Atmospheric Waves Experiment

Comprehensive Exam

Introduction to Research

The Atmospheric Waves Experiment (AWE) project is a telescope that will look down at Earth from the International Space Station. Its goal is to measure the effect of gravity waves in the atmosphere (not to be confused with gravitational waves). These gravity waves begin from storms, prominent features like cliffs or mountains, and other sources, they propagate upward in the atmosphere and as they do, they grow in intensity. The AWE project will image these waves, send back the raw data to Earth, and when analyzed they will show how space weather and normal weather interact.

Summary of Synergy of Optics Topics

The AWE project is strongly tied to a synergy of topics within optics. The emissions being imaged are understood through optical physics. Understanding the detector being used requires a base knowledge in photonics. The telescope design is based in geometric optics, radiometry, opto-mechanical principles, and others. The measurement of the image quality is strongly tied to image science. Each of these topics will be discussed in more detail.

Science Background

Because of their importance in this project, it is necessary to give a background on gravity waves. They transport energy through the atmosphere and are a vital, little understood phenomenon that connect weather in the troposphere with space weather. Most people have experienced gravity waves through airplane turbulence, but gravity waves extend far beyond those altitudes. If they get high enough, they get to the OH airglow layer and beyond. When reaching the airglow layer, the waves begin to break, or in other words, they deposit a lot of energy into the OH molecules. In this way they are similar to waves in the ocean: they are present under water, but their energy is deposited at the boundary of where the water meets the air.

Gravity waves start from many sources: storms, other weather, mountains, valleys, islands, other geographic features, and many more. At these events and locations, buoyancy forces propagate the air up and out, and gravity pulls them down, creating a wave. When propagating, they can go almost any direction. If they go in a direction that increases with altitude, their amplitudes also increase in altitude. They can also break up into groups of smaller waves.

Between the Mesosphere and the Thermosphere, at a roughly 87 km altitude, there is an OH airglow layer. The airglow layer has emissions in the near infrared due to ro-vibrational transitions. In ro-vibrational transitions, a molecule's vibrations are analyzed like a harmonic oscillator with quantized energy states. The wavelengths of the emissions are due to energy level changes along with a change of total angular momentum, with a selection rule of $\Delta J = \pm 1$. In this case, these transitions give rise to sharp peaks throughout the near-infrared spectrum[1]. The peak amplitudes are dependent on the temperature of the airglow layer. When looking at the ratio between certain narrow bands, an accurate temperature reading can be performed.

When gravity waves are incident on the airglow layer, they cause pressure changes, which then cause temperature changes in the airglow layer due to the standard equation $PV = nRT$. If these temperatures across the airglow layer can be measured with proper precision and resolution, the gravity waves in the OH airglow layer can be imaged. This has been done before, but it is generally with a relatively limited FOV and from the ground looking up [2].

Instrument Overview

An instrumentation requirement is that the system needs to be able to image gravity waves with wavelengths from 30-300km. To do this, the instrument will be a combination of four telescopes; each telescope will be ~F/1 with a ~90 degree FFOV. In order to get the desired spot size, the telescope will have 16 lens elements. These elements can be put in groups: a telecentric fish-eye lens, the filter, a field lens [3], and a re-imager. With a FOV so large, careful precautions were made to prevent stray light issues. One telescope will have a filter for the OH(3,1) P1(4) band at 1543nm, one telescope will have a filter for the OH(3,1) P1(2) band at 1524nm, and another will have a filter at 1521nm. These filters will have a FWHM of 1nm and will be resistant to the temperature changes found in a low-earth orbit. The fourth telescope will be an extra in case of issues with one of the other three.

