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OPTIMIZING AN INFRARED CAMERA FOR OBSERVATION OF ATMOSPHERIC GRAVITY WAVES FROM A CUBESAT PLATFORM

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Abstract. The NUTS (NTNU Test Satellite) is a satellite being built in a student CubeSat project at the Norwegian University of Science and Technology. The project was started in September 2010 and is a part of the Norwegian student satellite program run by NAROM (Norwegian Centre for Space-related Education). The NUTS project goals are to design, manufacture and launch a double CubeSat by 2014. The satellite will fly two transceivers in the amateur radio bands. Final year master students from several departments are the main contributors in the project.

As a main payload, an infrared camera system designed to observe gravity waves in the Mesosphere and lower Thermosphere is planned. Gravity waves can be found throughout the atmosphere and originate from flow over topography, convection and jet imbalance. As these waves propagate upwards in the atmosphere they transport energy and momentum. This transport will have an affect on the circulation in the middle atmosphere. At an altitude of approximately 90 km we find a layer of hydroxyl molecules that emit short wave infrared radiation during the night. When gravity waves propagate through this layer, wave patterns in the radiation intensity are observed. These observations have been limited to a few ground stations, and the possibility of global coverage from a satellite will be a useful contribution to further research.

We discuss the design of an off-the-shelf camera system based on the mechanical limitations offered by the CubeSat platform, and the scientific requirements based on data from ground observations. Due to a limited downlink, signal processing techniques and algorithms to make sure the scientific data are detected, restored and compressed are presented.

1. INTRODUCTION TO THE NUTS PROJECT

The NTNU Test Satellite (NUTS) project is a student satellite project at the Norwegian University of Science and Technology (NTNU). The NUTS project aims to design, develop, test, launch and operate a double CubeSat by 2014. Students from different study programs will do the main part of the work, supported by project management and technical staff. The work will be performed as part of the students project- and master thesis. The design has been chosen to be generic and modular, so the satellite-bus can support different payloads. Recruitment and education of skillful students constitute a main part of the projects goals. Through hands-on experience, the students will be able to master different skills needed in their jobs after graduation. NTNU is a university offering a wide range of field of technological studies. Accordingly, a strategy to develop all subsystems in-house has been chosen. This means that if problems and delays in the project are experienced, this could not be repaired by buying missing sub-systems. The internal layout of the satellite electronics is different from most CubeSat projects. A backplane layout where cards for other systems can be slotted in, will be implemented. The system is distributed in hardware, meaning different subsystems, such as the OBC, ADCS and radio subsystem, will have their own MCUs. The main processor will be an Atmel AVR32 UC3. Use of solar panels as sun sensors for the ADCS-system is being investigated. The actuators will be magnetic coils integrated in the main structure of the satellite. This structure will mainly use composite material instead of using aluminum, and to our knowledge, this is unique compared to other CubeSat missions.

2. Atmospheric Gravity Waves

As a result of the atmospheric structure, internal waves will occur at the interfaces of regions with different densities. These waves are classified as gravity waves when the only restoring force is gravity. Typical sources for atmospheric gravity waves are flow over topography, convection and jet imbalance. The waves are quite frequent, and can be found throughout the atmosphere. Based on their location, there can be large variations in amplitude, wavelength and frequency. As the waves propagate upwards, they are responsible for momentum and energy transport. This is an important factor in the global scale circulation of the upper atmosphere[3].

When propagating upwards, the waves can under the right circumstances reach a height of approximately 90 km. This is a region called the Mesosphere and lower Thermosphere, and here the waves will encounter a layer of hydroxyl airglow. The layer is composed of the hydroxyl radical (OH), and has a thickness of approximately 10 km. The temperature range from 150 K in summer, to $\approx$ 230 K in winter. During the night, this layer will emit infrared radiation, and as the waves propagate through the layer, intensity perturbations of 1-5% can be observed with infrared detectors. The production of hydroxyl is at its highest five hours after local sunset, and it is at this time one can expect to make the best observations[6].

