A case study of 2D-fft based horizontal wavelength calculation of the gravity waves

Absract:

Introduction:

Gravity wave is a natural occurring due to pressure gradient in the atmosphere. Earlier, scientist used to regard gravity wave as an idle wave and used to believe that it has no significant effect in the motion of the atmosphere [1]. In the last decade, meteorologists faced some problem while calculating mean winds flow and building good forecasting model. A part of the reason of that problem was that they did not consider gravity waves effect in model. After that, scientists have focused on gravity waves proper parameterization and using them in global model. Gravity wave covers a broad spectrum of frequency, horizontal and vertical wavelength. Therefore, it is not easy to understand gravity waves from the global dataset. Another major impediment in detecting gravity waves is that resolution of the satellite image is not enough to detect signature of the GWs. Therefore, now-a-days, innovative data processing technique are being used by researcher to make improvement in GW detection. Earlier, Richter et al used satellite temperature variance maps to find out convectively generated gravity waves and topographic waves [2]. Schirber *et al.* worked on gravity wave parameterization forced by convection process (convective heating depth, convective heating rate, and the background wind) [3]. Interestingly, Alexander *et al* introduced a statistical signal processing based technique to detect short scale gravity wave. They performed multi-scale analysis of the AIRS data by taking S-transform of every cross-track row and use covariance spectrum to find the horizontal wavelength [4]. In 2019, Chang Li *et* introduced a much improved image processing based method where the region of the gravity waves were automatically detected by the convolutional neural networking (CNN) method [5]. They developed a 2D-FFT based method to automatically determine the gravity waves parameters (horizontal wavelength, direction). As a term paper of this ATM 666 (Atmospheric Remote Sensing), I have tried to explore the issues related to FFT-based gravity waves' horizontal wavelength determination. I have detected the region manually where there is a strong appearance of gravity waves and tried to apply 2D-FFT at that region to determine the horizontal wavelength. Briefly, I have tried to implement a part of the work done by Chang Li *et.* as my ATM 666 term paper project.

Background perspective:

In this section, introductory discussion about gravity waves, AIRS and 2D-FFT is done and this will make the description of my works sound legible and logical.

Gravity waves:

When fluid displaced from their equilibrium position, gravity tries to restore the initial state. This creates an oscillation which is called the gravity wave. In the atmosphere, it is created due to vertical pressure gradient. Gravity wave is basically resulting from the imbalance between gravity and buoyancy force. It carries energy and momentum to the Mesosphere and Lower Thermosphere and thermosphere. Their significant role in the different layers of atmosphere is recognized by the scientists [6-8]. In recent years, exciting research has improved understanding of the small scale wave's effect in global model. Mid-altitude circulation changing by the gravity waves is being used in the weather forecasting. Moreover, gravity wave can influence the lower stratospheric circulation and ice cloud formation [4]. For those mentioned reason, gravity waves parameterization is on the key issue for stratospheric circulation and proper understanding of the global climate model. Richter *et al* provides a configuration of the Whole Atmosphere Community Climate Model (WACCM) with GW source parameterizations which improves mid atmospheric circulation [9].

Satellite observation of gravity waves:

Generally, gravity wave is observed by temperature fluctuation in the middle atmosphere. Since radiation perturbation is linked to temperature variation, measurement of gravity wave also can be done by radiation perturbation in the temperature sensitive area. The global maps of temperature alteration are achieved by subtracting background noise from the dataset which is quite different for different dataset. In 2000, Tsuda *et al* used GPS beam refraction data to isolate short vertical scale temperature perturbation [10]. On the other hand, from a temperature sensitive channel of UARS (Upper Atmospheric Research satellite) Microwave Limber sounder, Wu et extracted short radiance perturbation [11]. In this process, GPS has been used to detect short vertical scale gravity waves (slow waves) and UARS MLS in long vertical wavelength detection. L.A.Holt et al investigated non-orographic gravity waves from high-resolution GEOS-5 data in the southern hemisphere [12]. Alexander et al. used AIRS radiance perturbation along with intelligent statistical technique to detect gravity waves [4]. Moreover, Satellite observation can provide information about GW locations and energy which is important for understanding importance of GW with respect to altitude, convection etc.

Some limitations of the temperature perturbation based GW parameterization was described by Alexander *et* al [4]. Two of them are averaging effect and spectrum limitation. When averaging large amplitude GW with low amplitude GW, the result signal will be diluted. Secondly, every sorts of spectrum estimation has some boundary and its band is limited. For an example, FFT is limited by the sampling frequency. Therefore, spectrum estimation can't detect spectrum at full range. For this reason, it is only possible detect gravity wave within a band of spectrum.

