Cross-correlation coefficients of gravity waves measured by airglow imagers in Antarctica

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Abstract

Airglow images were processed to find the characteristics of momentum dispersion of gravity waves.

1. Introduction

Acoustic gravity waves (AGW) are perturbations in the atmosphere at 80-100km. They can be seen as waves propagating in the chemiluminescent atmosphere (the airglow) at that height. These intensity perturbations are related to the relative atmospheric density perturbations, and thus to the wave amplitude [*Swenson*, *Haque*, *Yang*, *Gardner*, 1999]. From the wave amplitude, the momentum dispersion can be calculated. AGW's are so called since their wavelength and time period are long enough to enable gravity to affect their propagation. In some cases their wavelength is long enough so that gravity, rather than compression, is the dominant restoring force.

It has been shown [*Fritts* and *VanZant* 1993; *Hamilton*, 1996; *McLandress* 1998] that the vertical transport of gravity waves has a significant effect on the movement of the middle atmosphere. This effect is characterised and measured by the vertical flux of horizontal momentum [*Lindzen*, 1981; *Waltersheid*, 1981; *Weinstock*, 1983; *Fritts* and *van Zandt*, 1993]. An analogous 2-D situation is the vertical movement of a particle in the propagation of a transverse wave. It has been shown [*Swenson* and *Lui*, 1998] that the momentum fluxes which are associated with monochromatic gravity waves can be estimated using airglow imagers. The vertical flux of horizontal momentum is measured at about 90km (depending on the filter, eg O2 ~ 94km and OH ~ 87km). A qualative description of the vertical flux of horizontal momentum is given in section 2.

Gravity waves could have more than one source, particularly in the polar regions. Firstly, their origin could be in the movement of air upwards as it approaches a mountainous region. This block of air would act as a driver of an acoustic wave, whose horizontal amplitude would increase as the density of the atmosphere decreased (due to conservation of momentum) until its motion could not be distinguished from the normal motion of the atmosphere (at about 110km). This particular source can be demonstrated, at least partly, by measuring an increase in the momentum of gravity waves along with an increase in the ground wind speed over nearby mountainous regions. The second source of gravity waves could be due to heavy auroral activity. Rather than being a driver of a wave of continuously increasing amplitude, the aurora would displace atmosphere at the maximum extent of the amplitude of the gravity wave, and this would propagate downwards, decreasing its amplitude with the increasing density of the atmosphere. If the vertical flux of horizontal momentum increases significantly on or just after large aurora, it would not conclusively show a direct correlation between momentum flux and the aurora. The results would need to be analysed alongside wind data throughout the atmosphere. A comparison with the momentum flux on aurora free days would be needed as well. The data would have to be analysed knowing that on average fewer than 20% of AGW's propagate downwards [*Lintleman* and *Gardner*, 1994; *Gavrilov et al*, 1996; *Yang*, 1998]. However, this figure could be position dependent. There would also need to be a physical mechanism for driving such large oscillations in the 80-90km region. The third possible driving mechanism is the polar vortex. The variations on the edge of the vortex could act as sources for AGW's. If the propagation of a gravity wave could be extrapolated back to a particular perturbation, it would have to be shown that that was the only possible source for that particular wave. Due to the influence of the other two sources this would be complicated to demonstrate conclusively.

2. Theory of vertical flux of horizontal momentum

(Summary of section 2 of [*Gardner et al*, 1999][1])

The vertical flux of horizontal momentum is a vector quantity which is defined as the expectation value of the product of the vertical wind w with the orthogonal components of the horizontal wind, u and v. The momentum flux is a measure of the correlation between the vertical and horizontal wind perturbations. For example, if the eastward (northward) momentum flux equals the westward (southward) momentum flux the zonal (meridional) momentum flux will be zero. There are two components of velocity, the in-phase and the quadrature, directed respectively along the azimuth of propagation and normally to propagation. Low frequency waves are nearly circularly polarized and high frequency waves are nearly linearly polarized. The relationship between the two polarizations can be used to express the complex vertical wind velocity in terms of the complex in-phase horizontal velocity [*Hines* 1960, 1964]. The complex zonal and meridional wind components are calculated by projecting the two components of the velocity onto the appropriate coordinate axes. The total w, u and v perturbations are calculated by integrating over all frequencies and azimuths. It is assumed that the wind perturbations are temporally stationary, and that since waves propagating at different azimuths would probably have different sources, it is also assumed that the perturbations arising from waves with different propagation directions are statistically independent. These assumptions enable the real components of the zonal and meridional momentum fluxes to be written in terms of the spectrum of the in-phase wind component. These new results are simplified if it is assumed that the horizontal wind spectrum is separable. Then the canonical power law spectrum model is applied to the total horizontal wind component. This new result includes a spectral index, p, which if independent of azimuth and therefore constant, means the model is separable (which was a necessary assumption for simplification). Airglow imagers have a poor response to low frequency waves, so the limits of integration begin at a low frequency cut off. The upper limit, obviously, is the Nyquist frequency. These high frequency waves are highly polarized, meaning the contributions of their quadrature components are small. This means the cross correlation coefficients can be expressed strictly in terms of the expectation value of the square of the in-phase velocity component.

These coefficients reach their extreme values when all the waves are propagating in the same direction. The absolute values of the momentum flux are sensitive to the spectral index, p, since the rms vertical and horizontal winds are sensitive to p. However, the correlation coefficients are not sensitive to p. The value of the vertical flux of horizontal momentum depends on the azimuthal distribution of energy propagation. To calculate the correlation coefficients image observations of the relative intensities of the airglow are needed. These intensities are proportional to the expectation value of the square of the in-phase velocity component, and have been shown to be proportional to the azimuthal distribution of relative intensity variance [*Swenson* and *Gardner*, 1998]. Waves with periods larger than 2 hrs will not be included due to the way in which the data is processed. However, depending on the value of the spectral index, more than 80% of AGW's have periods less than 2 hrs, so airglow images lead to quite accurate measurements of the total vertical flux of horizontal momentum.

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[1] *Gardner et al*, Measuring gravity wave momentum fluxes with airglow imagers, *Journal of Geophysical Research*, Vol. 104, NO. D10, Pages 11,903 – 11,915, May 27th, 1999

3. Summary of Method (See Appendix 4 for more detailed explanation of programs used and tutorial on running them)

A camera head was connected to a CCD. The all-sky images were taken using a fish eye lens. Four different filters were used OH, Na, O2 and a background filter. The exposure times were 2 minutes for OH, and 6 minutes for the others. The times are catalogued in *times.dat*. The programs were checked using results from Utah (see appendix 2), and they were in agreement to the third decimal place.

Before the images were processed, they were viewed so that the images which were saturated (eg. those which included the dawn and the moon) were omitted. Then to enable the processing of periods of one or three hours, the exact times the images were taken were noted from *times.dat* (see appendix 1).

The original 512 by 512 tiff images were rotated 37° clockwise, cropped around a zenith pixel, and reduced to 385 by 385. The images were then flipped to interchange east and west, to make them appear the same as a compass.

Firstly, the raw image average was found for a set of data. Each image was then flat-fielded and interpolated. The stars were removed and the image detrended. A Hanning apodization function was then used to filter the images. The data was then pre-whitened temporally and spatially. The three-dimensional FFT was taken of both the positive and negative spatial frequencies. From the 3-D FFT the unambiguous 2-D spectrum was derived. The unambiguous spectrum is required due to the 180° ambiguity in the direction of the wave at any time t. Then the zonal and meridional correlation coefficients were calculated from the unambiguous spectrum using the method qualitatively described in section 2. The angular spectrum of the airglow variance was then obtained by integrating the unambiguous spectrum. The lower limit was defined as the inverse of the size of the sky as seen by the camera (the field of view [FOV]) and the upper limit was defined as the inverse of the smallest observable wavelength. Finally, from this angular spectrum the mean cross-correlation coefficient versus the angle with respect to north was computed.

