Predicting Good Conditions for High Frequency Observing with the Green Bank Telescope

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Abstract

This research investigated what atmospheric conditions create good seeing for high frequency radio observations. A 400-day period of data from the site radio seeing interferometer was combined with model vertical atmospheric profiles using the READY internet archive. A total of 222 individual data sets were examined, representing 95 periods of good seeing and 127 periods of poor seeing. Multivariate analysis revealed seven key predictors in the vertical atmospheric profile. Five of the seven deal with wind speeds or directions, and none correlate with the amount of precipitable water in the atmosphere.

These predictors were used to create phase contour maps which may be used as templates for predicting times of good seeing. In addition, the factors derived from the analysis were extrapolated into common weather scenarios that can be identified using site data or weather products commonly available on the Internet. Additionally, they can be employed as forecast elements through the use of READY or a freeware program called BUFKIT. BUFKIT can build forecasts up to 84 hours in advance.

Project History, June 2000- May 2001

In the summer of 2000 I first studied the comprehensive conditions that affect high frequency observing in Green Bank, working under the direction of Ron Maddalena. These included the effects of topography, seasonal, climate and diurnal changes as well as the effects of weather systems. I did extensive reading and research to understand the ideas behind currently favored "frozen turbulence"[1] model that explains the differential atmospheric refraction over a large collecting area such as the dish of the GBT.

I then analyzed three types of site information: data from the tipper, the radio-seeing test interferometer and the OVLBI weather station. Using these together I developed profiles of how often and when good observing conditions might be expected to occur. One early finding was that there were many times when the atmospheric opacity was good but the phase was not, and vice versa. This indicated different mechanisms responsible for each.

During the rest of the summer I attempted to find classic weather patterns that permitted high frequency observing. I combined opacity and phase data to find good days and times from the spring of 2000, the only time period for which such data was available. I analyzed surface weather data from OVLBI as well as a variety of archived mesoscale weather products: upper air maps, surface maps, satellite images and radiosonde soundings. I continued this research through the school year with some of my high school students. We did a similar study of weather during unfavorable times, to see if we could notice any distinct differences.

Although weak trends were found, they did not consistently point to any indicator or product that could be used reliably to predict good observing. This led to a change in research direction and the development of the next phase of this study.

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[1] Taylor, G.I. 1938 "The Spectrum of Turbulence", Proc. R. Soc. Lond. A. 164, 476-490.

Research Plan, June – August 2001

From an exhaustive study of many types of mesoscale weather products, I concluded that site-specific data would be needed to predict good observing periods, since the resolution would account for local microclimate factors. But surface data had already been analyzed and found to be ineffective as predictors. I decided to analyze data from the vertical atmospheric profile directly over the observatory, since air aloft is often remarkably different in character from the surface layer. The idea that winds aloft are responsible for the deterioration in seeing has been proposed by a number of researchers, among them O.P. Lay[2] and M.A. Holdaway et al[3]. I also determined from the prior research that this might be a complex issue involving multiple interacting weather variables. To make the search more effective, I studied only periods of good phase measurements, even if the opacities were poor, since opacity is already well defined and is predictable by a measurement of PW, the amount of precipitable water in the atmosphere.

There were a few problems to overcome with this approach. First, there are no vertical weather products for the site. The closest atmospheric soundings are done at Blacksburg, VA and Pittsburgh, PA. Neither of these sites has closely comparable weather to Green Bank. Secondly, there was no firm knowledge of the natural processes at work in the transport of the water vapor affecting the seeing: for instance, what levels of the atmosphere were involved and how could the process be modeled mathematically?

Procedures

The NOAA Air Resources Laboratory maintains an Internet archive that can be used to generate model atmospheric profiles anywhere in the contiguous United States. It is READY[4]: The Real-time Environmental Applications and Display system. READY uses Eta model forecasts generated from data collected by aircraft, Nexrad and wind profiler sources and interpolates them into a high resolution 48 km grid with 3 hour time and 38 level atmospheric resolution. This is currently the most accurate way to analyze the vertical atmospheric conditions over the observatory.

To select periods of good and poor seeing, I studied interferometer data from March 2000 to April 2001. From these, I compiled two sets of dates in the cooler months between October and April. These times were carefully examined to rule out the possibility that they represented anomalous phase excursions, such as when the interferometer loses its lock on the satellite signal. Times were selected no closer than 9 hours apart so a bias would not be introduced by a few long periods of consistent weather. I eliminated any data set that had low time resolution- typically these phase data are averaged in 15-30 minute bins. The good times had to have acceptable phase values at least 75% of the time. In about 20% of the good data sets, anomalous large spikes in amplitude that lasted for less than 15 minutes were removed. The total set of dates represented 95 periods of good seeing and 127 times of poor seeing.

