rand.org/content/dam/rand/pubs/reports/2006/R1694.pdf

Eismann, M. T., Schwartz, C. R., Cederquist, J. N., Hackwell, J. A., & Huppi, R. J. (1996). Comparison of infrared imaging hyperspectral sensors for military target detection applications. *Proceedings of SPIE Imaging Spectrometry II, 2891*(91). doi:10.1117/12.258056

Leong, S. C., & Foo, Y. C. (2007, December). Singapore rain rate distributions. *6th International Conference on Information, Communications & Signal Processing, 2007*. doi: 10.1109/ICICS.2007.4449534

Li, W. J., Shao, L.Y., & Buseck, P. R. (2010). Haze types in Beijing and the influence of agricultural biomass burning. *Atmospheric Chemistry and Physics*, 10(17), 8119–8130. doi: 10.5194/acp-10-8119-2010

Malm, W. C. (1999). *Introduction to Visibility*. National Park Service and Colorado State Institute for Research on the Atmosphere, Fort Collins, Colorado.

Renhorn, I. et al. (2013). Hyperspectral reconnaissance in urban environment. *Proceedings of SPIE, Infrared Technology and Applications XXXIX, 8704*. doi:10.1117/12.2019348

See, S. W., Balasuhramanian, R., & Wang, W. (2006). A study of the physical, chemical, and optical properties of ambient aerosol particles in Southeast Asia during hazy and nonhazy days. *Journal of Geophysical Research Atmospheres, 111*(D10S08). doi: 10.1029/2005JD006180

Ting, D. Z., Soibel, A., Keo, S. A., Rafol, S. B., Mumolo, J. M., Liu, J. K., … Gunapala, S. D. (2014). Development of quantum well, quantum dot, and type II superlattice infrared photodetectors. *Journal of Applied Remote Sensing, 8*(1). doi:10.1117/1.JRS.8.084998

Wolcott. (2013). File:Haze obscuring Marine Parade.jpg. In *Wikimedia Commons*. Retrieved March 10, 2015, from http://commons.wikimedia.org/wiki/File:Haze_obscuring_Marine_Parade.JPG#mediaviewer/File:Haze_obscuring_Marine_Parade.jpg

Wolcott. (2013). File:Marine Parade Road (2).jpg. In *Wikimedia Commons*. Retrieved from March 10, 2015, http://commons.wikimedia.org/wiki/File:Marine_Parade_Road_(2).JPG#mediaviewer/File:Marine_Parade_Road_(2).jpg

BIOGRAPHY

LEE Cheow Gim is a Project Lead (Advanced Systems) who manages electro-optical (EO) projects for the Singapore Army. He graduated with a Bachelor of Engineering (Electrical and Electronic Engineering) degree from Nanyang Technological University (NTU) in 2003.

EE Kok Tiong is a Project Manager (Advanced Systems) who manages EO projects for the Republic of Singapore Navy. He graduated with a Bachelor of Engineering (Electrical Engineering) degree from the National University of Singapore (NUS) in 2002 and a Master of Science degree in Electrical Engineering (Computer Networks) from the University of Southern California, USA, in 2008.

HENG Yinghui Elizabeth is a Programme Manager (Advanced Systems) who oversees EO projects across the Singapore Armed Forces. She graduated with a Bachelor of Engineering (Electrical and Electronic Engineering) degree from NTU in 2003. She also obtained a Master of Science (Electrical Engineering) degree from the Naval Postgraduate School, USA, and a Master of Science (Defence Technology and Systems) degree from Temasek Defence Systems Institute in 2013.