4. Results and Discussion

These are all in *graphs* in *airglow_scripts*. Figure 1 shows days with very heavy auroral contamination. There is also a possible diurnal periodicity. Figure 2 is also a heavy auroral night. This possible diurnal periodicity is shown again on June 06-07. Compare these results with figure 3 and figure 4, which are clear nights with very slight auroral contamination. These do not have the same auroral influence and do not show the same possible periodicity. However, no conclusions can be drawn without a comparison with wind data for those nights. Figure's 5 and 6 are a comparison between filtered and unfiltered data. The filtering was done by subtracting the background images. The filtering seems generally only to affect the data within the error bars. There is no obvious diurnal periodicity in these results. Figure 7 plots the difference between the filtered and unfiltered results, a negative value means the filtered result was larger than the unfiltered one.

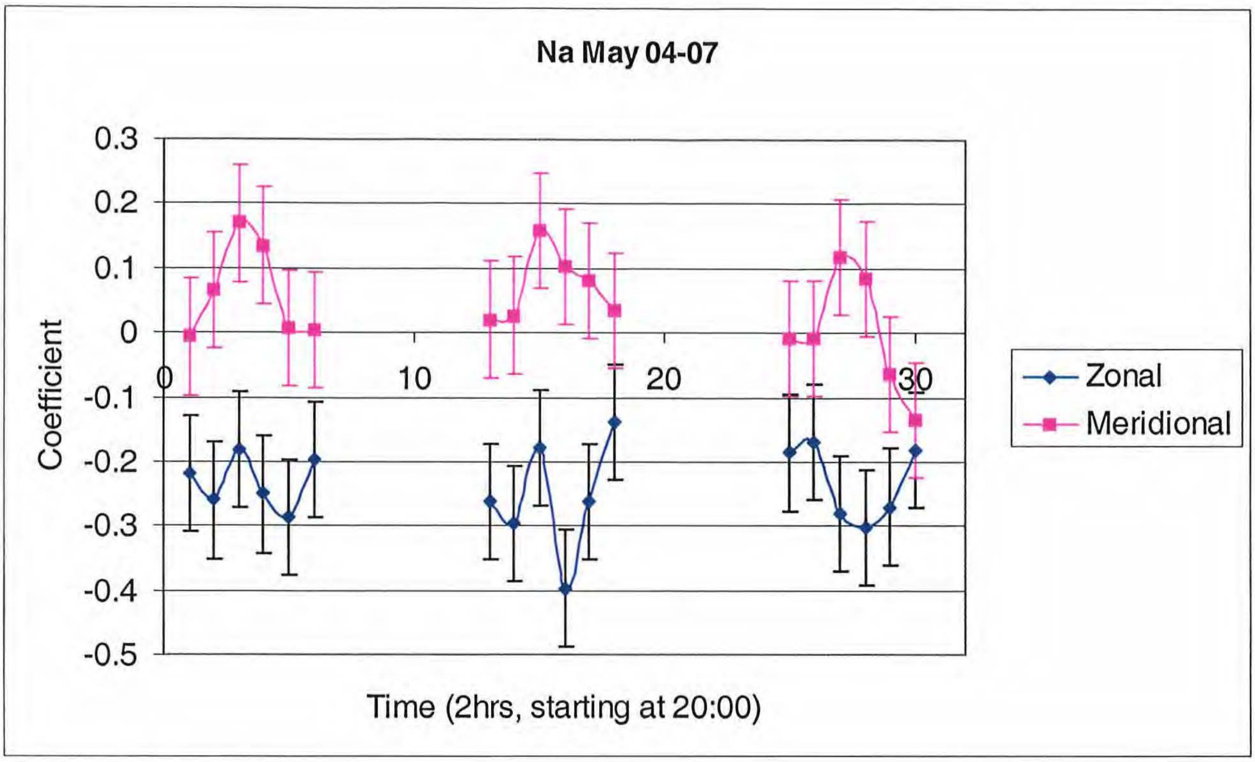


Figure 1

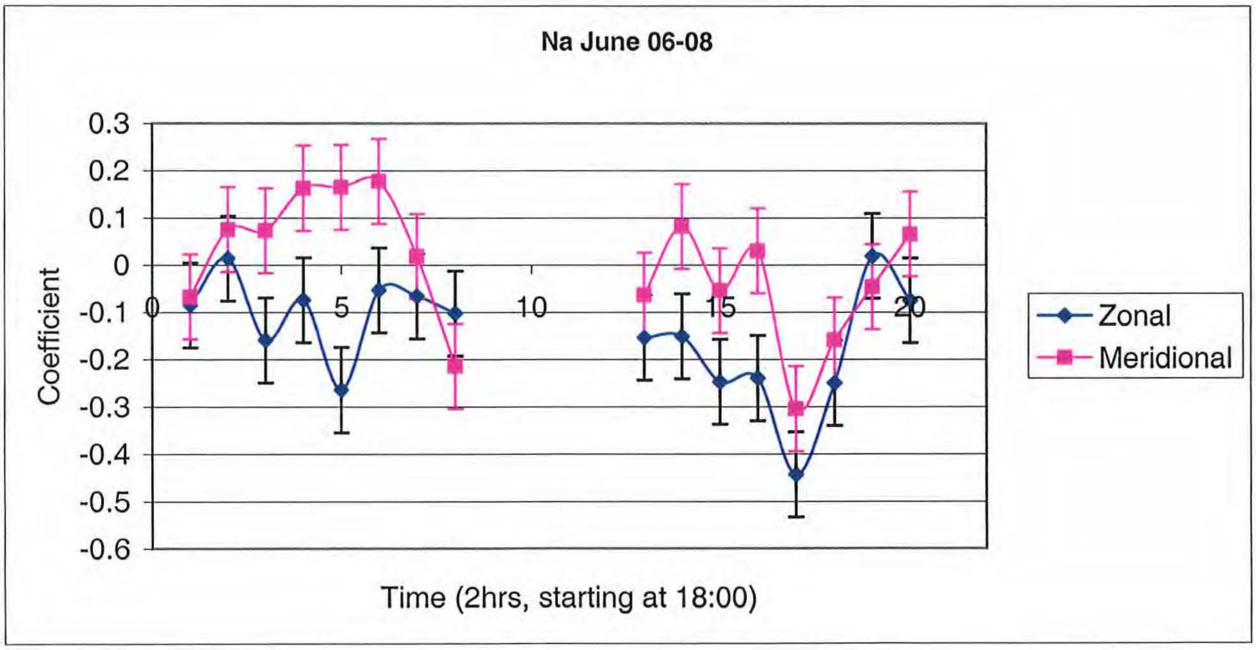


Figure 2

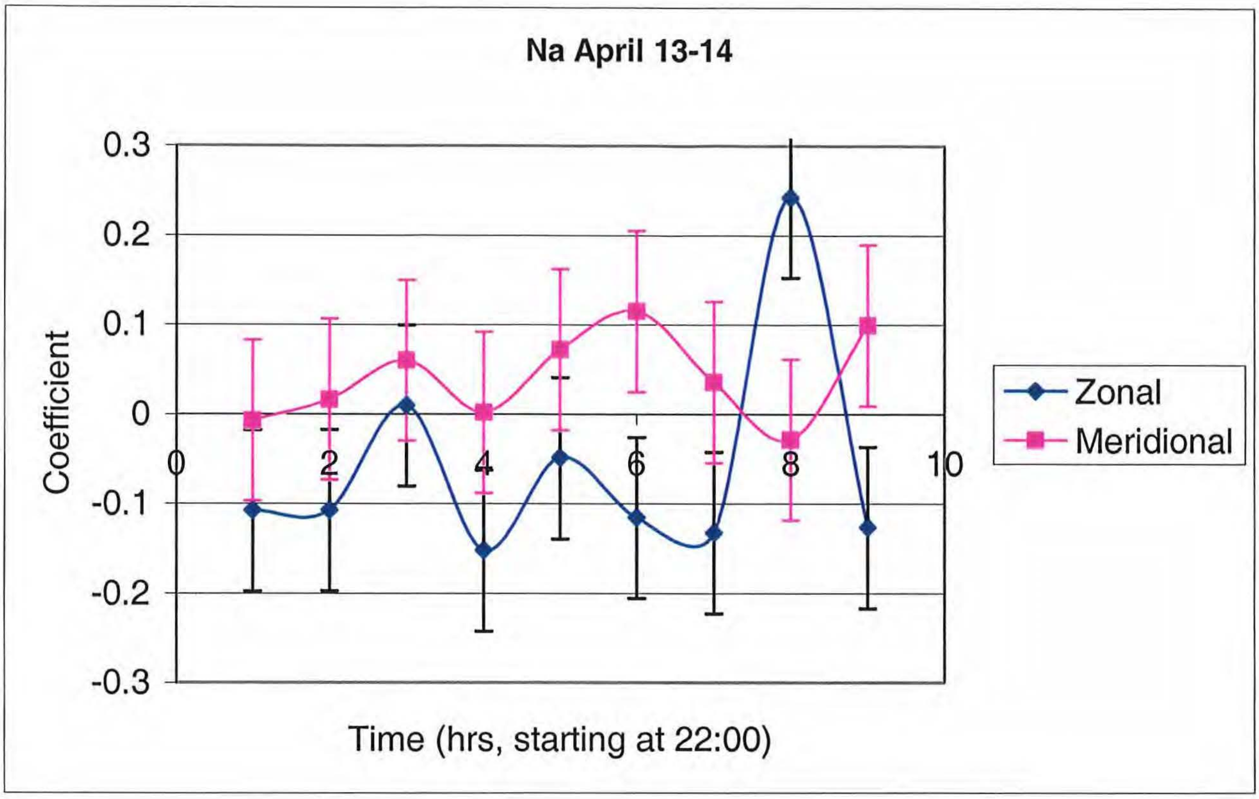


Figure 3

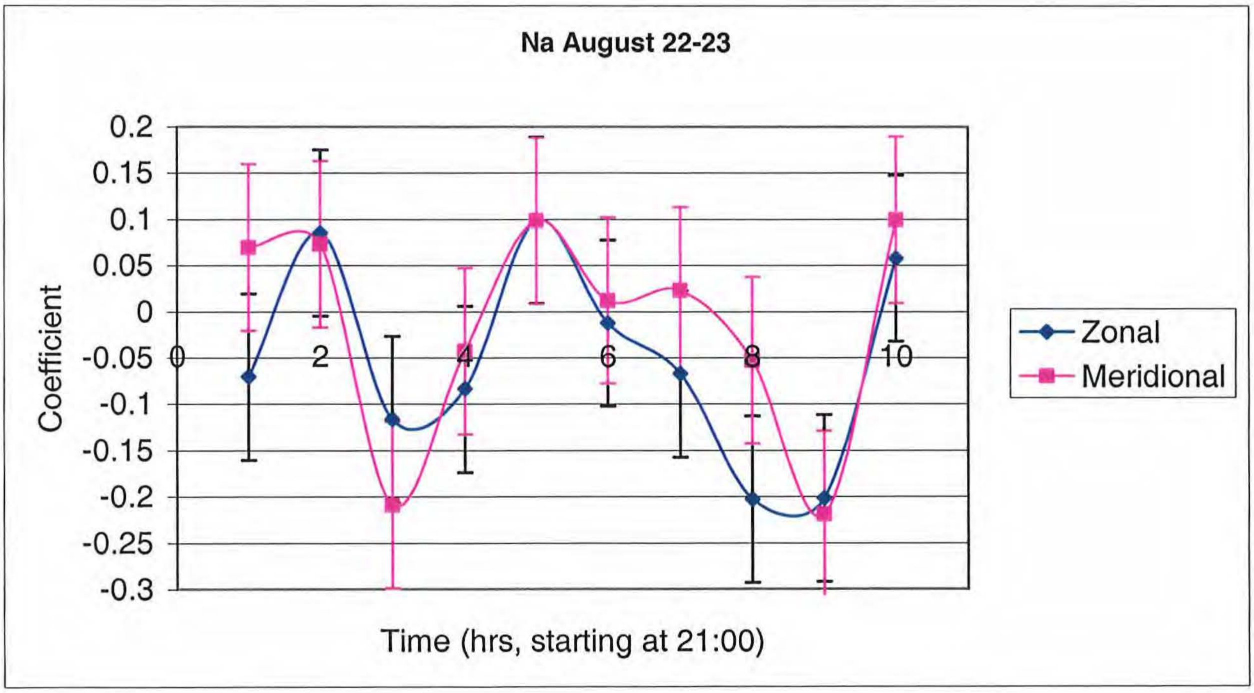


Figure 4

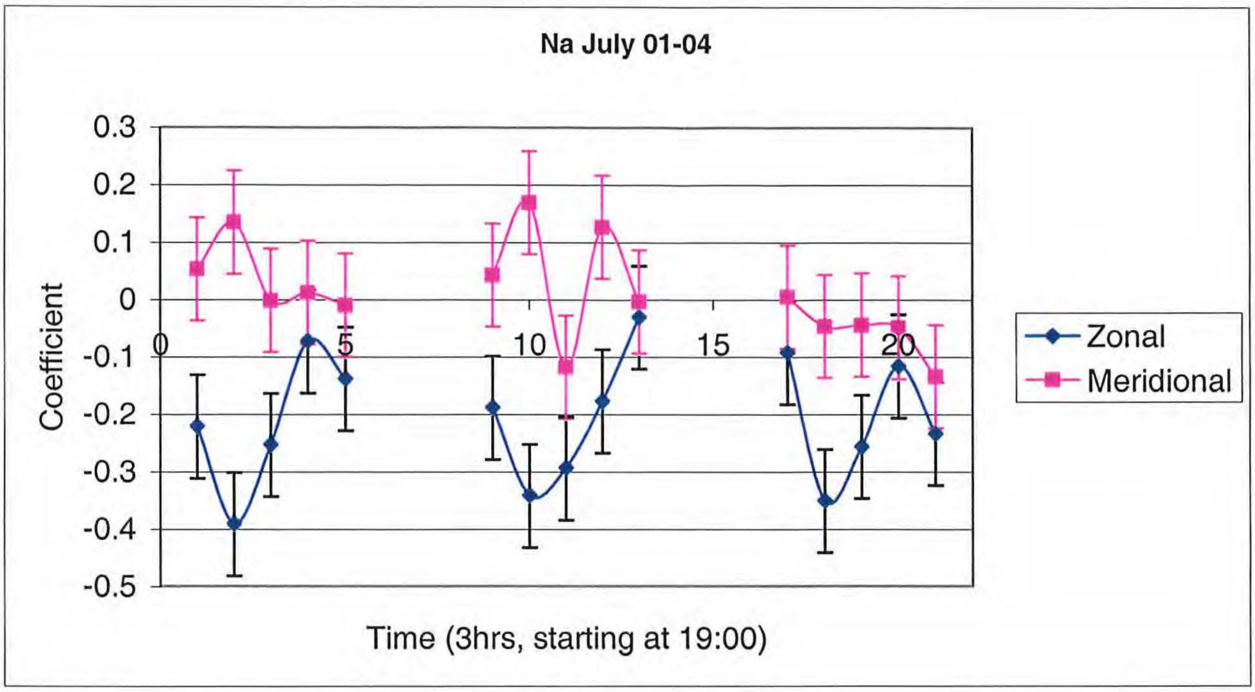


Figure 5

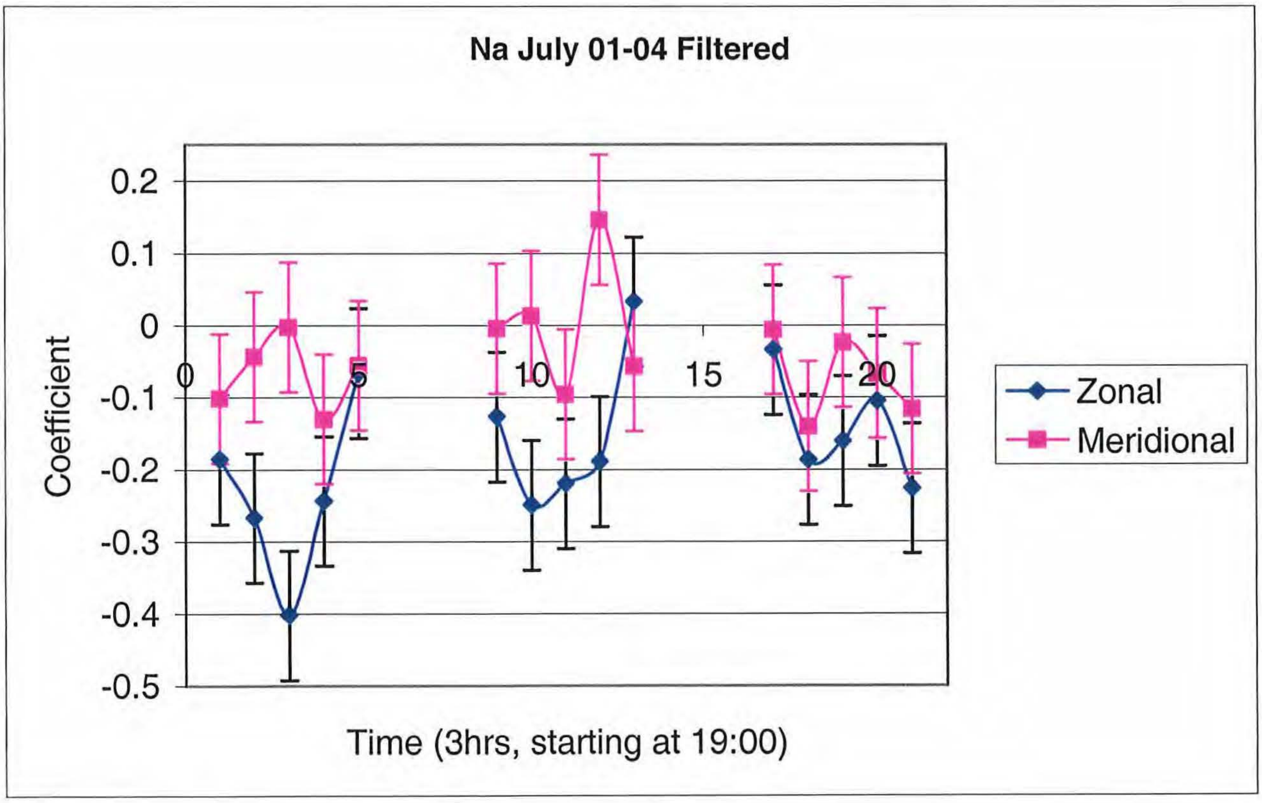
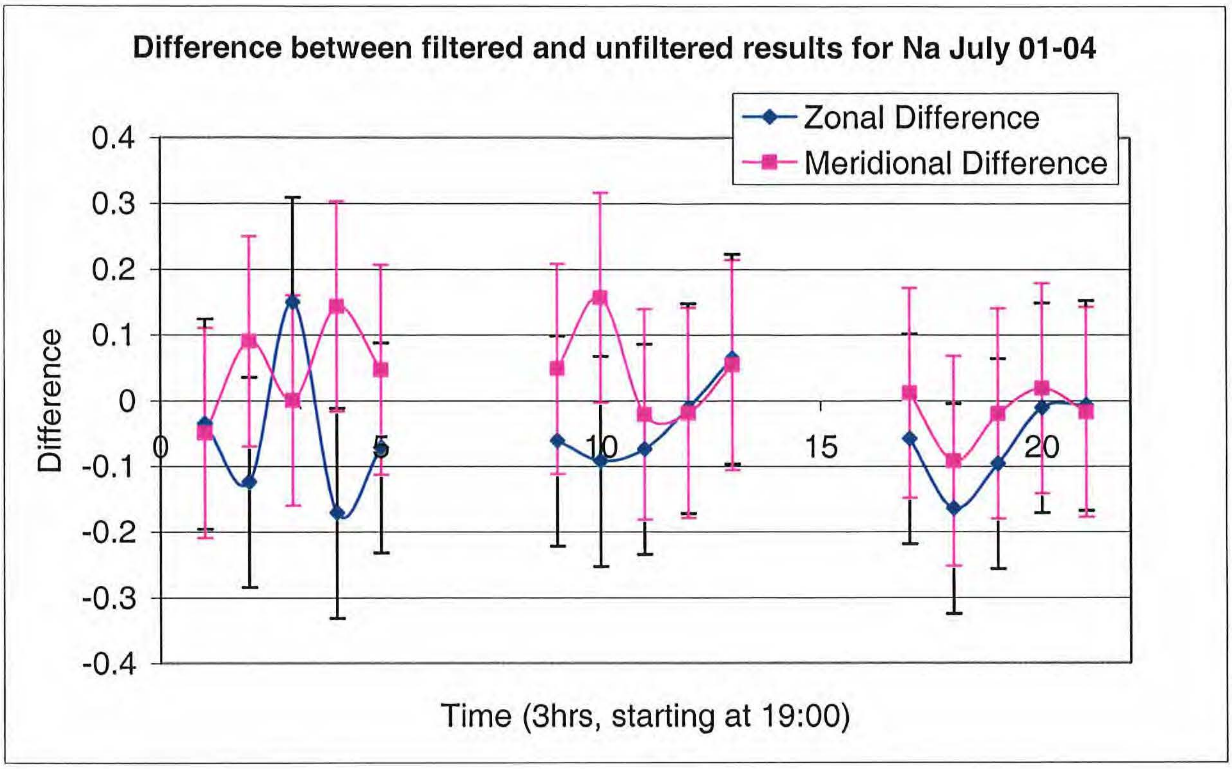


Figure 6



Difference between filtered and unfiltered results for Na July 01-04
Zonal Difference
Meridional Difference
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
Difference
0
5
10
15
20
Time (3hrs, starting at 19:00)

Figure 7

5. Conclusion