Due to the thickness of the layer, only waves with a vertical wavelength larger than approximately 10 km can be detected. The NUTS project will aim to have a payload design that can detect the most frequent wavelengths. Figure 1 illustrates the wave parameters from ground observation done at Halley, Antarctica [5]. The mean value for horizontal wavelengths are approximately 26 km, the observed phase speed have an average of approximatetley 48 m/s, and the observed period has a mean value of 10 min. This data will be the basis for camera requirements and image processing parameters.

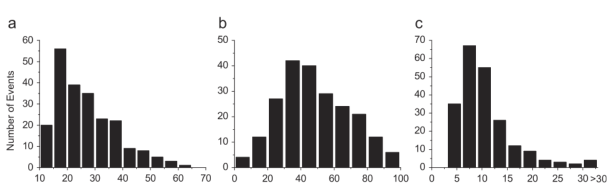

Figure 1. Waveparameters from Halley, Antartica.[5]

3. Choosing an Infrared Camera

In order to choose the correct camera as payload, a list of different requirements have been made. The most limiting factors are the mechanical restrictions of the CubeSat platform. There will also be strict requirements regarding the use of power and data processing. In addition to this, the camera must fulfill the scientific requirements in order to make satisfying observations.

3.1. Mechanical Limitations. The size, weight, voltage and power available to the payload is listed below:

- Size: $92 \times 88 \times 65$ mm^3
- Weight: 200-300 g
- Backplane 5 V
- Battery 30 Wh

The camera will also have to go through a series of tests to make sure it would survive launch, and then function under the expected conditions. The test criterions are listed in the tables below:

Test	Frequency	g-force
Shock	80-125 Hz	10 g
Vibration	5-20 Hz	1g

Characteritics	Proto-flight
Vacuum level	10^{-5} bar
Temperature	+ 60 °C
Duration	24 h

3.2. Detector and Radiaton. The infrared radiation to be detected originates from the OH(2,0), OH(3,1) and OH(9,6) bands of the airglow layer. The wavelengths of the bands range from 1.3 -1.7 μm. The detector has to be made of Indium Gallium Arsenide (InGaAs) to detect these wavelengths.

One of the advantages to study OH at this range, is water vapors ability to absorbs radiation at 1.45 μm. The majority of water vapor is contained in the troposphere, and since the airglow layer is situated above the troposphere, the vapor will have a filtering effect, and absorb the radiation coming from Earth at this wavelength. By adding an optical bandpass filter for 1.45 μm to the payload, the noise from earth and other sources will be low/eliminated.

3.3. **Optics and Resolution.** The observation setup for the satellite is illustrated in Figure 2. The spacing between the red dots indicate the minimum distance one pixel should detect in order to fulfill the Nyquist theorem. From this figure, one can see that in order to collect sufficient data about gravity waves, a minimum field of view and resolution is required. From Figure 1, the mean wavelength is approximately 26 km, and this will correspond to a maximum ground sample distance (GSD) of 13 km in the nadir direction. The minimum focal length for the camera system is given by the following relation:

$$f = \frac{p \cdot H}{GSD_{nadir}} \tag{1}$$

where p is the pixel pitch of the detector and H is height of the satellite[7]. From the expected height of around 600 km, with an average pixel pitch of 30 μm, the minimum focal length will be around 1.4 mm. From Equation 1, one can see that a larger focal length will provide a higher resolution, but at the expense of a lower field of view from Equation 2. A large field of view is necessary to detect multiple waves:

$$FOV \approx \frac{N_{pix} \cdot p}{f} \tag{2}$$

where N_{pix} is the number of pixels on one of the detector sides. The resolution will also depend on the look angle of the satellite and the orientation of the detector (β) relative to the direction of the satellite. The results from Eq.1 and Eq.2 are summarized in Figure 3.