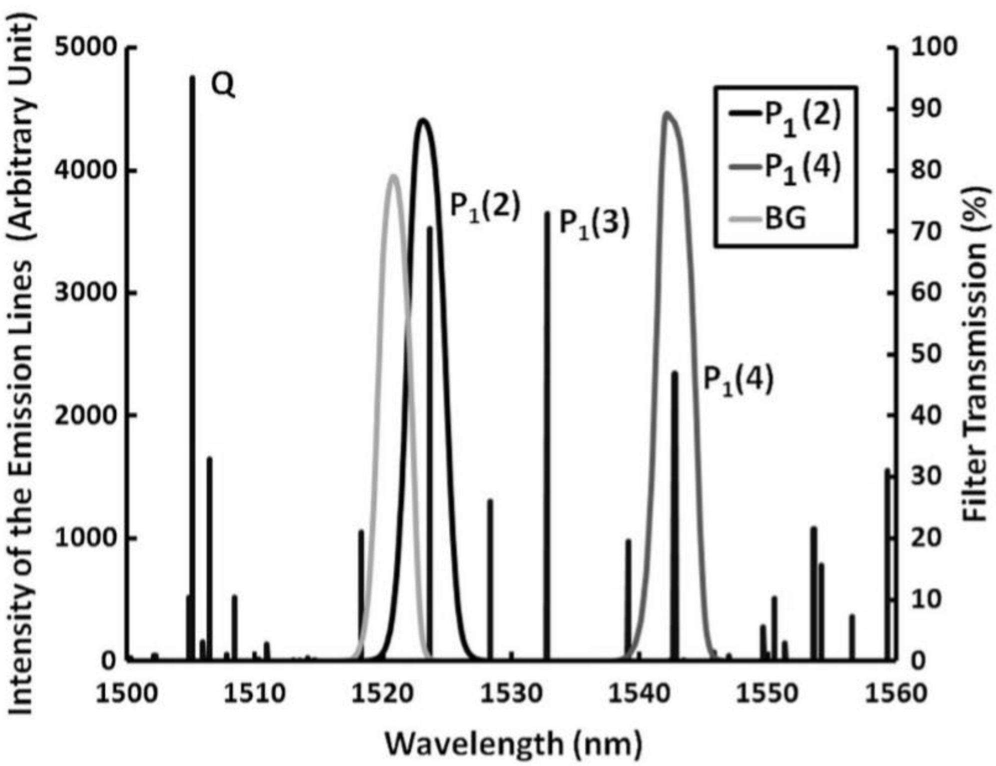
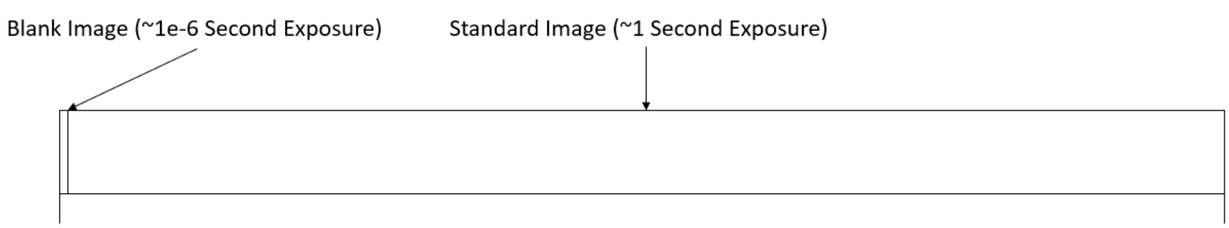


Figure 1: OH (3,1) Band. The gaussian lines are the filter's transmission

Detector Overview

The detector used for each telescope will be an InGaAs detector with deep wells (digital values ranging from 0 - 65535). These detectors are not traditionally used in space, but are used for tactical, high-signal imaging. They also have higher noise values than a traditional detector. The signal will tend to be at the lower end of the detector's range. The InGaAs detectors were chosen because they cover the desired wavelength range, they are cheaper than traditional detectors for space, and there was current availability for the initial design. InGaAs detectors have p-n junctions but with a low bandgap, which allows for reliable infrared imaging. A high noise level, due to the low bandgap, will be minimized by operating this detector at around -20C.

A technique called correlated double sampling will be used to eliminate some of the noise in the detector. This means that when an image is about to be taken, the detector will be left in its original, supposedly noise-free state. Because there is a lot of noise in the detector, at the next clock cycle, a blank image will be taken. When the next 1 second exposure happens, that image will be subtracted by the blank (that has noise) and a cleaner image will result. The figure below shows it further:



Final Image = Standard Image – Blank Image

Figure 2: Correlated Double Sampling takes a blank image, which has some noise, and subtracts it from the 1 standard image.