I downloaded all the vertical analysis soundings corresponding to those dates from the READY archive. In selecting which time to download, I chose points which were centered in the data sets, not near either end where the conditions might be changing. I cross-checked the accuracy of the READY model data by downloading a random series of READY archives for Pittsburgh and comparing them to actual Pittsburgh rawinsonde data for the same times. The agreement was excellent for parameters such as temperatures, wind velocities and the calculation of PW. In general, the major deviation is that the READY model data develops profiles that are more smoothed, devoid of some of the minor real variations recorded by the rawinsonde.

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[2] Lay, O.P. 1996 "The temporal power spectrum of atmospheric fluctuations due to water vapor", A&A 19.7, .

[3] Holdaway, M.A., Ishiguro, M. et al 1996 "MMA Memo 152: Comparison of Rio Frio and Chajnantor Site Testing Data".

[4] http://www.arl.noaa.gov/ready/amet.html

Meteorologist Jeffrey Hovis[5], the Science Operations Officer at the Charleston, WV office of the National Weather Service helped to develop procedures for reduction of READY files using the SHARP program and statistical analysis. We also discussed the best forecasting stations to use for Green Bank, and whether or not they should change with seasons. We determined that Elkins will be the best station to use year-round, due not only to its proximity but because it is the one most similar to Green Bank in terms of topography and climate.

Ron Maddalena wrote a data reduction program "Vertical" that gives the user the ability to select which atmospheric layers to study and also batch-processed all READY files into one output file. In addition this program incorporated subroutines that calculates PW per layer and as a measure over the total atmospheric column. Next, the program calculates the derivatives of these values over the layer. A few total atmospheric variables are also produced: KI, an index of atmospheric instability, and LHTF, a measure of how much heat is transferred to or from the atmosphere by air and water vapor. These two variables were an attempt to measure turbulence potential (vertical motion components) that might not be detected as wind. A final feature is the ability to sum the wind speeds within a selected layer in such a manner that each layer is weighted with its particular amount of PW. The reasoning behind this is as follows: wind-induced turbulence is more significant if the layer contains more water vapor, so the actual values for the PW of each layer are factored into the wind speed. Thus a wind with a longer crossing time may have a higher weight if it contains a high amount of water vapor.

These variables were examined in each layer: the air and dew point temperatures, PW, wind speeds and directions, and the layer thickness in meters. A second set of values calculated their changes from the surface to the layer boundary. In addition, these values were calculated for the entire atmosphere: PW, KI, LHTF, surface pressure, and the sum of winds, weighted with PW.

The following layers were analyzed:

- -Surface (ground level) to these pressure levels: 925mb, 900mb, 875mb, 850mb, 825, 800mb, 700mb, 500mb, 400mb, 300mb and 250mb.
- -The inversion layer of 875-750mb
- -The steering layer of 750-400mb

Since the "sum of winds" was a tunable feature of the program and any layers could be summed, wind shear effects were calculated for the interfaces between these primary layers of the troposphere: the boundary layer (875mb, 1250m above surface), the top of the advection layer (750mb, 2520m) and the jet stream (300mb, 9240m). The altitude and pressure levels cited are estimates that reflect values close to the mean of the data sets.

A large amount of data was generated. The challenge then became how to look for multiple correlations between atmospheric variables and phase. I began by using a statistics software package to perform principal multivariate component analysis. This was done iteratively with different combinations of layers to test the validity of the correlations and their relative significance. I retained any variable that had a phase correlation of .20 or higher. Many were strongly intra-correlated, so those with a correlation of greater .70 or higher with another variable were eliminated. This produced a final set of 7 factors.

I experimented with various regression routines (linear and non-linear) to see if I could determine a relative importance of the variables if all were considered significant. Then I graphed each pair of variables vs. phase to create three-dimensional phase contour maps. These maps were examined for patterns, and of the 21 plots produced, five were selected as representative of all major trends noted.

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Biases and Limitations

The phase data have at least two complications that affect their quality. First, the interferometer often loses its lock on the satellite signal. When this happens the phase errors appear to increase dramatically. There is no pattern to when this occurs, it sometimes happens daily. Unfortunately, this effect was only noticed and documented for a period of a few months of the study. In general, the error does not have a characteristic pattern and so it is difficult to discriminate it from periods of very bad seeing. There is a second problem with the insulation connector near the PC interface- even small vibrations can cause a jump in the signal, similar to the above pattern. This was only recently discovered (August 2001).

The method of analysis used does not represent a true multivariate analysis. Due to the degree of sophistication of the software, I was able to only consider three factors at a time. Three of the eight significant factors were wind directions. These present a special problem since the software handles numbers in a linear ascending fashion, and does not account for cyclical variance. For example, a direction of 1 degree and 359 degrees both represent north winds, but they are discriminated as being extremely different in numerical analyses.