AIRS:

Aqua satellite started on May 4, 2002 which orbit is sun Synchronous (orbital period around 16 days). It consists of six instruments and AIRS is one of those on board six instruments. It functions along with Advanced Microwave Sounding Unit (AMSU) and the Microwave Humidity Sounder (MHS). The primary objective was to support extensive climate research and improve weather forecasting. From the name (Sounder), we can understand that it measures temperature and water vapor as functions of height. From measuring radiance, it detects clouds, ozone, carbon monoxide, carbon dioxide, methane, and sulfur dioxide, and dust particles. The Atmospheric Infrared Sounder (AIRS) is a cross-track scanning instrument which scans across the track while orbiting. It has a scan mirror which rotates around an axis along the line of flight and diverts infrared energy coming from the Earth into the photo-detector. Its' scan 'swath' is roughly 800 km from any side of the ground track which makes swath.1600 kilometers wide. While orbiting the earth, AIRS collects data and the collected data is then fragmented into pieces called "granules". Each granule is 90 samples across the track and 135 samples along the track. In distance, each granule is approximately 2250 x 1650 kilometers, and covers 6 minutes of data. The infrared energy is separated into wavelengths, sent the Aqua spacecraft, which relays it to the ground.

AIRS compares the radiances from the earth's surface and from the atmosphere's constituent wavelength. It has 2378 infrared detector and each detector senses a particular wavelength. Since, each wavelength is temperature and water vapor sensitive from surface to stratosphere, the data from each channel is used to create temperature profile. AIRS covers +/- 49.5 ground from nadir every scan cycle which repeats every 8/3 seconds. AIRS collects ninety ground footprints in each scan and there are 2378 spectral samples in each footprint which gives a ground footprint in every 22.4 milliseconds. For general channel, the spatial resolution of AIRS IR is about 13.5 km at nadir from the 705.3 kilometer orbit but it has set of visible and near infrared (Vis/NIR) channel which provides 2.3 kilometers spatial resolution. That special Vis/NIR is capable of providing a diagnostic imaging for low clouds observation. For calibration, AIRS compares space views and on-board blackbody by software (running on the ground) and develop an algorithm to provide an absolute accuracy 3% or better.

AIRS components:

A full image of the AIRS instruments is illustrated in figure (1) [13]. Its main components are:

1. A four-color imaging photometer
2. A multi-aperture spectrometer

3. Vis/NIR detector

A four-color imaging photometer uses photo-resistor, photodiode, or photomultiplier for the conversion of light into an electric current. From ultraviolet to infrared spectrum, photometer measures electromagnetic radiation by measuring the current. The IR light is received in the instrument in multiple apertures spectrometer. The elements in the multiple apertures spectrometer are passively cooled to about 155 K by a two-stage radiator assembly. In total, IR spectrometer has 11 aperture and in each optical path a gratings of 13 lines per millimeter. The light from aperture and grating are focused on the focal plane. The main reason for using gratings' diffraction property to divide the light into its' constituents wavelength. Grating disperses the light into its component wavelengths. The filters apertures, gratings order and order-separating filters on the focal plane ensure that one narrow wavelength band has been exposed to each IR detector. IR detectors are arranged in 2D of dimension 12×17. The detectors are two types- Photovoltaic (PV) and Photoconductive (PC). It may seem surprising to see PC in AIRS structure and the reason was some technical limitation. The time Aqua satellite was launched, longest AIRS wavelength sensitive PV detectors were not designed. Therefore, for measuring long wavelength, they keep two out of the twelve detectors modules as PC.