Temperature

The detectors are very sensitive to temperature. As the temperature decreases, the spectral response shifts left slightly toward higher energies. The dark current is also greatly affected by temperature. The dark current rate equation is as follows:

$$D = 2.55 * 10^{15} P_A D_{FM} T^{1.5} e^{\frac{-E_g}{2kT}}$$

Where T is temperature, P_A is pixel area, D_{FM} is the dark current figure of merit at 300K, k is Boltzmann's constant, and E_g is the energy bandgap for the material [3]. From this, a rough rule of thumb for the range around the operating temperature is that the dark current noise will double for every 8 degree temperature increase. Because of its dependence on temperature, the detector will be temperature controlled to ensure it does not rise above a critical temperature.

Image Quality

The goal of the project is to detect gravity waves, and therefore sufficient emphasis is placed on if they can be seen, how visible they have to be, and if there any factors that make them difficult to see.

Processing/Radiometry

The emission lines give a minimum of 2.3kR (kilorayleighs). To convert kR to traditional photon radiance is:

$$1\ R = \frac{4\pi}{10^{-10}} J/(m^2 * sr * sec)$$

The integration time of each image is 1 second. Using the radiative transfer equation,

$$LA\Omega = L'A'\Omega' = \Phi$$

and accounting for light losses due to each lens and the detector QE, the number of photons per pixel is about 724. The detector has a value of 3 photons per digital number (DN) which means that the signal will be ~241, which is fairly low in the range of the detector.

Low light

Because of the low light levels on the detector, actions will be taken to get a better signal. As discussed earlier, each image capture will be a 1 second exposure. The ISS travels at 7.66 km/sec which means that at a 600 km square FOV, over 75 pictures can be added on top of each other (which is called co-adding). Because the gravity waves move around 180m/sec, though, too many pictures cannot be coadded. For this application, 30 pictures will be coadded to get increased signal.

Reflection

When looking down at the earth, the airglow layer will give signal, but so will reflections of the airglow layer off the earth. This includes high clouds, low clouds, water, soil, and vegetation. Each of these have different reflection values, and it is a minor concern that these reflections will interfere with the image quality. High clouds are of special concern because they have a high reflectivity (~40%). The equation for visibility is:

$$V = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

and with 40% reflectance, that leads to visibility of 55%.

Because of this issue, an alternative design has been proposed where the telescope that is detecting the background signal is placed at 1420nm, where lower atmospheric transmission is very low, instead of 1521nm. This would mitigate the reflection problem in the background signal.

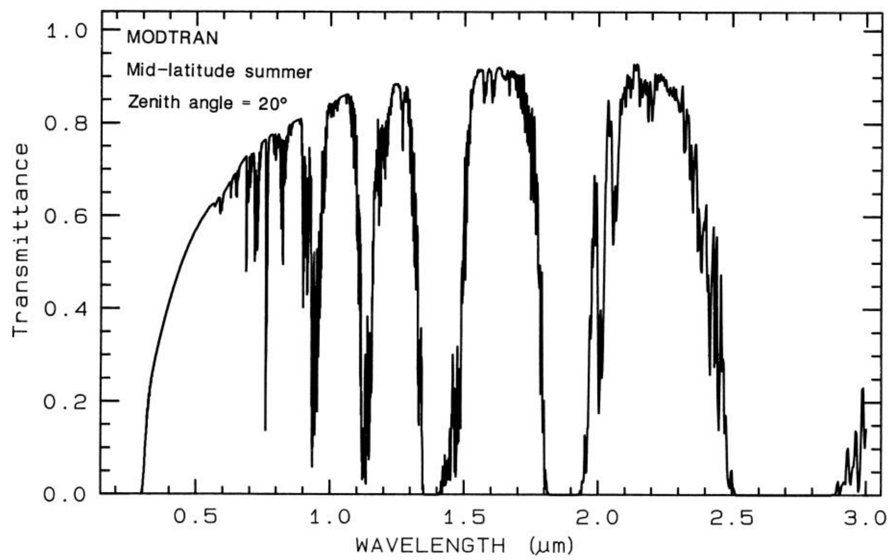


Figure 3: Transmission spectrum of the atmosphere. From https://archive.usgs.gov/archive/sites/speclab.cr.usgs.gov/PAPERS.refl-mrs/refl4.html

The ratio between the two OH bands will still have some extra signal due to reflections. These reflections also are unequal for different wavelengths, but this new design is still a step forward.