A factor that is not accounted for is the vertical component of air motion. Turbulence is three-dimensional, but winds represent only two dimensions of this motion. The READY archive also contains files for measuring this component as part of the HYSPLIT Transport and Dispersion Model[6]. HYSPLIT allows the user to input up to three starting levels for a particle in the atmosphere; it will then compute vertical velocities for the particle's trajectory for a selected number of hours. Using HYSPLIT data would have made this analysis more complete and potentially more accurate. It was not done simply due to time constraints.

Results

From a study of the interferometer and opacity data over 396 days, it appears that the prime season for high frequency observing is from November through March. During this time, both opacity and phase values are at their lowest. The opacity values are acceptable 41% of the time, while the phase errors are minimal 23% of the time. However, the times when both are good occur only 13% of the time. The best time is from sunset to sunrise.

From the above observation one might infer that air temperature is the predominant factor in predicting such times, but that is not true in the case of phase measurements. Perhaps more surprising is that the amount of precipitable water has little effect on phase stability. In repeated multivariate correlations, the PW factor correlates with phase at about -.06. Wind speed and direction are the best factors to use for predicting good seeing, with correlations ranging from .43 to .22.

These seven factors have some significant correlation with phase:

Surface Wind Speed	.43 correlation
850mb Wind Speed	.32
Surface Wind Direction	.30
Temp. gradient, surface to 850mb	-.25
Sum of Wind Speeds, Surface to 300mb	.25
LHTF	-.24
850mb Wind Direction	.22

6 http://www.arl.noaa.gov/ready-bin/traj1file.pl?metdata=EDAS

In sampling winds, there are at least two layers of the atmosphere that need to be assessed: the surface and the 850 mb layer. Surface data makes sense from the standpoint that most of the water vapor is concentrated there, and ground-induced turbulence arises from differential heating of the land-air interface as well as frictional effects introduced by topography. However, the 850mb level has significant implications as well:

-It represents a typical level for inversions.
-The air does not undergo diurnal temperature changes.
-It is the layer most likely to indicate advection
-This level is equivalent to the highest points on Back Allegheny Mountain, the highest range to the west. It may indicate the boundary level of ridge-induced turbulence.

A more comprehensive picture may be gained by summing the winds through 300mb (the entire troposphere) to get a relative snapshot of the average wind speeds at a particular time.

There are trends in each of the above variables that would make for an ideal setting. However the atmosphere is so complex that all of these factors do not happen simultaneously. Therefore a delicate balancing act is always in progress, with the ill-fated tendencies of some factors offsetting the positive trends of others. The optimum scenario for each factor is:

Surface Wind Speed	3-10 m/s
850mb Wind Speed	5-18 m/s
Surface Wind Direction	N, NE, S, SW
Temp. gradient, surface to 850mb	isothermal (no change) or positive (inversion)
Sum of Wind Speeds, Surface to 300mb	moderate
LHTF	positive
850mb Wind Direction	N, NE, E, SW

Some good observing scenarios can be inferred from combinations of the optimum factors:

1. A strong inversion with light surface winds.
2. 850 mb winds from the N, NE or E.
3. Snow cover or heavy dew or frost.
4. Orographic (standing) waves, typically set up by 700mb winds from the N-NW at speeds exceeding 18 m/s.
5. A cold-core high pressure center overhead or to the W.
6. A low pressure center to the E or NE.
7. Soon after the passage of a cold front.
8. An upper air trough to the E or a ridge to the W.

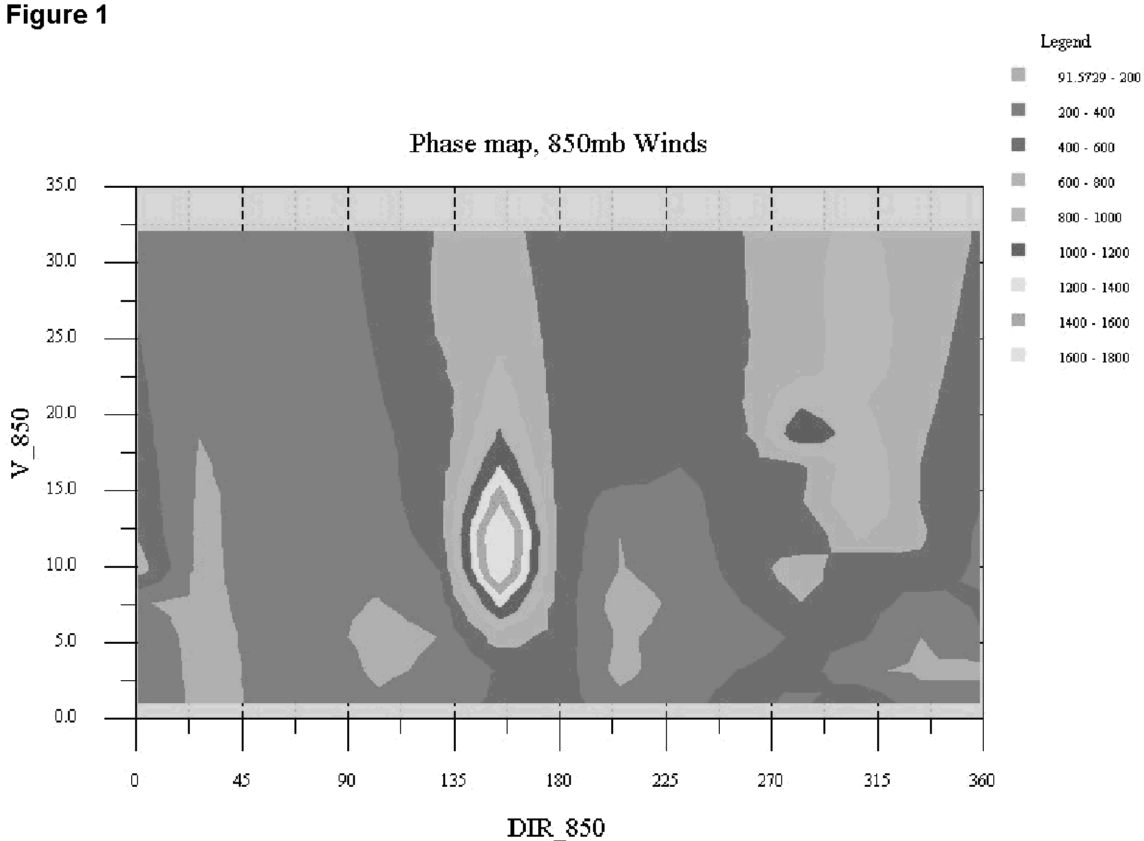
<u>Analysis and Use of the Phase Contour Maps</u>