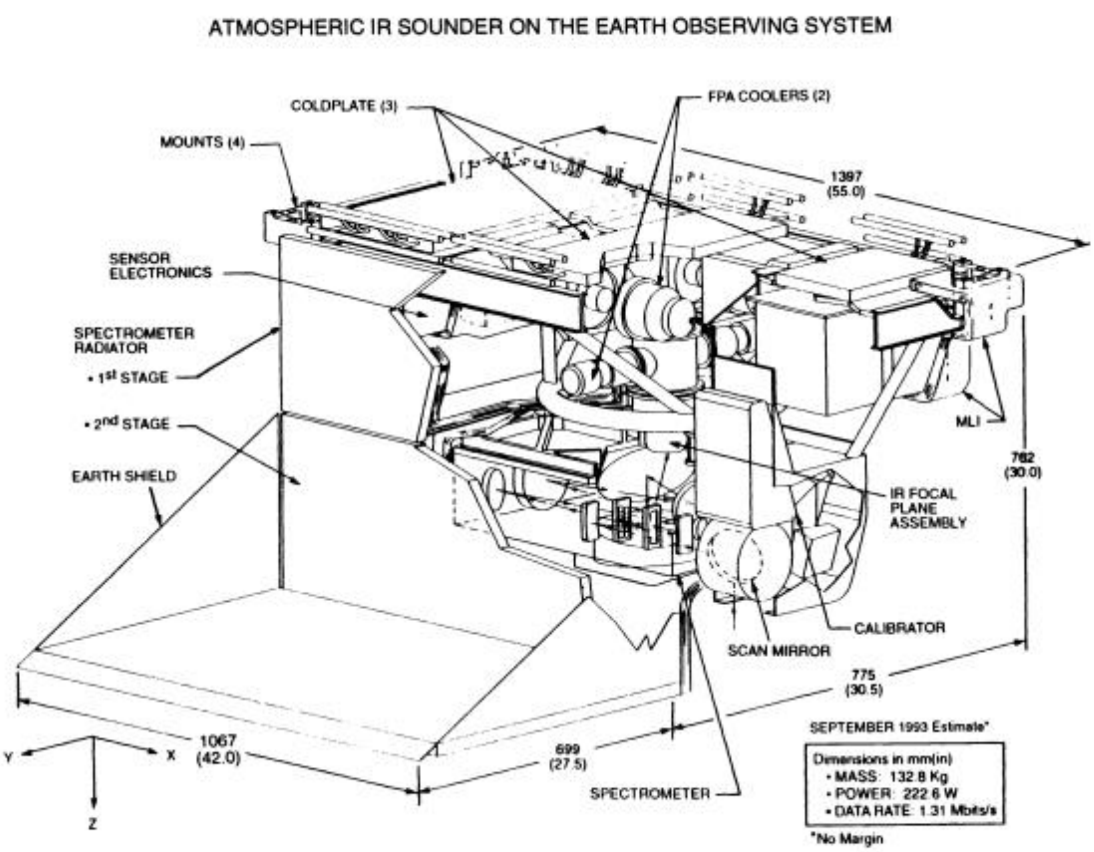

Figure 1: Components of AIRS

2D-FFT:

2D-FFT is an efficient spatial frequency estimation tool. Like fft, it take 8 point DFT of every array given as a input. It first take the fft of all the cross track row in the horizontal direction and then take the fft in the vertical direction. In case of spatial wave, it outputs wave number in the range from –fs/2 to fs/2. For an example, from 2D-FFT of the signal [Cos(-(2*pi)/0.01)X-((-(2*pi)/0.05)Y), we will get, wave number 100 in the X direction and 20 in the Y direction (figure-8).

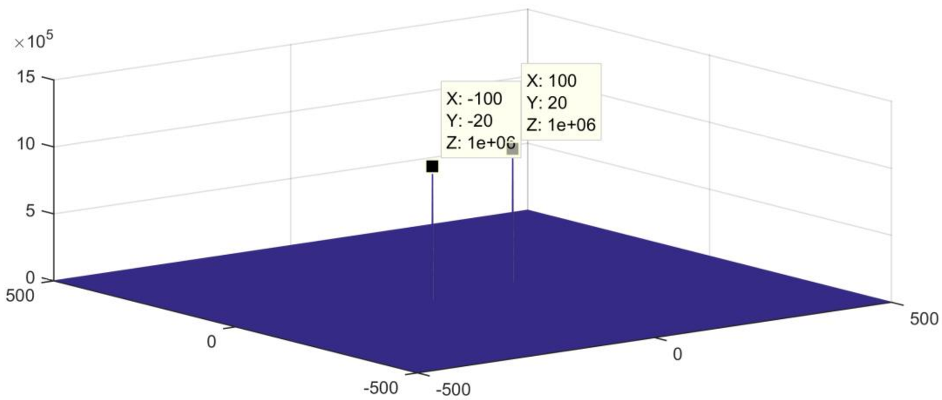

Figure 02: FFT of a sinusoidal signal

My Work:

In my work, I have tried to calculate the gravity waves horizontal wavelength from AIRS radiance data. The method was 2D-FFT based. The methodology can be summarized in a flow chart below (Figure-03):