MTF

The modulation transfer function is important in this case because of the desired gravity wave wavelength range of 30-300km. An MTF analysis can show how much of these frequencies will get through[5]. The items that will affect the MTF are the optical design, detector optical crosstalk, detector electric crosstalk, ISS jitter, ISS speed, pixel size, and coadding. Their contributions to the MTF are shown below with ISS Smearing and pixel size being combined on the same image:

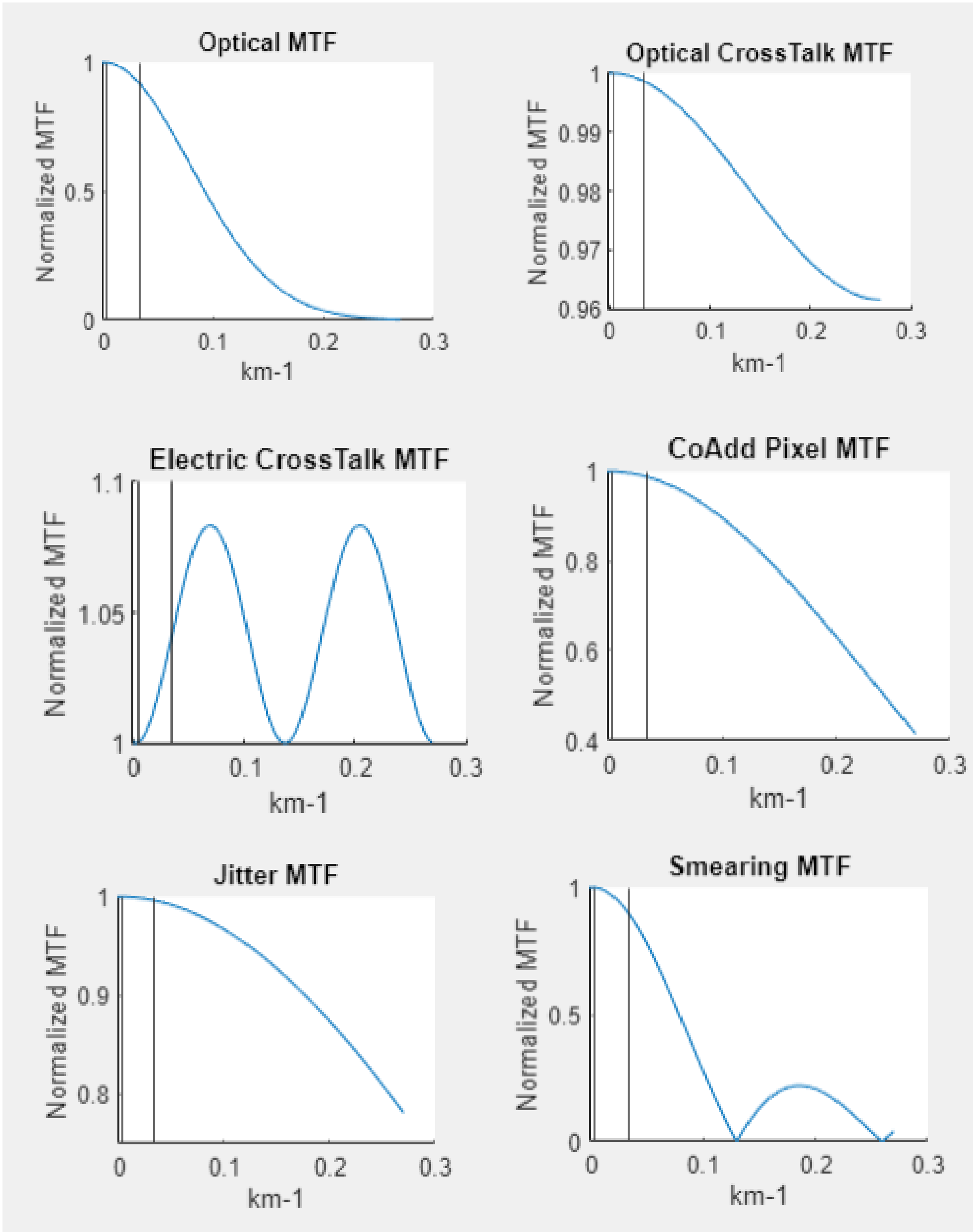


Figure 4: Components of the Overall MTF. The left vertical line on each graph corresponds to visibility for 300km waves and the rightmost vertical line corresponds to visibility for 30km waves.

It is important to note in the picture above that the electric crosstalk values range from 1 – 1.08. The overall MTF is given here:

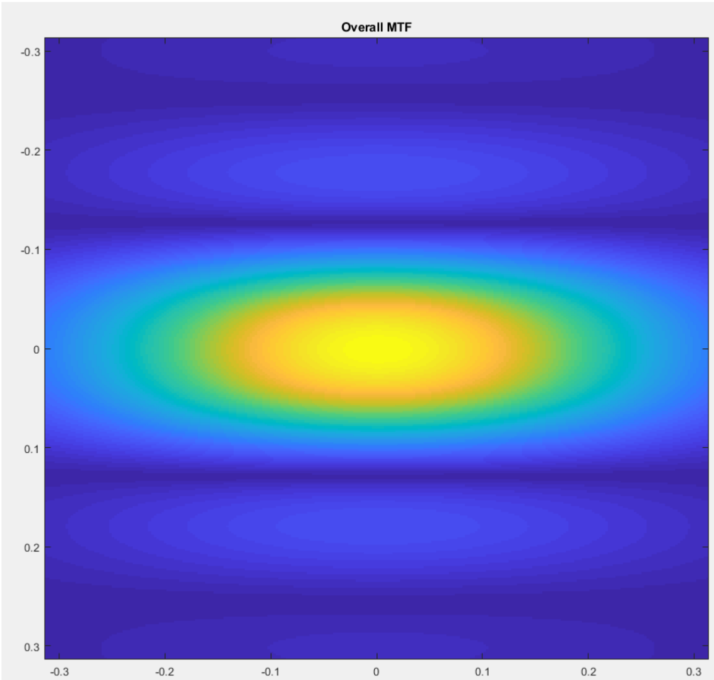


Figure 5: The overall MTF

For a 30km wave, the current best estimate is for 90% of the signal to make it through. For a 300km wave, it is >99%. If the optical PSF, optical crosstalk, or jitter were to get worse, the amount of 30km signal that gets through could go down to as little as 80%. For the desired range, the MTF shows that there will be adequate amounts of signal.