The programs from Utah are working, with only the *settings.m* program needing changing for each run. The apparent influence of the aurora for May 04-07 is neither conclusive nor inconclusive without comparison with wind data. June 06-07 is also an aurorally contaminated night, and should be compared with wind data in the same way as May 04-07. Subtracting the background images from the data has only a small influence on the correlation coefficients.

References

1. Gardner, C.S., M. Coble, G.C. Papen and Swenson, G, "Observations of the unambiguous 2-dimensional horizontal wave number spectrum of OH intensity perturbations", *Geophys. Res. Lett.*, Vol. **23**, No 25, 3739-3742, 1996.
2. Gardner et al, "Measuring gravity wave momentum fluxes with airglow imagers", *Journal of Geophysical Research*, Vol. **104**, No. D10, Pages 11,903 – 11,915, May 27th, 1999
3. Garcia, F.J., M. Taylor and M.C. Kelley, "Two-dimensional spectral analysis of mesospheric airglow image data", *Applied Optics*, Vol. **36**, No 29, 1997.
4. Haque, R. and G. Swenson, "Extraction of motion parameters of gravity-structures from all-sky OH image sequences", *Applied Optics*, Vol. **38**, No 21, 1999.
5. Swenson, G., M. J. Alexander and R. Haque, "Dispersion Imposed Limits on Atmospheric Gravity Waves in the Mesosphere: Observations from OH Airglow." *Geophys. Res. Lett.*, Vol **27**, No 6, 875-878, 2000
5. Swenson, G., R Haque, W. Yang and C. S. Gardner, "Momentum and energy fluxes of monochromatic gravity waves observed by an OH imager at Starfire Optical Range, New Mexico", *J. Geophys. Res.*, Vol. **104**, No D6, 6067-6080,

Appendix 1

List of files, programs and directories

Directory: *airglow_scripts*

This directory contains all the programs which process the images and output the correlation coefficients. These are all fully described in appendix 4.

times.dat: has all the exact times when the all-sky images were taken.

zenith.m: given an input zenith pixel, this program finds the size of the maximum square around the input coordinate, and crops the image to this size

bgtest.m: this program subtracts a series of images from another series, (to enable the background images to be subtracted). It subtracts them after they have been through *process.m* (ie all the stars are gone). The variable 'pint' in *process.m* has to be changed to 'pin' for the background images to enable bgtest.m to work. The images are outputtedas .mat files 'filtNa_#_int', where # denotes the four figure file number.

robzen.txt: this has the IDL script which Rob Hibbins wrote to find the zenith pixel in the all sky images. The star Alpha Phi should be omitted when the script is run. The output of the program gives the coordinates of the pixel measured with the origin at the bottom left corner of the image. Owen Jones used the same method to find zenith pixel for an image taken about six months later, and found the value for zenith pixel to be (259, 266 – where the origin is taken as the top left corner of the image). This showed no significant change in the zenith pixel value, and so it was assumed that the value for zenith pixel was constant throughout the year. The program *zenith.pro* is the IDL script, which is ready for running.