The 21 phase contour maps were constructed in a consistent manner so they could all be compared: the contour interval was 200 microns for each map, with phase being the Z axis component. A standard color scheme was used for each map. Green represents the best phase measurements. Five repeated patterns emerged in the maps. Based on their abstract designs, I nicknamed each: Idol Head, Beak and Egg, Gas Giant, Diags, and Half Joves. I eliminated similar patterns until I reduced the set to 6 key diagrams. They are (x and y components):

-Ground wind direction vs. ground wind velocity (Idol Head)
-850mb wind direction vs. LHTF (Beak and Egg)
-850mb wind direction vs. temperature gradient to 850mb (Gas Giant)
-850mb wind direction vs. 850mb wind velocity (a combination of Idol Head & Gas Giant)
-Ground wind velocity vs. LHTF (Half Jove)
-Ground wind velocity vs. temperature gradient to 850mb (Diag)

In addition to studying these plots to see relationships among the variables, they may be used to predict times of high frequency observing. An operator or technician can call up a vertical forecast profile in READY or BUFKIT. Then using key parameters selected for a certain time, the contour plots can be examined to see if good seeing is forecast. In the below example, suppose the speed and direction of the 850mb wind is measured and found to be: 10m/s, at 155 degrees (SE). Should the high frequency observer be alerted??