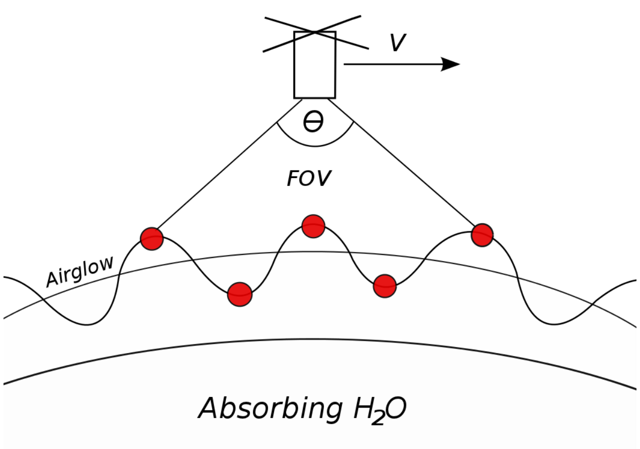

FIGURE 2. Observation of GW, the red dots indicate the minimum sampling frequency.

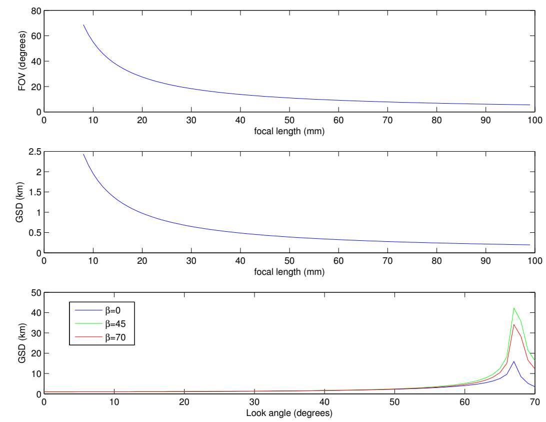

FIGURE 3. FOV and GSD for the satellite.

3.4. **Intensity and Filter.** The total intensity that can be expected from the airglow layer is an important parameter in calculation of the signal to noise ratio (SNR). Since low intensities are expected, different image processing techniques will be utilized to increase the SNR. From high resolution spectroscopy of OH [2], the relative intensity data of the relevant bands are plotted together with an optical filter in Figure 4. Figure 5 illustrates the expected contributions from the different bands with an optical filter with a transmittance of 70%. If the detector has a quantum efficiency (QM) of 80%, the total average intensity one can expect from the three bands is 3.599 kR [8].

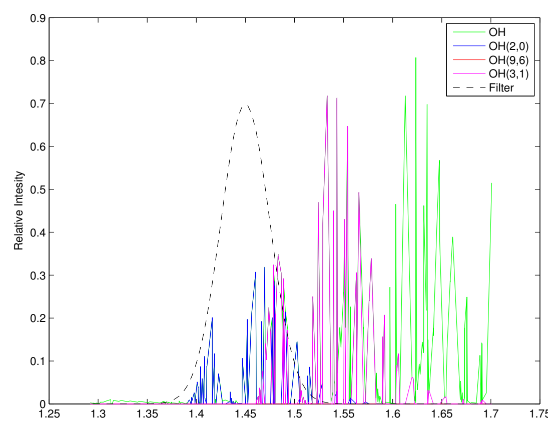

FIGURE 4. Intensities for OH bands, and the optimal location for a filter.

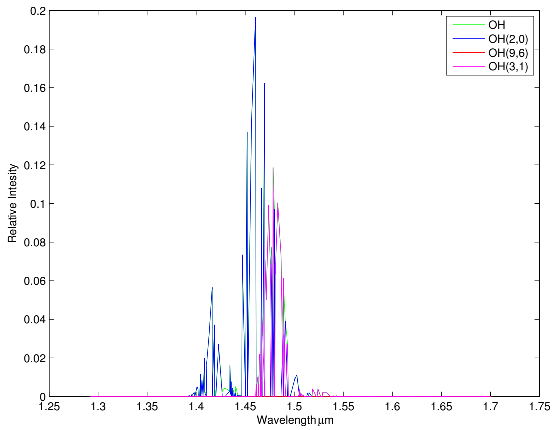

FIGURE 5. Filter response for the relative intensities.