Directory: *output*

*bkg** : these contain the files which have had the background subtracted using *bgtest.m*. They also contain the meridional and zonal correlation coefficients calculated over three hour periods.

jul, jun*, may** : contain all the files with zenith pixel, with the origin at the top left corner, at (265, 244). This is the incorrect placing, as the zenith pixel should be at (265, 244) with the origin at the bottom left corner. These results are also rotated wrongly: 30° counter clockwise instead of 37° clockwise, which puts north at the top of the image.

*rjul** : these are results which are rotated correctly, but which still have the zenith pixel in the wrong quadrant.

*r2jul** : these results are rotated correctly and have the zenith pixel in the correct place. The days were chosen because they were clear (see appendix 3)

*mcl**: these are all correctly rotated and with the zenith pixel in the right place. These days were chosen to correspond to aurora free or aurora heavy days for Mark Clilverd's research (appendix 3 has a catalogue of aurora [un]contaminated nights). See the introduction for physical description of possible sources of AGW's.

May 04 -07: massive aurora

Jun06-07: aurora days
Aug18-19: no aurora
Apr13-14: no aurora
Aug22-23: no aurora

temp: contains the Utah programs and files in their original form. It also contains *airglow_zip* which is the file from the website below, which contains all the original programs, in case the unzipped versions get lost or deleted.

temp/synthetic: files oh_* are a sine wave travelling east. This was used as a test for the unambiguous spectrum.

temp/synthetic/jing: contains identical tiff and iplab images, and the matlab files once the images have been pre-processed. These can also be found on
ftp://conrad.csl.uiuc.edu/pub/Jing/Airglow_Pro/

*shw** : contains filtered matlab files for July 01-02. These are rotated correctly and have the correct zenith pixel.

Directory: *graphs*
Contains graphs of the correlation coefficients.

Directory: *sequence*
Contains a sequence of images, which have been equalized by Xnview. The direction of gravity waves is quite clear on a movie of the images and should correspond visually to the unambiguous spectrum.

Note:
The graphs in the results section and in the directory are of correlation coefficients which have been calculated using an even number of files. Only the correlation coefficients in documents with a prefix 'eo' were calculated using an even number of files. These are labelled as follows. For example, processed sodium images, from July 03-04, beginning at file 125 would be labelled 'eoczmJul0304Na_0125.doc'. Only these results are trustworthy.

Appendix 2

The comparison of results of *process.m* and *fluxerr.m.* These results are from the sor* files given us by UTAH. Figure 1 and figure 2 are the result of *show.m* and the phi spectrum generated by *phi_int.m.* for the same data set.

alambda = 1.35

File	Utah Star %	BAS Star %
sor0000	10.6113	10.2299
sor0002	10.5052	10.313
sor0004	10.7143	10.416
sor0006	11.5925	11.2526
sor0008	11.311	10.902
sor0010	10.6851	10.3975
sor0012	10.9912	10.5867
sor0014	11.4202	11.0296
sor0016	11.7309	11.1511
sor0018	11.777	11.5002

	Utah	BAS
corrz:	-0.3681 ± 0.059706	-0.36597 ± 0.059863
corrm:	-0.15945 ± 0.065028	-0.15759 ± 0.064905

alambda = 1.3

File	Utah Star %	BAS Star %
sor0000	22.0008	20.9227
sor0002	23.6586	22.1499
sor0004	23.3464	21.9762
sor0006	23.6694	22.8143
sor0008	25.078	23.5094
sor0010	23.9739	22.9235
sor0012	24.4552	23.331
sor0014	25.6255	23.8585
sor0016	25.927	24.3168
sor0018	25.4348	23.8155

	Utah	BAS
corrz:	-0.36357 ± 0.061993	-0.36096 ± 0.06201
corrm:	-0.15762 ± 0.066082	-0.15395 ± 0.0657

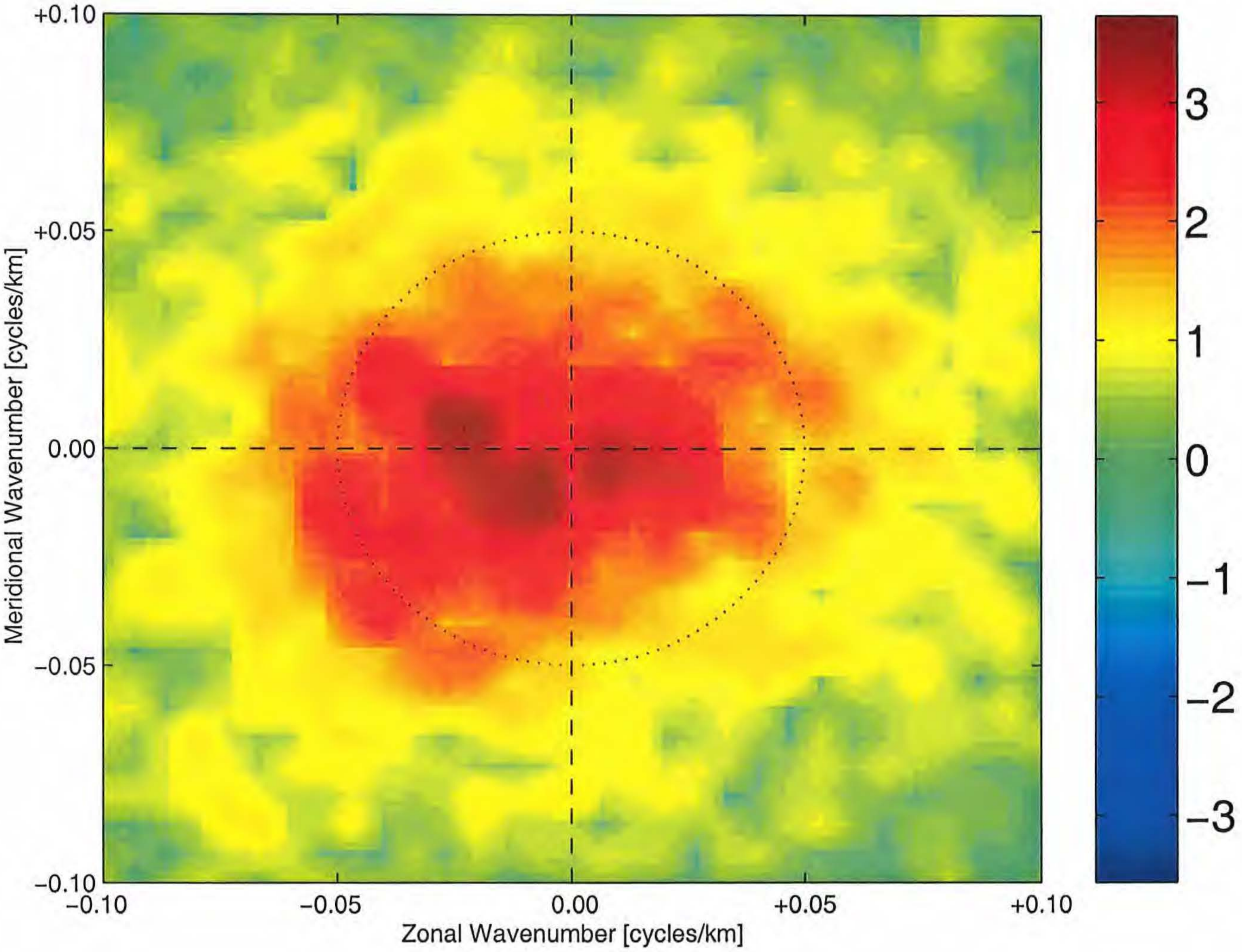

+0.10
+0.05
0.00
−0.05
−0.10
Meridional Wavenumber [cycles/km]
−0.10
−0.05
0.00
+0.05
+0.10
Zonal Wavenumber [cycles/km]
3
2
1
0
−1
−2
−3