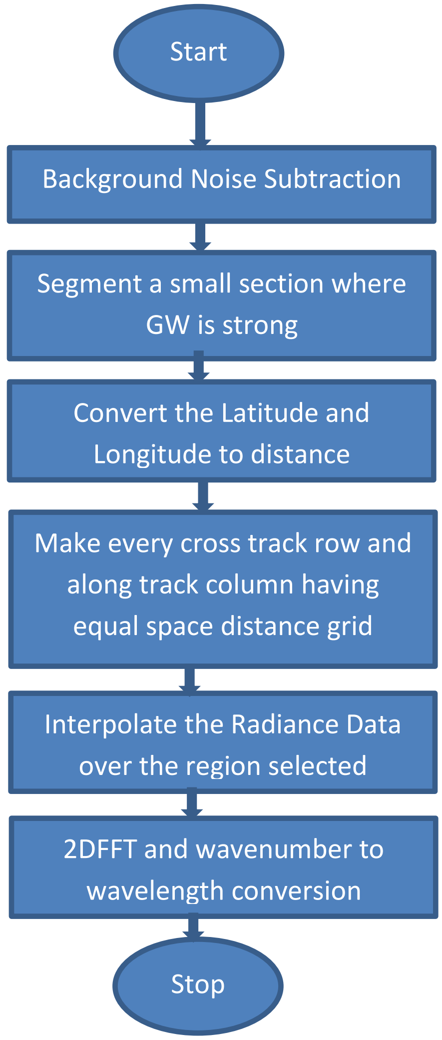

Figure 03: Methodology of 2D-FFT based GW horizontal wavelength calculation

Data Choosing:

For this analysis, I have chosen the region of Alaska. My aim was to explore other regions with this method. But, most of my time was spent in adjusting the script in MATLAB; therefore I did not get time to explore other regions. Figure (04) is showing the AIRS channel 75th radiance data over Alaska on December 24th, 2018 in mid-day (12.00). The altitude was taken as 35 kilometers because, Alexander et al. mentioned that gravity wave is strong in the stratosphere [4]. Winter time in Alaska was preferred because large amplitude events occur during that time. AIRS covers almost all the infrared range [14]. But, channel 75th collects data in the CO_2 emission band and gravity wave temperature variance is apparent in this channel. Therefore, from 1-130th channel, I have selected channel 75th data for analysis. The data was a granule of size 90×135 which is shown in figure (05) where 90 samples were taken in the cross track direction and 135 samples were taken along track direction. Each data point is a radiance data in a single geographic coordinate (Latitude and Longitude). From Figure (05), it is hardly possible to detect gravity wave since there is no signature of the waves in the image that FFT can detect. Therefore, in the first step, we have to filter the background noise from the data and the resultant image will be used in 2D-FFT based gravity wave detection.

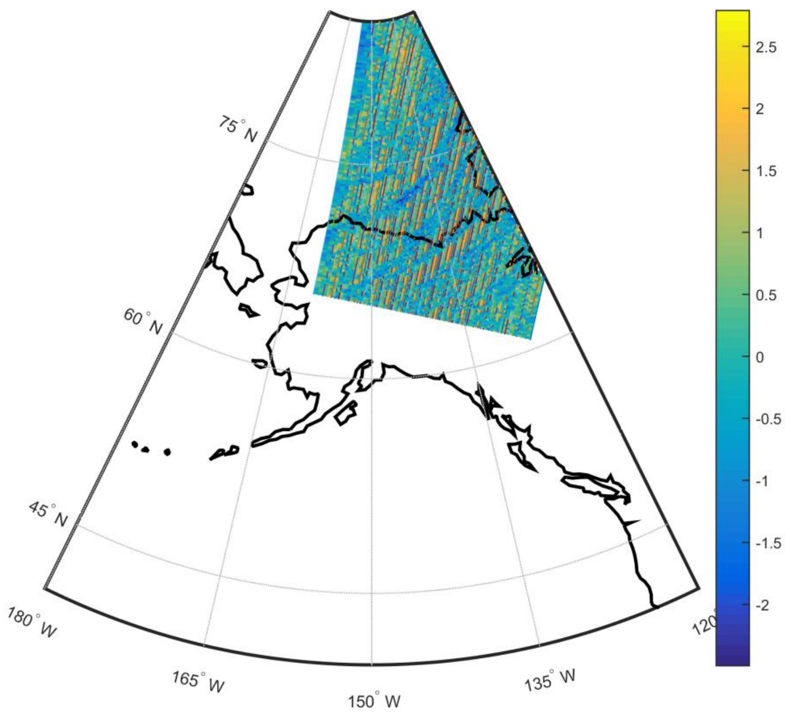

Figure 04: AIRS channel 75th radiance data over Alaska on December 24th, 2018 in mid-day