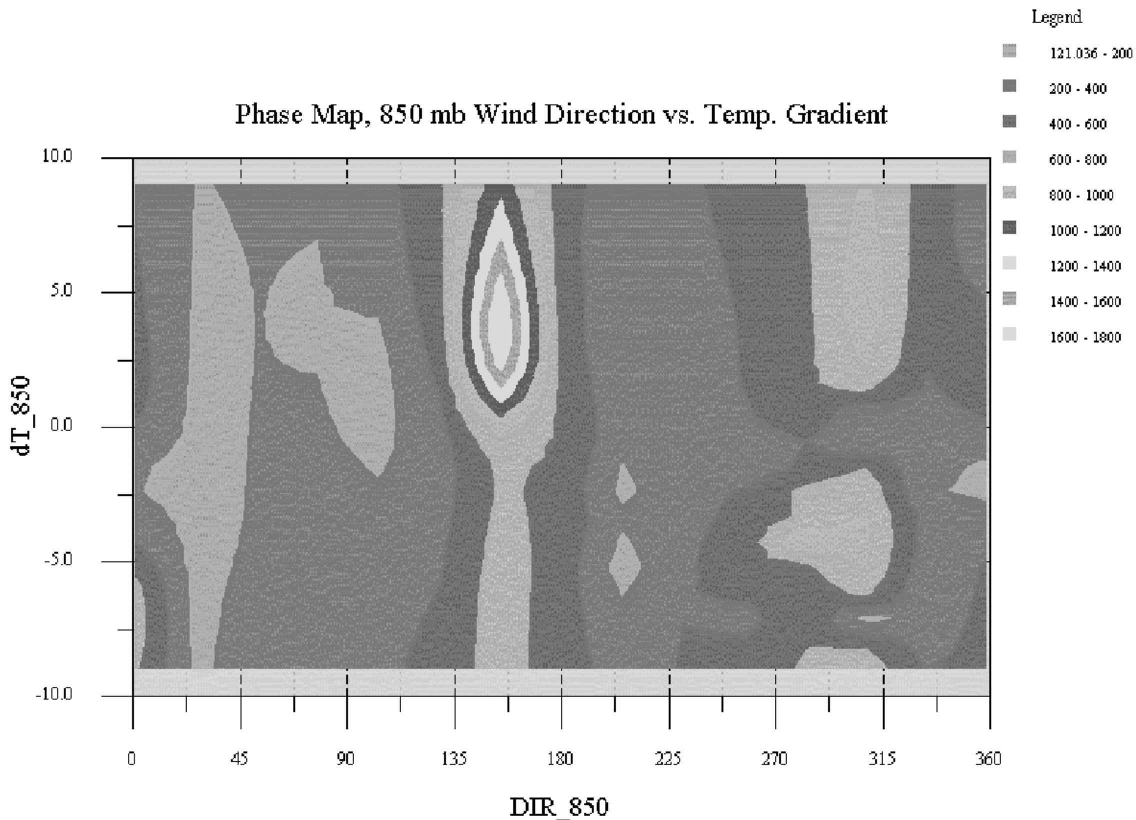
Figure 1



If other factors are also measured and the set of six plots are examined, a consistent agreement should be reached about the forecast for radio seeing. This is proposed as a model to be tested.

<u>Notes on Specific Contour Maps</u>
The 850 Flame: An area of intensely poor seeing conditions appears as a flame-shaped feature on all seven of the 850mb maps. It may be seen in *Figure 1* centered at 10 m/s and 155 degrees. The indication is that winds from the SSE (155-175^{o}) at this level in the atmosphere are particularly unfavorable. The same effect is noticed at 800mb but there it is centered on 180 ^{o}, due south. This may be due to the fact that S-SE advecting air typically tends to be high in water vapor content. This may be further confirmed by inspection of the feature on the dT850 contour map:

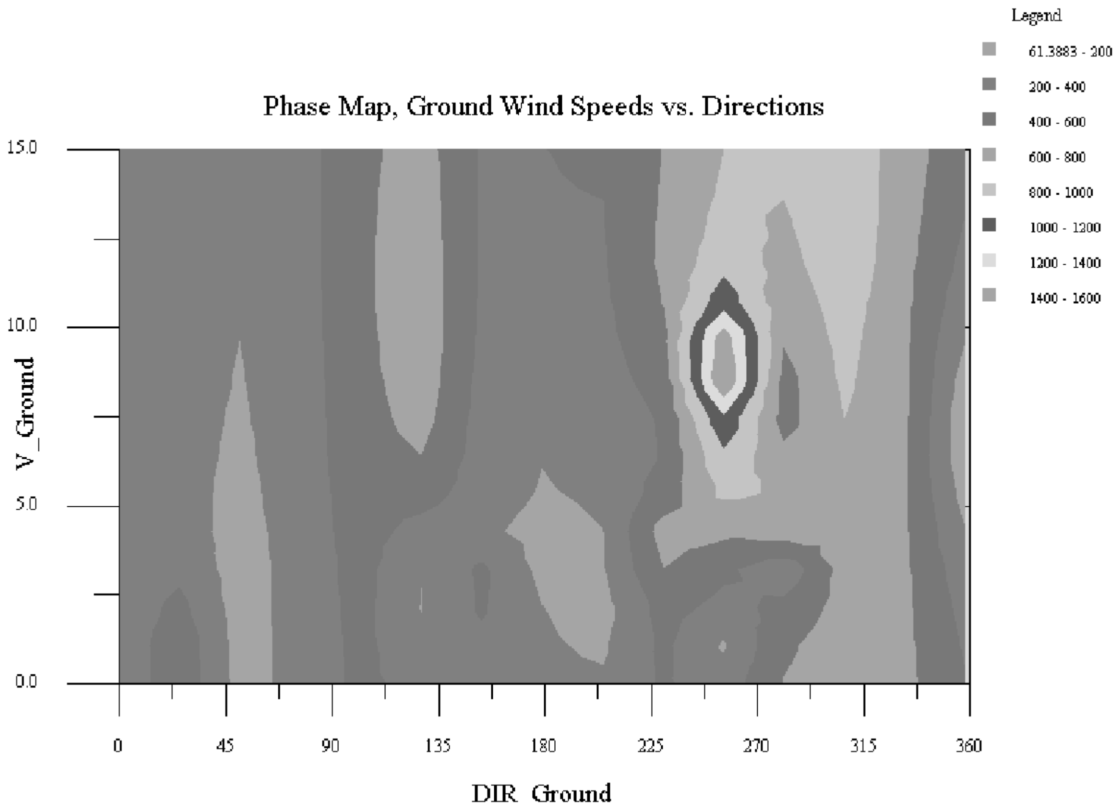
Figure 2



Here (Fig. 2), the flame occurs during times of strong inversions (positive dT850 values). Inversions occur because a layer of warm air advects over cooler surface air. The same trend may be seen in LHTF plots, where the flame masquerades as the "egg" part of the "Beak and Egg" pattern, as seen in Fig. 5.