figure 1

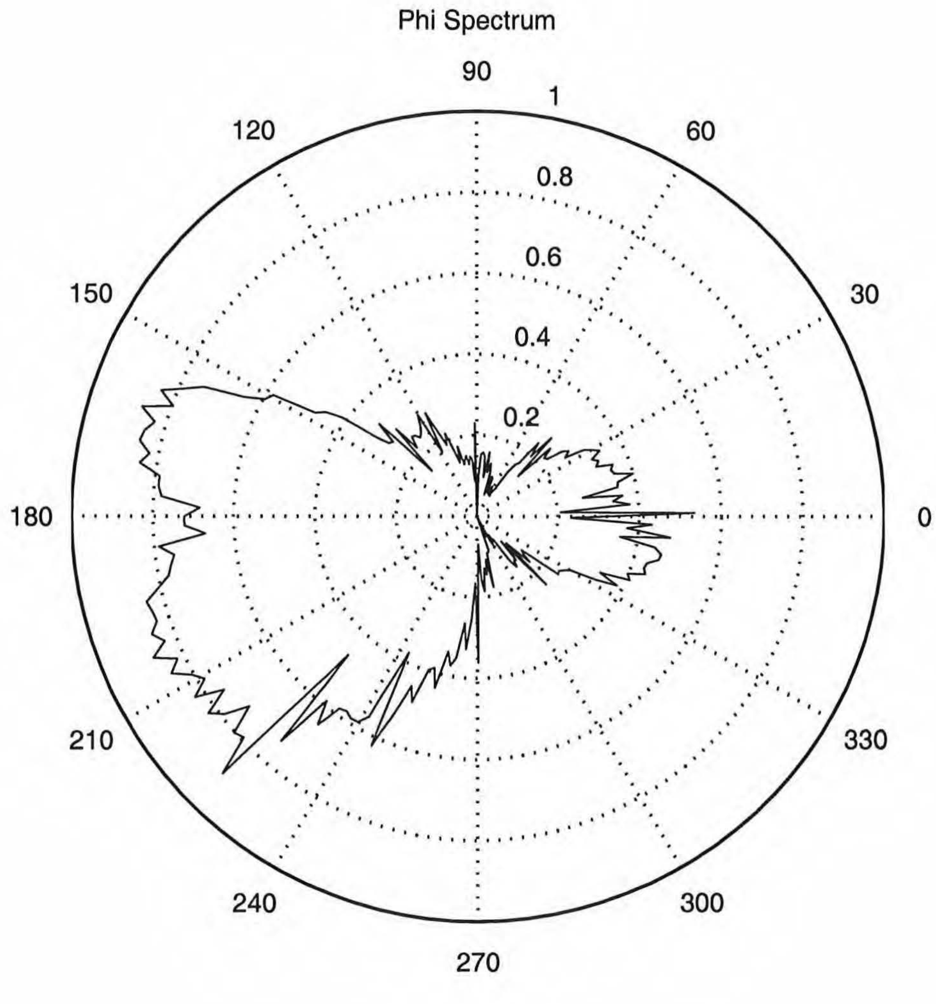

Phi Spectrum
90
60
30
0
330
300
270
240
210
180
150
120
1
0.8
0.6
0.4
0.2

figure 2

Appendix 3

These are all the days without complete cloud contamination from the OH movies. It is sometimes unclear whether the images have a slight haze or whether they have structure. It would be sensible to observe these days again. The aurora is not seen through the Na filter.

March	15-16	aurora through zenith
	16-17	aurora through zenith
	17-18	aurora through zenith and moon
	28-29	aurora through zenith and moon
	29-30	aurora and moon
	30-31	aurora through zenith and moon
	31-01	aurora through zenith, moon and possible haze
April	01-02	aurora through zenith
	02-03	aurora and possible haze
	08-09	aurora
	11-12	aurora and becomes cloudy half way through
	13-14	light aurora
	14-15	light aurora and moon
	28-29	aurora and moon
May	02-03	light aurora
	03-04	light aurora and haze
	04-05	aurora
	05-06	aurora through zenith
	06-07	aurora
	11-12	aurora through zenith and moon
	12-13	aurora through zenith, moon and haze
	14-15	aurora and moon
	15-16	aurora through zenith and moon
	16-17	aurora through zenith and moon
	25-26	aurora and haze
	26-27	aurora
	27-28	moon
	30-31	aurora through zenith
June	02-03	slight aurora
	03-04	slight aurora
	06-07	aurora through zenith
	07-08	slight aurora
	12-13	aurora and moon
	20-21	aurora and moon
	21-22	aurora through zenith
	24-25	becomes cloudy
	26-27	aurora through zenith
	27-28	aurora through zenith
July	01-02	slight haze and aurora
	02-03	aurora

	04-05	aurora
	05-06	possible haze
	06-07	moon, then hazy
	07-08	moon, then cloudy
	09-10	slight moon and slight aurora
	10-11	aurora through zenith
	20-21	moon, but good in middle
	25-26	cloudy towards end but otherwise good
August	01-02	slight haze and aurora
	04-05	moon
	06-07	moon with cloud at the end
	17-18	moon and aurora
	18-19	moon
	20-21	haze and aurora
	22-23	possible haze
	23-24	aurora through zenith and possible haze
	27-28	slight aurora
	28-29	aurora through zenith
	29-30	aurora
	30-31	aurora
September	03-04	aurora and moon
	06-07	slight aurora and moon
	17-18	aurora through zenith
	18-19	aurora
	19-20	possible haze and aurora
	22-23	slight aurora and light contamination
	23-24	aurora and light contamination
	24-25	aurora through zenith

Appendix 4

HOW TO PROCESS AN AIRGLOW DATA SET

1.0 Overview

The program master.m runs the whole process, which is shown explicitly on the flow chart following the text. Settings.m is the control program used to change all the necessary variables, and is the only program which needs to be altered by the user. This is shown below. The Matlab programs are run by typing the name of the program (leaving out '.m') at the matlab prompt.