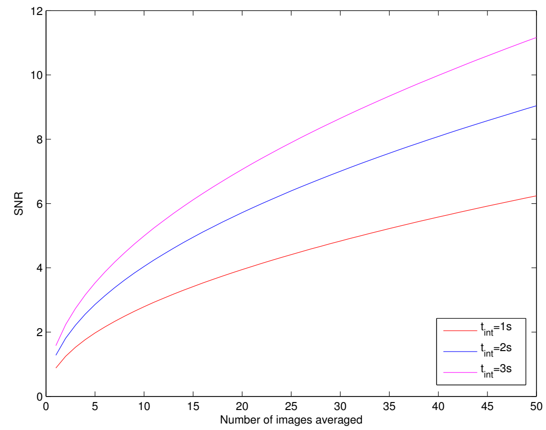

FIGURE 6. SNR for averaged images

3.5. **Signal to Noise.** To detect waves in the airglow layer, the payload must be able to distinguish between the intensities of the waves crests and troughs. In more specific terms, the payload must be able to detect the mean signal difference produced by the waves perturbations. The SNR is given as:

$$\Delta SNR = \frac{\Delta P Q_e t_{int}}{(\Delta P Q_e t_{int} + D_{dark} t_{int} + N_r^2)^{\frac{1}{2}}} \quad (3)$$

Where ΔP is the difference in photon flux, Q_e is the quantum efficiency, t_{int} is the integration time, D_{dark} is the dark current and N_r is the read noise of the detector. From Equation 3 one can see that the SNR is proportional to the square root of the integration time (ignoring read noise), and inversely proportional to the noise. Since the expected intensities are low, it is important to minimize the noise. Reducing the noise by cooling the detector can only be done by a limited set of techniques that are power consuming, and is therefore disregarded.

Another technique is to average a series of images that cover the same area. This will reduce random distributed noise, and be proportional to increasing the integration time. In Figure 6 the SNR for a number of averaged images taken with different integration time are illustrated. The calculations are based on an ideal camera (see discussion). The minimum SNR to detect the waves is two.

The integration time will be limited by motion blur. In Figure 7 from [1], we can see the image degradation function for horizontal blur, i.e. waves moving in the same direction as the satellite. The first zero occur at frequency of 20 cycles/image, and this will correspond to a wavelength of 15 km. By choosing an integration time of 3 s, only waves with wavelength 15 km and below will be blurred. From figure 1 we can see that only a small portion of the expected number of waves will be affected by the choice if integration time. Waves moving perpendicular to the direction of the satellite will not be affected blur. Blur affected by rotation of the satellite has not yet been investigated in this project.

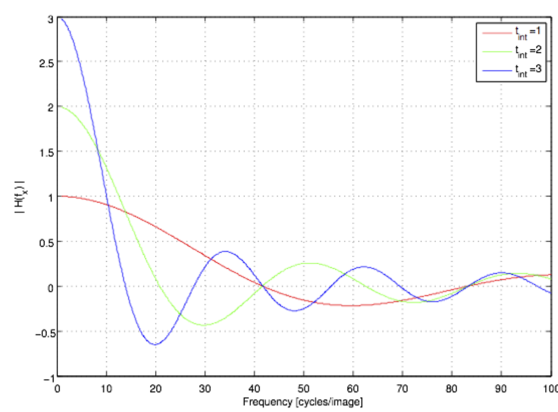

FIGURE 7. Image degradation function.The zeroes describes which spatial frequencies that are totally blurred out.

When averaging a number of images to reduce the noise, only the areas that overlap will have a higher SNR. Since the images are taken consecutive, the area that overlap will be smaller for each images. Figure 8 illustrate the visible ground segment, i.e. the area of the airglow with a higher SNR, for different integration times and number of overlapping images. Since the mean wavelength was approximately 26 km, one can e.g. expect to observe around 3-4 wavelengths when averaging approximately 20 images each with an integration time of 3 s. From Figure 6, one can see that this would correspond to a SNR of approximately seven.