Conclusion

The AWE project will be able to detect gravity waves for the benefit of learning how terrestrial weather affects space weather. There are potential setbacks and challenges, but this project will be accomplished using 3 telescopes that will work together, InGaAs detectors with deep wells, and processing of the data to get a better signal. Future work for this project includes more accurate radiometry and noise calculations, further detector characterizations, and finalizing the processing of the collected images.

1) Oliva, E., Origlia, L. The OH airglow spectrum: a calibration source for infrared spectrometers, *Astronomy and Astrophysics, 254, 466-471 (1992)*
2) Pautet, P.-D., Taylor, M. J., Pendleton, W. R., Zhao, Y., Yuan, T., Esplin, R., & McLain, D. (2014). Advanced mesospheric temperature mapper for high-latitude airglow studies. *Applied Optics*, *53*(26), 5934. https://doi.org/10.1364/ao.53.005934
3) Greivenkamp, J. (2004). *Field guide to geometrical optics* (Spie field guides, v. fg01). Bellingham, Wash.: SPIE Press.
4) Janesick, James R., 2007, *Photon Transfer*, SPIE Press, Bellingham, Washington, 168 p
5) Barrett, H., & Myers, K. (2004). Foundations of image science (Wiley series in pure and applied optics). Hoboken, NJ: Wiley-Interscience.