2.0 Settings

See section 2.1 for a detailed description of the various variables in settings.

```
%*******************************************************************
%       settings.m
%*******************************************************************
%
%       settings file for the airglow runs
%
%*******************************************************************
%       interpolation settings
%       WARNING: You must re-run weights.m if anything changes here
%*******************************************************************
FOV=150;                          %field-of-view in km
NN=385;                           %size of the input CCD images
LL=255;                           %size of interpolated images (must be odd)
afov = 3.27*(385/512);                 %angular field-of-view in radians
re=6400;                           %earth radius
z=87;                             %airglow altitude
hammingsize=9;  %size of the hamming apodization function
%*******************************************************************

%*******************************************************************
%       General settings
%*******************************************************************
zx=265;        %zenith pixel x coordinate
zy=244;        %zenith pixel y coordinate
fini=061;      %for loop beginning used in save_image_spectrum.m and labels.m
finc=1;        %loop increment
fend=090;       %loop end
angl=323;       %Rotation angle used in read_tif_spectrum
corplot='JulNa0304corr_'; %file name which is string concatenated with fini which
stores the result of corr_phi1.m, the variables 'kx' and 'abs(corr)'
```

```
flux='czmJul0304'; %file name which is string concatenated with fini which stores
%numerical result of fluxerr, which are the zonal and meridional correlation
%coefficients.
data_dir = '/data/airglow6/rehi/Jul03-04/'; %directory containing
% raw tif files
data_directory = '/users/uasd/pgb/output/jul03-04/'; %data directory containing
% files which have been processed by save_tif_spectrum, which are now ready to be
%processed by
%the rest of the programs
spec='Na_*'; %file specification used by save_tif_spectrum for inputting files
file_pre='Na_0'; %file beginning used by output in the for loop in save_tif_spectrum
labels;                         %number of files must be even (why? – I don't
%know)
t=load('text020295.txt');       %file containing Rezaul's points
fnames = cellstr(fnames);       %filenames stored in cell array
deltaT = 2*60;                  %sampling period in seconds
%path = '/users/uasd/pgb/output/Jun06-07OH/';   % path for average.m
%current working directory is assumed if not stated
%*****************************************************************

%*****************************************************************
%       Wavelength of the artificial wave used to set the moving
%       star threshold. Tt is chosen to be near the Nyquist wavelength
%       For FOV=150, LL=255 it is 1.3 km; for FOV=300, LL=255 it is 2.6 km
%*****************************************************************
alambda = 1.35;
%*****************************************************************

%*****************************************************************
%       fft3d.m and unamb.m settings
%*****************************************************************
%       Number of points in zero-padded spatial FFT; choose a power of 2
spatial_fft_size = 256;
%       Size of 2-D FIR spatial prewhitening filter
spatial_window_size = 11;
%       Size of 1-D FIR temporal prewhitening filter
temporal_window_size = 5;
%       Temporal low frequency integration cutoff (radians/sec)
%       Chosen to prevent ghosting due to sidelobes
%       (see page 25 in Mark Coble's thesis)
wl = 2*pi/(2*3600);
%*****************************************************************

%*****************************************************************
%       fluxerr.m and corr_phi1.m settings
%*****************************************************************
%       Inertial frequency for the atmosphere (due to coriolis effect)
f = sin(35*pi/180)/(12*60*60);
%       Buoyancy frequency for ~90 km altitude is ~5 min
N = 1/(5*60);
```

```
%       G(w1, p), where w1 is the low-frequency cutoff used in
%       the gravity wave model mentioned in the Gardner etal. paper
%       NOTE: code is currently hardwired for spectral index p = 2
wone = f;
wone = 1/(2*60*60);  %2-hr period alternative
%*****************************************************************

%*****************************************************************
%       phi_int settings
%*****************************************************************
%       Minimum wavelength in kilometers to consider in the
%       phi spectrum; it is 2.4 km for 150 km FOV or 4.75 km for
%       300 km FOV.  See page 7 in Kapil Gulati's thesis.
lambda_min = 2.4;
%*****************************************************************

%*****************************************************************
%       auto.m settings...
%*****************************************************************
%       If autoset.mat exists, read the file for speed settings
if exist('autoset.mat')==2
  load autoset.mat
end
%*****************************************************************

%*****************************************************************
%       Ensure that we have the proper settings for alambda and lambdamin
%*****************************************************************
if(round(FOV)==150)
  alambda = 1.35;
  lambdamin = 2.4;
end

if(round(FOV)==300)
  alambda = 2.59;
        lambdamin = 4.75;
end
%*****************************************************************
```

2.1 Before running master.m

The tif images are pre-processed by save_image_spectrum.m, which calls read_tif_spectrum.m. Settings should be altered in settings.m (as shown above) by the user as follows. 'fini' is the number of the initial file, 'finc' is the increment by which 'fini' increases each time and 'fend' is the number of the last file. 'fini' and 'fend' are concatenated with 'file_pre', which is in turn concatenated with 'save_dir' and 'data_dir'. The variable 'angl' inputs the amount of anticlockwise rotation into read_tif_spectrum.m. It is the offset from north of the tif images in the anticlockwise direction.

The variables 'data_dir' and 'data_directory' should be changed to the relevant directories. 'data_dir' is the directory with the raw tif images, and 'data_directory' is the directory where the pre processed images are placed. 'data_directory' is called by all the other programs which need to use the processed tif files.
'spec' is the specification of the files used by save_image_spectrum.m and relates to the type of data being called (eg, OH, Na).
'file_pre' is the file prefix or the way in which the name of each processed and saved tif image will begin. For example: OH_0546.tif, where the OH_0 is 'file_pre' and the final three digits run from 'fini' to 'fend' in increments of 'finc'.

read_tif_spectrum calls zenith.m, which takes an input zenith pixel, and crops the image to a square surrounding that pixel. zenith.m maximises the size of the square inside the 512*512 input image. In settings.m the coordinates of the zenith pixel are 'zx' and 'zy', and should be altered accordingly for a set of images.

Make sure that in settings.m the 'data_directory' variable indicates the directory that will contain the pre-processed tif images, that is the images after they have been processed by save_image_spectrum.
The field of view (FOV) variable can be altered in settings.m. It is set at 150km, and is used to label many of the data products generated by the airglow code. If 150km is selected for the FOV, 'alambda' should be around 1.3. At a FOV of 300km it should be around 2.6. The relationship between the FOV and alambda was given us by Utah. Alambda defines the integration limits which are used by fluxerr.m. See Gardner et al, "Measuring gravity wave momentum fluxes with airglow imagers", *Journal of Geophysical Research*, Vol. **104**, No. D10, Pages 11,903 - 11,915, May 27th, 1999

weights.m, which is commented out in master, should be run if the FOV is changed in settings.
Once it has been run for a particular field of view it does not need to be run again. weights.m creates a matrix called 'interp_xxx' in the 'data_directory', where 'xxx' is the FOV. weights.m generates a set of sinc interpolation weights that are used in the sincint.m function. sincint_mex.c should be recompiled every time the hammingsize variable is changed in settings.m. This recompiling is not done inside master unless desired.
sincint_mex.c is compiled using the path name (already in master): mex -O -f $MATLAB/bin/cxxopts.sh sincint_mex.c

Settings runs labels.m. This tells the scripts which names and numbers are to be string concatenated with data_directory, and therefore labels.m requires fini, finc, fend, file_pre, and spec. The number of input files must be even, or an error will be outputted to the workspace.

3.0 master.m

This automatically deletes avg.mat before it processes a new set of images.
master.m runs these programs in the following order:

pre) save_image_spectrum.m
i) process.m
ii) fft3d.m
iii) unamb.m
iv) show.m (only if required)
v) fluxerr.m
vi) phi_int.m
vii) corr_phi1.m

3.1 save_image_spectrum.m

save_image_spectrum.m calls read_tif_spectrum.m, rotates each image, puts north at the top, truncates each image to size indicated by NN in settings.m. It saves each image as a Matlab matrix file 'yyy.mat' where 'yyy' is defined by 'file_pre' and 'fini'/'finc'/'fend'. This is described in more detail above. read_tif_spectrum.m calls zenith.m which centers the zenith pixel (inputted in settings) inside a square, whose size is maximized.

3.2 process.m

This flat fields, normalizes, detrends and interpolates each image. It then removes the stars. It prints the name of each file as it is processed, along with the percentage of pixels that were recognized as stars. Each processed image is then stored in a file called 'yyy_int.mat' where 'yyy' is the name of the original image, as defined by labels.m. The images are of size LL*LL, where LL is determined by settings.m. The default setting is LL=255. process.m calls nanmean.m and average.m. average.m finds the average raw image for a sequence, and
forms a radial imager distortion image from this average.

3.3 fft3d.m

This performs spatial and temporal pre-whitening and windowing before it takes the three dimensional Fourier transform of the data. It generates two files: 'fft_first_quad_xxx.mat' and 'fft_fourth_quad_xxx.mat', where 'xxx' is the field of view. These files contain the first and fourth quadrants of the FFT. The other two quadrants are redundant. fft3d.m calls sincint.m, which calculates the sinc interpolation function from Appendix A of Lee Ramsey's thesis.

3.4 unamb.m

This generates the unambiguous 2-D spectrum from the 3-D FFT and stores it in a file called 'unambspec_xxx.mat'. 'xxx' is the FOV.

3.5 show.m (optional)

This shows the result of unamb.m. It is commented out in master.m, so this must be changed if you want to see the spectrum.
It also includes the option of plotting Rezaul Haque's data points on the same

chart. However, this is not possible since we are not in possession of the necessary text files.

3.6 fluxerr.m

This calculates the zonal and meridonal correlation coefficients using the results from unamb.m. They are outputted, with errors, to the workspace and to the string concatenation of 'flux' with 'fini' in the data_directory. These are all set in settings.m.

3.7 phi_int.m

This finds the angular phi spectrum from the result of unamb.m.
It generates a matrix called 'phi_int_xxx.mat' which is used by the next program corr_phi1.m. In the code there is the option of creating a file for generating a polar plot with the Kaleidagraph plotting package. If this is not needed, it can just be ignored as the code is commented out. A matlab plot will not automatically be created.