The Idol Head: In both Fig. 1 and Fig. 3 (below), a region of unfavorable phase occurs between 240-335 °. It is roughly an inverted "L" shape with a pocket of extremely high phase located almost due west (270 °). This is the "Idol Head". The Head appears much more pronounced in surface layer maps but is weakly persistent in maps extending up to 850 mb. This may be a key to understanding its nature.

Figure 3



The general strike of the mountains locally is N 20 E. With respect to the observatory, the western (closer) mountains are located from 220 (SW) to 20 (NE). Keeping in mind that the contour plots were generated from model data with 40km resolution, any surface artifacts are mesoscale in nature. It is possible that this zone represents ridge-induced turbulence. This may also explain the Idol's "chin"- a transition area at about 4m/s, where the air transitions from laminar to turbulent flow. The secondary turbulent zone located at 110-140 ° may be due to the eastern range, which are more distant.

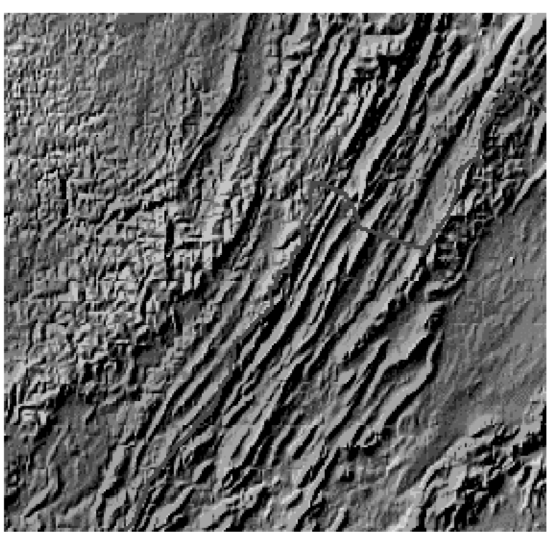
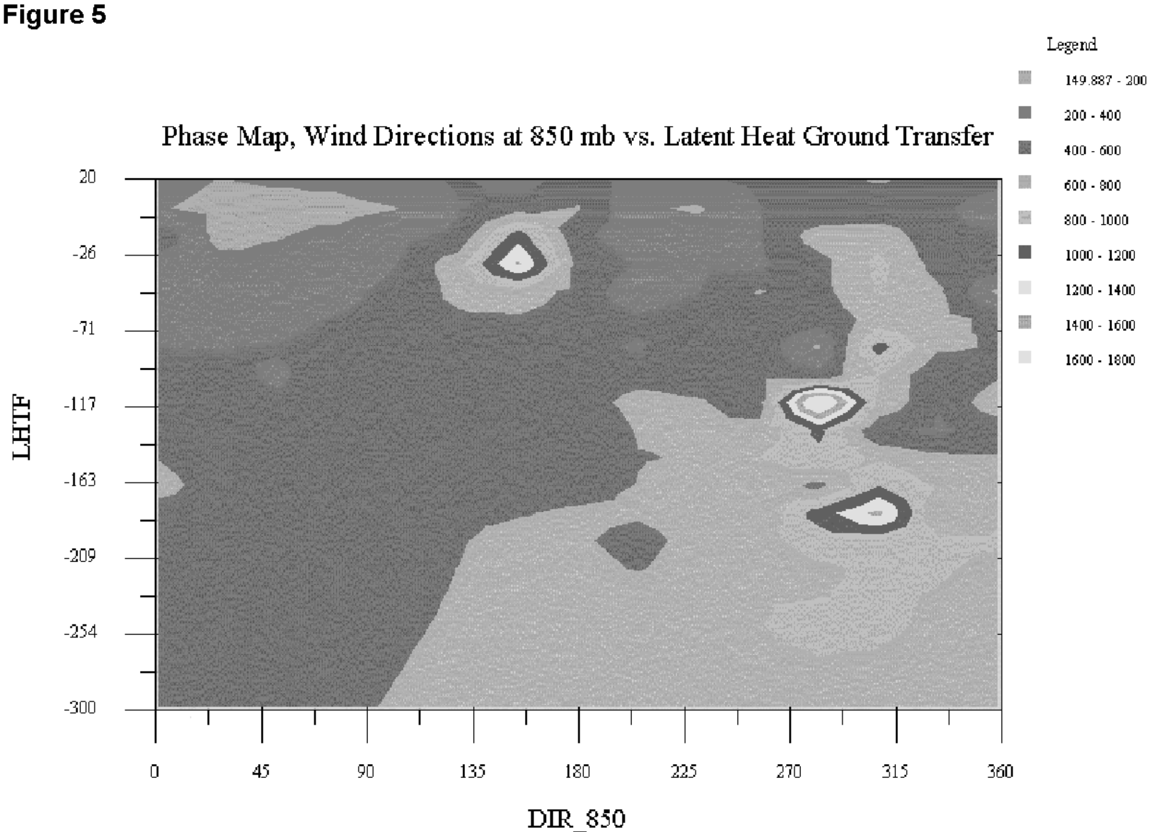