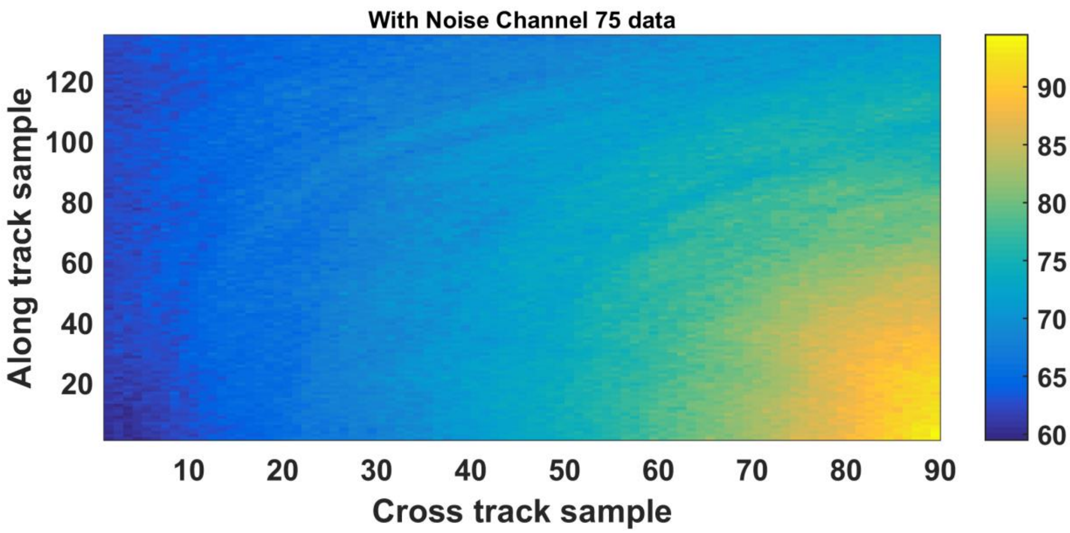

Figure 05: Radiance data in a granule

Filtering:

For filtering purpose, Alexander et al in their paper suggested fourth order polynomial fitting [4]. Fourth order polynomial fitting was done in the cross track direction (along every row of the granule) data by MATLAB. In order to show the polynomial fitting effect, figure(5) is illustrated here. The top image of figure (06) is showing the raw data and polynomial fitted data of the 135th cross track AIRS L1B data over Alaska (coordinate [60N 87N -77W -160W]). Since, 4th order polynomial fitted data will be a curve of 4th order, when raw data is subtracted from that polynomial fitted data, the fluctuation above and the below the curve will appear as a wave (bottom image of figure-06). The resultant data will be used for analysis in the next section. Finally figure (07) is showing the filtered radiance data of the whole granule of figure 05 and it is nicely showing gravity waves across the diagonal of the image.

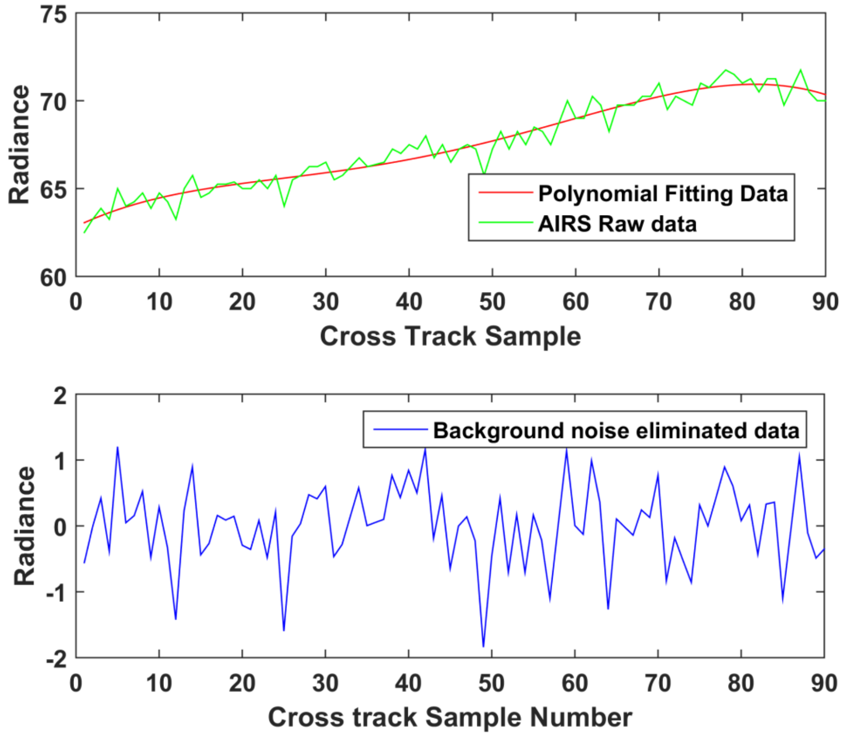

Figure 06: Filtering of AIRS data by 4th order polynomial fitting.