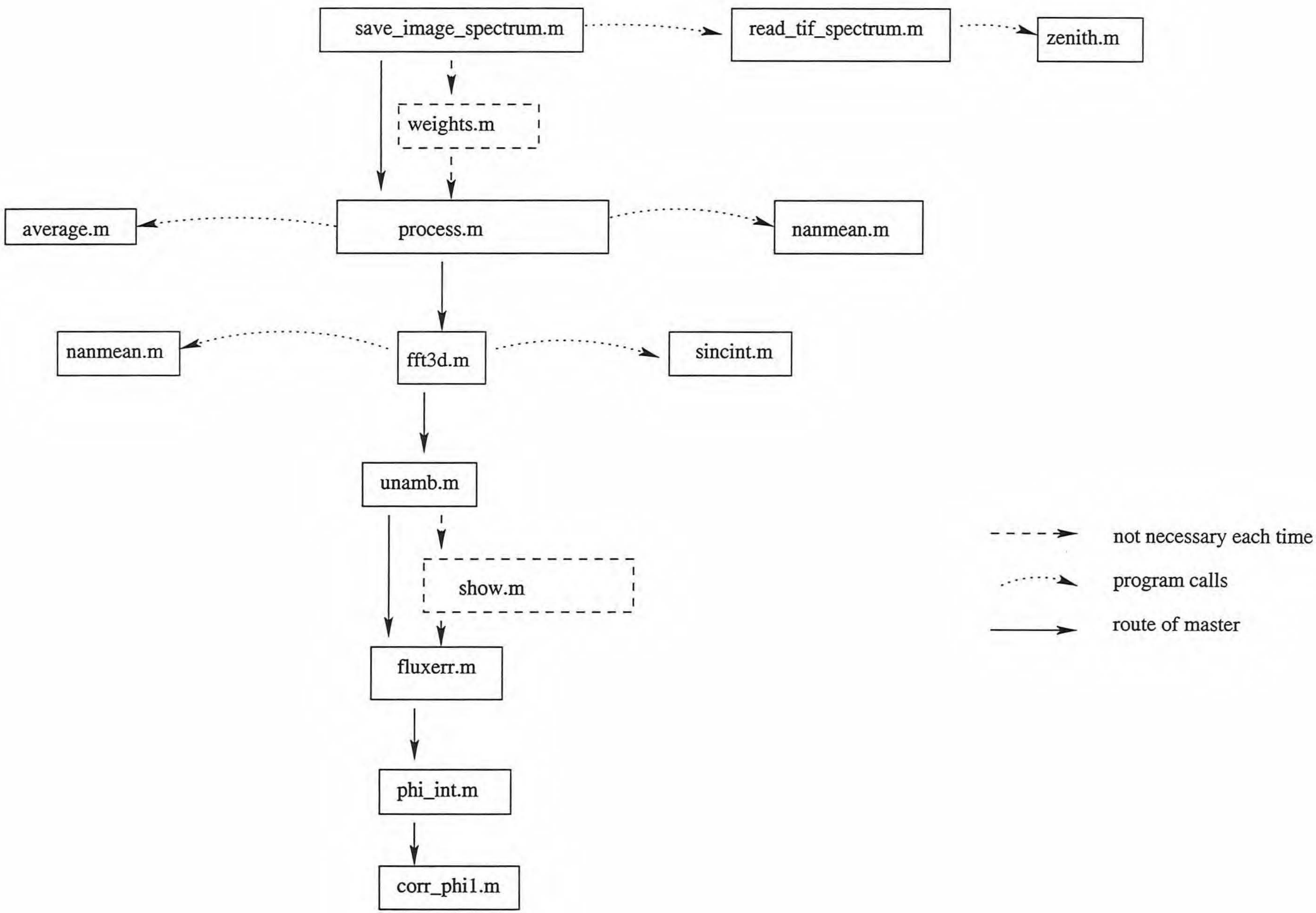
3.8 corr_phi1.m

This finds the correlation coefficient vs phi using the spectrum generated by phi_int.m. A coordinate system with north as zero is used. The integration is over [-pi/2, pi/2] for the numerator and [0, 2pi] for the denominator. G(w1,p) can be changed in settings.m.

It plots the correlation coefficient as a function of azimuth angle on a Matlab graph. Again, there is the option of creating a Kaleidagraph plot, and again this is commented out. A matlab plot will automatically be created.

The images are saved as a .mat file under the file name data_directory, string concatenated with 'corplot' (as defined in settings.m) and 'fini'. When this is loaded into the workspace of matlab, the variable cor is already the absolute of cor, as required for the polar plot. So once it is loaded, polar(kx, cor) will reproduce the image.

Processing an Airglow Image



according to Peter Brooke

Processing an OH Airglow Data Set

1. Transfer the images to a computer containing MATLAB.
2. Start MATLAB. Switch to the directory that contains the airglow scripts.
3. Use save_image_spectrum.m to pre-process the raw Iplab images. Change the variables ‘data_dir’, ‘save_dir’, ‘fini’ and ‘fend’ to values needed. The program will rotate and flip each image so that north is at the top of the image. Then each image will be truncated to the size indicated by the variable *NN* in settings.m. The default setting is *NN*=385. Finally each image will be saved as MATLAB matrix file ‘yyy.mat’, where ‘yyy’ is the name that will be given in labels.m.
4. Edit the file called labels.m. This will tell the scripts what files to process.
5. Open the settings.m script for editing.
6. Change the ‘data_directory’ variable to indicate the directory containing the airglow data. This variable is in the “general settings” category.
7. Change the *FOV* variable to indicate which field of view you want to use. This variable is used to label many of the data products generated by the airglow code.
8. Change the value of ‘alambda’ around 1.3 if you select 150-km field of view to get reasonable star percentage when processing images. If you are running the program with 300-km field of view, ‘alambda’ should be around 2.6. ‘alambda’ is in “Ensure that we have the proper settings for alambda and lambdamin” category. (Try an ‘alambda’ value with 10 images first and find out if the star percentage is about 20%. Then change alambda accordingly. This might need to be done for every set of images.)
9. Save settings.m.
10. Run the weights.m script to prepare the image interpolator. Once you have run this script for a particular field of view, you need not run weights.m again. A

matrix called 'interp_xxx' will be created in the script directory, where 'xxx' is the field of view.

11. Delete avg.mat every time before you process a new set of images.
12. Run the script process.m. This script flat-fields, normalizes, detrends, and interpolates each image. Then it removes the stars. It will print the name of each file as it is processed, along with the percentage of pixels that were recognized as stars. Each processed image is then stored in a file called 'yyy_int.mat', where 'yyy' is the name of the original image. The images will be of size LL x LL (determined by settings.m). The default setting is LL=255.
13. Run the script fft3d.m. This will take the three-dimensional Fourier transform of the data set. It will generate two files: 'fft_first_quad_xxx.mat' and 'fft_forth_quad_xxx.mat', where 'xxx' is the field of view. These files contain the first and fourth quadrants of the FFT (the other two quadrants are redundant).
14. Run the script unamb.m. This generates the unambiguous two-dimensional spectrum and stores it in a file called 'unambspec_xxx.mat'. Once again, 'xxx' is the field of view.
15. If you want to see the spectrum, run the script show.m. This script may need some tweaking to display the spectrum correctly on a particular computer.
16. To calculate the zonal and meridional correlation coefficients, run fluxerr.m.
17. To calculate the angular (ϕ) spectrum, run phi_int.m. This will generate a matrix file called 'phi_int_xxx.mat' that is used by the script corr_phi1.m. Also, phi_int.m will generate a file called 'phi_xxx_int.dat'. This file can be used to generate a polar plot with the Kaleidagraph plotting package.
18. To plot the correlation coefficient as a function of azimuth angle, run corr_phi1.m. This script will generate a file called 'corr_xxx.dat', which can be used to generate a polar plot with Kaleidagraph.

19. Be sure to archive all data products for future use. Record the settings that were used for each particular run.