Figure 4 *Portion of shaded relief map of the mountains in the vicinity of NRAO. North is up. From Color Landform Atlas of the United States*[7]

[7] Maps by Ray Sterner, Johns Hopkins University Applied Physics Labs

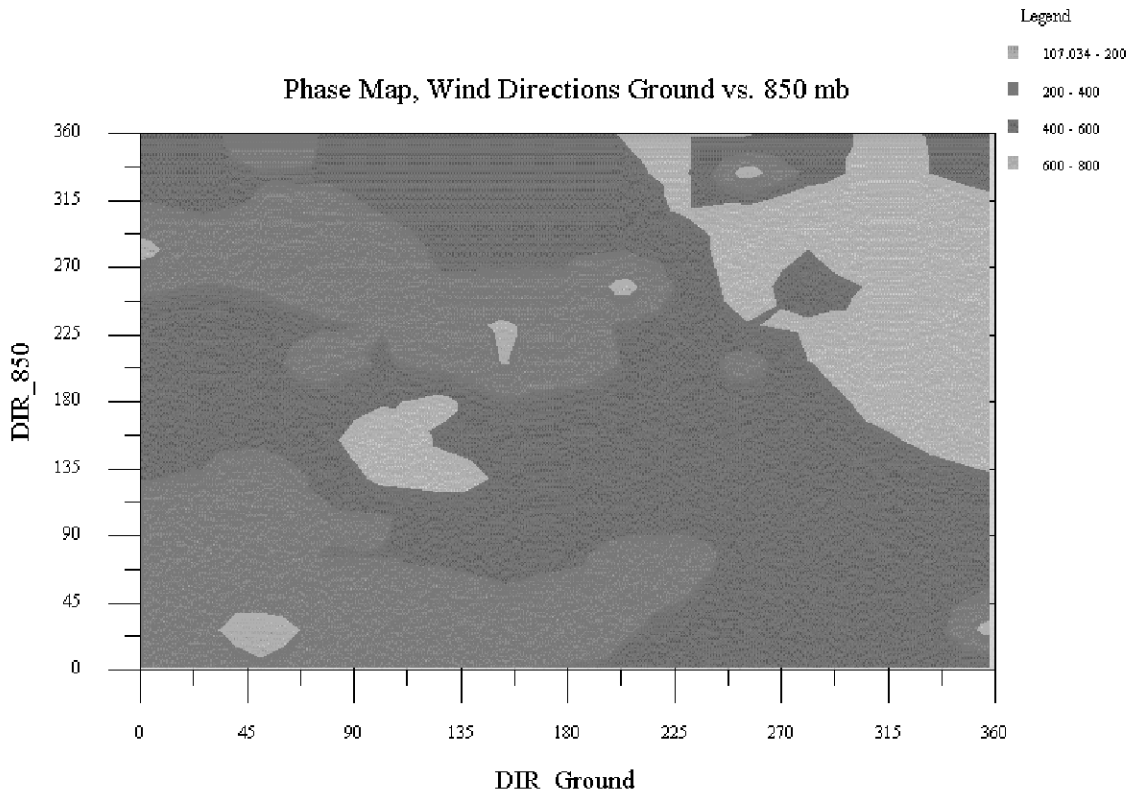
The Beak and Egg: In the first contour plot below, the “egg” is a variation of the “flame” feature previously described. The general trend of these plots is a diagonal progression from good phase (upper left) to poor phase (lower right). The “beak” feature (upper right) appears to be a residual of the “Idol head” region of western turbulence.