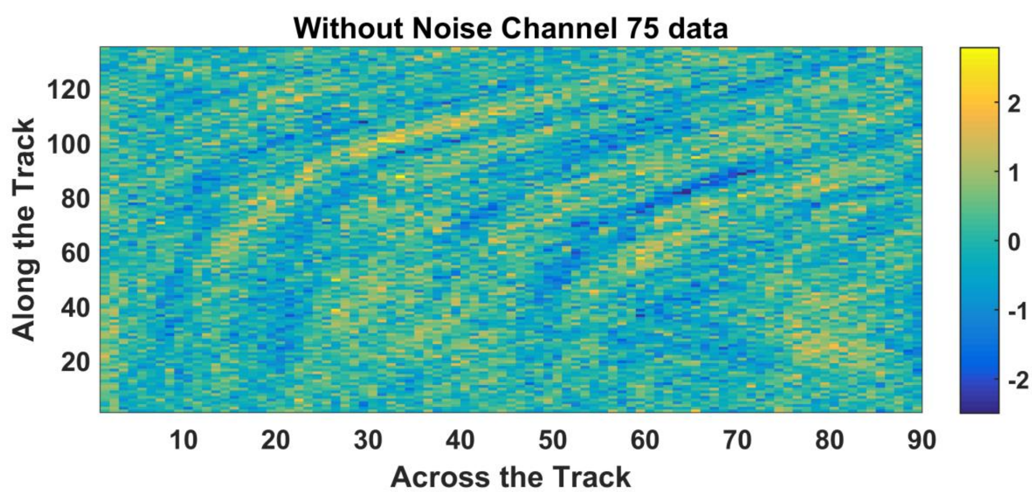

Figure 07: Filtered of AIRS radiance data of the same granule of figure (04)

Interpolation:

The data obtained from AIRS are not linearly spaced but for applying 2D-FFT in the data, we need linearly spaced data. Therefore, interpolation method is used to create linearly spaced radiance data from original non-linear radiance data. In my work, I preferred "spline" interpolation method over linear interpolation since it can follow fluctuation much better than linear interpolation. Figure (08) is showing the comparison of the raw data and interpolated data by spline for a single cross track row. Although, there is enough difference between these two, the interpolated data can follow the wave. When seeing carefully, I have found that, the fluctuation pattern is same for the interpolated data as the raw radiance data with some phase difference (peak comes a litter later). Since, I did not need to measure when certain frequency occurs, it was okay to use spline interpolation method. Before interpolation, part of the radiance data of equal latitude and longitude difference (where gravity wave signature is significant) were selected manually although Li *et al* detected those region automatically in their work [5]. The Latitude difference was 3 degree in the all cross track row and Longitude difference was 15 degree. Then, those coordinates were converted to equally spaced physical distance by measuring the distance between the coordinates using Matlab function (later tested with equation 1 for coordinate to distance transformation [15]) and linear spacing.

$$d = \mathrm{acos}(\sin \phi_1 \sin \phi_2 + \cos \phi_1 \cos \phi_2 \cos \Delta\lambda) \times R \tag{1}$$

where φ_1, φ_2 are the latitude of the two points, $\Delta\lambda$ is the longitude difference between those two points, R is the radius of the earth.

In the next phase, every cross track radiance data were interpolated for new distance grid using MATLAB function spline. Figure (09) is showing the comparison of the interpolated data with the original non-interpolated of data sample size 35×35 (demonstration are done here by the sample points because of realization of interpolation effectiveness). Figure (09) shows that the signature of the gravity wave is still visible with the interpolated data. This was the most challenging task in this project. Now, the data is now ready for 2D-FFT implementation.