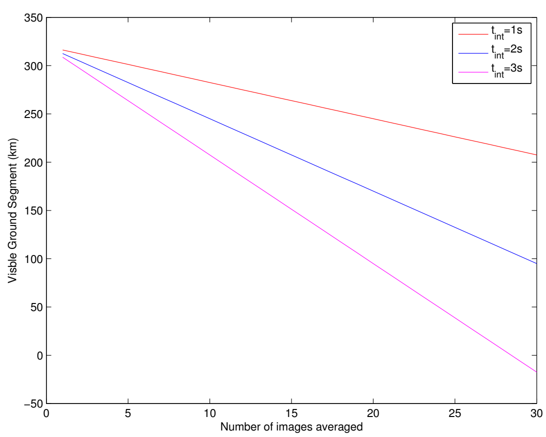

Figure 8

4. Image Processing

Two main image processing aspects must be addressed, namely motion blur and compressing data for transmission. The first problem is related to satellite movement over the target area. The ADCS-system will not be able to compensate for the forward motion of the satellite by for example change the pointing angle of the camera. Therefore, when the integration time is long, the captured image will be smeared. This situation will also occur when integrating several images with a shorter exposure time. The motion of the satellite relative the target can be estimated, and this knowledge can be used to restore a blurred image, for instance by shifting the images $\delta = v_{im} \cdot t_{frame}$ pixels, where t_{frame} is the inverse of the frame rate[1]. The compensation problem becomes harder if the satellites movement is non-linear. The second problem relates to the narrow downlink. A best-case estimate on downlink capacity for the payload is around 2 Mb/day. A series of ten uncompressed images will be more than 5 Mb in size, if one assumes a resolution of 256x256 pixels at 8 bit/pixel. This shows that it would take in the order of two days to download the image series, given that the series is not compressed. A loss-less compression method is favored.

A three-dimensional DPCM algorithm combined with a deadzone quantizer and stack-run coding was implemented in MATLAB. Simulations demonstrated that this simple compression scheme can provide a bit rate of less than 1 bit/px for a sequence of gravity wave images. One of the quantizers that was tried gave 0.83 bits per pixel with reasonable quality. If this number can be achieved in practice, the image transfer rate would be increased to 45 images per day, which is a significant improvement[1].

5. On-board Data Processing

An alternative to download the full image series from the satellite for post-processing on the ground, is to let the satellite itself process the images and only transmit the interesting parameters from the picture series. A 3D-FFT-processing method has been tested on simulated images and shows promising results to greatly reduce the data to be transmitted from the satellite to the ground [4]. If one still would like to transmit images for post-processing, onboard processing can identify the most interesting images to transmit, and discard images with none or less pronounced waves.

6. Conclusion

To observe atmospheric gravity waves from a CubeSat platform is a challenging task, but with the right equipment and image processing techniques it can be done. The results will be a great contribution to the numerous ground observations. With the satellite, wavelength and direction can be detected. Compared to ground observations, the satellite has the possibility of global coverage.

7. Discussion

The selection of the infrared camera is a difficult task, due to both scientific criteria and demands as well as the constraints the CubeSat bus sets. For a relatively small university mission relying greatly on student work, both monetary costs of a camera and the time cost to integrate this into the satellite also puts a strain on the overall mission. Several of the results presented in this paper are based on different camera parameters. These parameters and results are summarized in the table below:

Parameter	Result
Focal length	16 mm
F-number	1.4
GSD	2 km
Resolution	160×160
Binning factor	4
B_{max}	13
FOV	34°
Ground segment one image	320 km
Blurred wavelengths	≤15 km
Integration time	3 s
ΔSNR for one image	1.6
Effective FOV	200 km
N_{images}	11
Δ $SNR_{average}$	5.5

These parameters are not based on a specific camera, but based on several cameras that are available on the market with similar qualities, and will provide a guideline to what can be expected from different cameras.

8. Acknowledgments

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