Figure 5



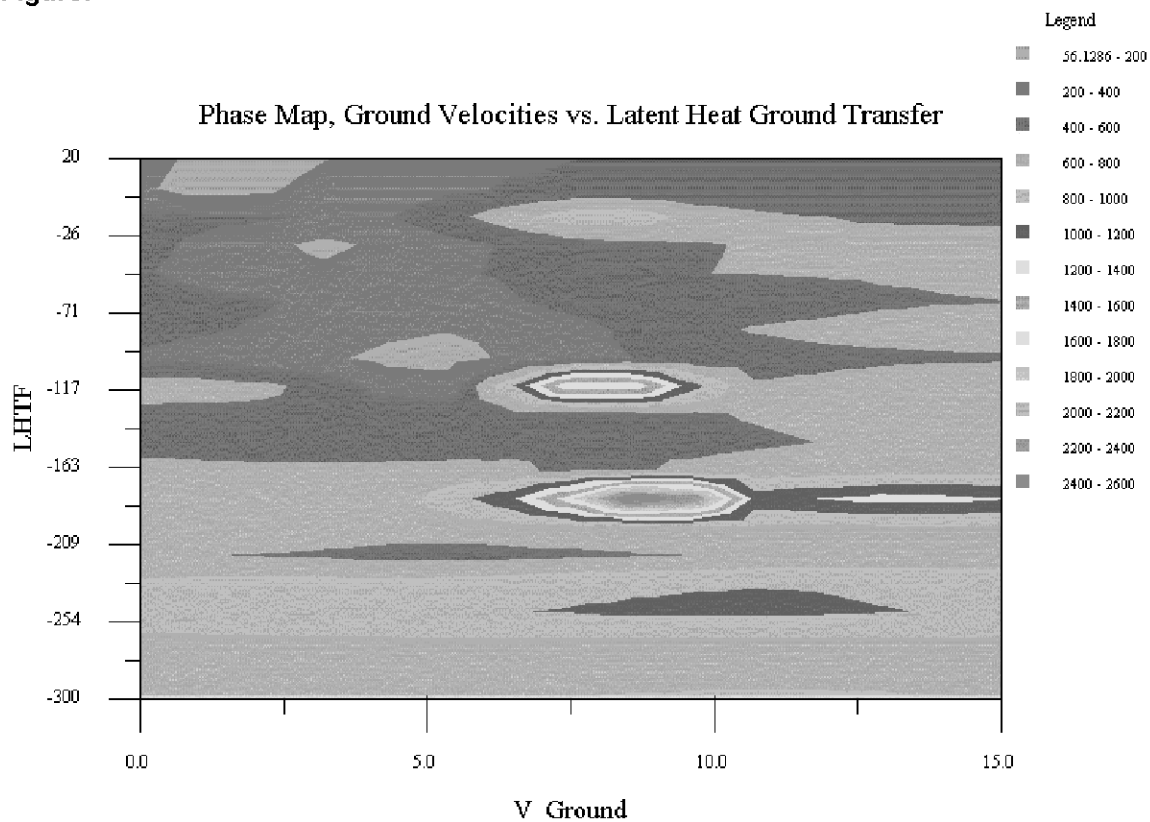
The next “beak and egg” (Fig. 6) pattern suggests that a condition of western winds where no directional shear exists through 800mb produces more turbulence than when a capping shear exists. This band (upper right) is a prominent feature in all of the bi-directional plots.

Figure6



The Mystery of the "Half-Joves": The phase plot of LHTF vs. surface velocities (Fig.7) shows a weak bimodal condition, with a general trend of less atmospheric heating producing more stability. However, two obvious "hot spots" appear at moderate wind speeds and LHTF values. The origin of this remains unresolved.

Figure7



Forecast Tools and Data Sites

The READY site is capable of producing forecast meteograms and vertical profiles as well as archived ones. The forecast models can go to 60 hours and produce animated loops of the profiles as well as the text files. A modification of Maddalena's "Vertical" program could allow a user to analyze these files just as the archived ones.

Another comprehensive and excellent forecast tool is BUFKIT[8], a visualization and analysis tool kit developed by the staff at the National Weather Service (NWS) office in Buffalo, NY. It is a freeware application that utilizes Eta model data to construct profiles in a manner similar to READY. The difference is that BUFKIT is much more powerful and interactive and can forecast out to 84 hours. It utilizes a friendly subroutine called BufGet to automatically download the files of choice from ftp sites. In the case of NRAO Green Bank, the closest data site is Elkins.[9]

I compared the consistency of analysis soundings using READY vs. BUFKIT using the same location: Elkins WV, lat. 38.96, long. –79.82. Both models agree very closely within short forecast scales of 24 hours or less. The BUFKIT soundings show more resolution along the temperature traces, especially the dew point trace. As the forecast time extends out to 60 hours, more variations in temperatures and wind directions may occur. The wind speeds agree consistently, but the directions sometimes show a variance up to 40 degrees at pressure levels of 600mb or higher and the dew point temperatures may differ significantly.

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[8] http://www.wbuf.noaa.gov/bufkit/bufkit.html

[9] ftp://ftp.werh.noaa.gov/share/cwsu/BUFKIT/erleta/etakit.ekn

Research Extensions

The issue of how to deal with wind direction in multivariate analysis routines remains unresolved. A better way to represent wind direction is needed to test if the correlations to phase are more significant than reported. Some method of incorporating vertical motion data such as HYSPLIT into a multivariate analysis should be tried and the component analysis re-evaluated. If necessary, new phase contour maps may need to be constructed. In either case, the method of predicting observing conditions by use of the phase contour map set should be thoroughly tested to evaluate its potential as a predictive tool.

The nature of the LHTF “hot spots” is worthy of further investigation.

A study should be conducted to find which best predicts atmospheric conditions for Green Bank: the READY EDAS model forecast soundings at the observatory location or the Elkins BUFKIT forecast soundings.