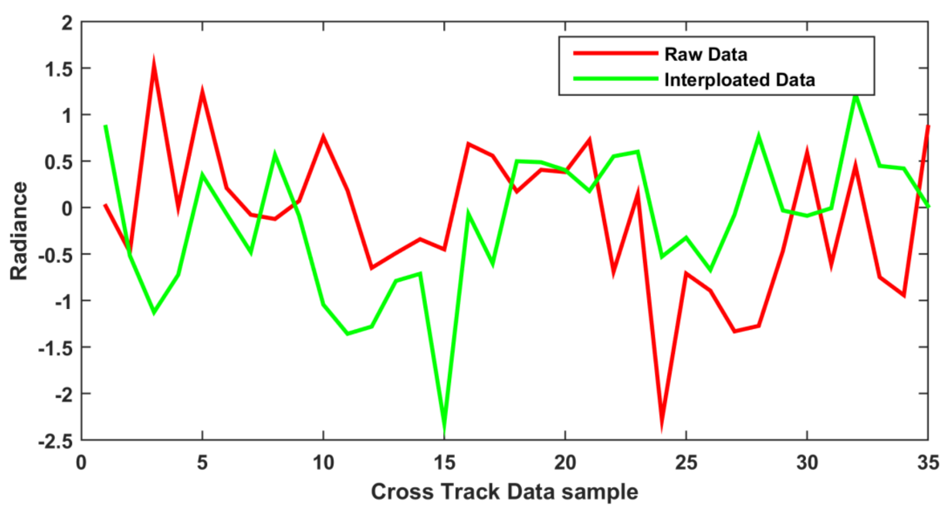

Figure 08: comparison of the raw data and interpolated data of single cross track row

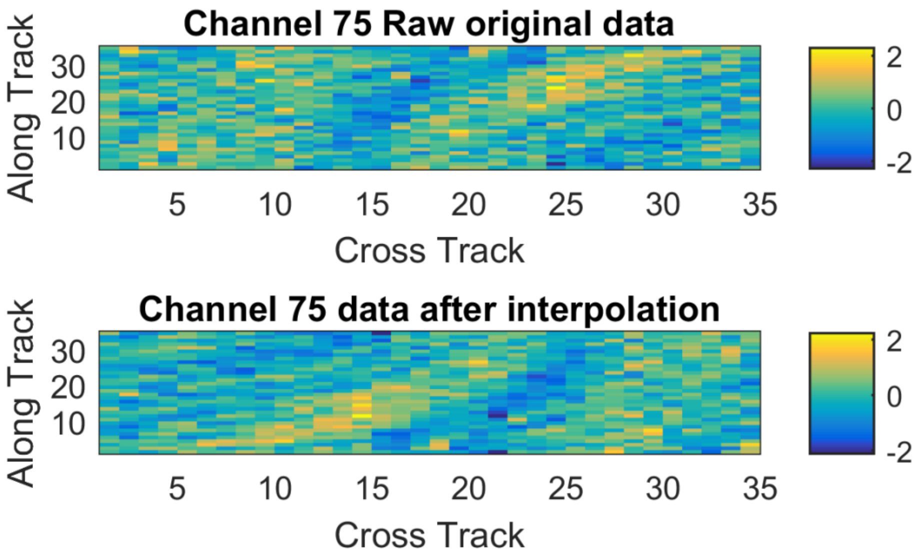

Figure 09: comparison of the raw data and interpolated data

2D-FFT:

Equally spaced data from previous steps were transformed to spatial frequency using 2D-FFT. I have used MATLAB built in function to do the task and then spectrum was centered. 2D-FFT provides the output in wavenumber (spatial frequency) in the window –fs/2 to fs/2 where fs is the spatial sampling frequency. The distance between two adjacent samples across the track was 43 kilometers in the interpolated data which gives wavenumber in the range +/- 2.3×10^{-5}/m across the track. Similarly, along the track, the wave within the wavenumber +/- 1.6×10^{-5}/m can be measured. Figure (10) is showing the result of the 2D-fft spectrum of the interpolated data. From this figure, horizontal wavelength can be calculated. Wavenumbers across the track and along the track were 2.698×10^{-6} and 9.444×10^{-7} respectively which gives wavelength of 370 kilometers and 1059 kilometers approximately. By using equation (2), horizontal wavelength is calculated as 1121 kilometers which is very long and expected due to limitations of my work

$$\lambda = \sqrt{(\lambda_{crosstrack})^2 + (\lambda_{alongtrack})^2} \tag{2}$$

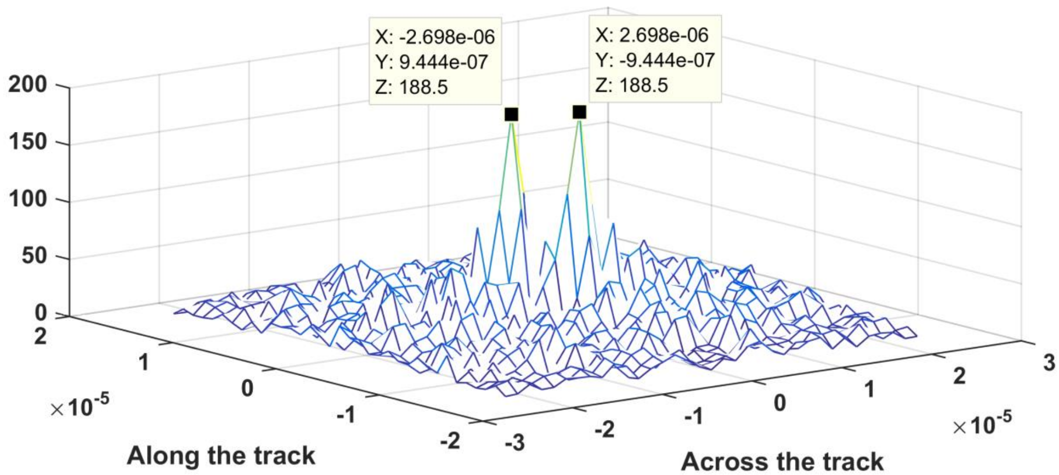

Figure 10: 2D-FFT spectrum of the radiance data

Result and Discussion:

For 2D-fft based gravity wave parameterization, interpolation is an important step and it is mandatory. Traditional method has some limitations. Therefore an intelligent combination of traditional methods may provide more accurate result. Since, spectral resolution is constrained by the data sample used in fft analysis, it needs to be analyzed how to create more data (intensive interpolation) keeping the signature of the wave unchanged. FFT has some limitation and therefore, before applying fft based method, a band pass filter of desired bandwidth should be implemented to filter out of band signal. As a part of my future work, I will try to look into how to design filter to obtain frequency response in a narrow band efficiently. Moreover, I will try to design algorithm to efficiently detect gravity wave signature in the image.

Conclusion:

2D-fft based method can detect very long wavelength gravity wave. Better method of interpolation may improve the result. For better measurement, spectral resolution needs to be improved and a band pass filter needs to be implemented to the interpolated data before doing fourier transform.

Acknowledgement:

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Reference:

[1] http://www.physics.uwo.ca/~whocking/p103/grav_wav.html

[2] Richter, Jadwiga H., Fabrizio Sassi, and Rolando R. Garcia. "Toward a physically based gravity wave source parameterization in a general circulation model." *Journal of the Atmospheric Sciences* 67.1 (2010): 136-156.

[3] Wu and J. W. Waters, 1996a: Gravity-wave-scale temperature fluctuations seen by the UARS MLS. *Geophys. Res. Lett.,* **23,** 3289–3292.

[4] Alexander, M. Joan, and Christopher Barnet. "Using satellite observations to constrain parameterizations of gravity wave effects for global models." *Journal of the atmospheric sciences* 64.5 (2007): 1652-1665.

[5] Lai, Chang, et al. "Automatic Extraction of Gravity Waves from All-Sky Airglow Image Based on Machine Learning." *Remote Sensing* 11.13 (2019): 1516.

[6] Fritts, D.C. Gravity wave saturation in the middle atmosphere: A review of theory and observation. *Rev. Geophys.1984*,*22*,275–308.

[7] Fritts, D.C.; Alexander, M.J. Gravity wave dynamics and effects in the middle atmosphere. *Rev. Geophys.* 2003, 41,1003.

[8] 5. Hoffmann, L.; Xue, X.; Alexander, M.J. A global view of stratospheric gravity wavehostspots located with Atmospheric Infrared Sounder observations. *J. Geophys. Res. Atmos.* 2013, *118*, 416–434.

[9] Richter, Jadwiga H., Fabrizio Sassi, and Rolando R. Garcia. "Toward a physically based gravity wave source parameterization in a general circulation model." *Journal of the Atmospheric Sciences* 67.1 (2010): 136-156.

[10] Tsuda, T., M. Nishida, C. Rocken, and R. Ware, 2000: A global morphology of gravity wave activity in the stratosphere revealed by the GPS occultation data (GPS/MET). *J. Geophys.Res.*, **105** (D6), 7257–7274.

[11] Wu, D. L., and J. W. Waters. "Gravity-wave-scale temperature fluctuations seen by the UARS MLS." *Geophysical research letters* 23.23 (1996): 3289-3292.

[12] Holt, L. A., et al. "An evaluation of gravity waves and gravity wave sources in the Southern Hemisphere in a 7 km global climate simulation." *Quarterly Journal of the Royal Meteorological Society* 143.707 (2017): 2481-2495.

[13] Hartmut H. Aumann and Christopher R. Miller "Atmospheric infrared sounder (AIRS) on the earth observing system", Proc. SPIE 2583, Advanced and Next-Generation Satellites, (15 December 1995).

[14] Crevoisier, Cyril, Alain Chedin, and Noelle A. Scott. "AIRS channel selection for CO2 and other trace-gas retrievals." *Quarterly Journal of the Royal Meteorological Society: A journal of the atmospheric sciences, applied meteorology and physical oceanography* 129.593 (2003): 2719-2740.

[15] https://www.movable-type.co.uk/scripts/latlong.html