Exploring the Effects of Applying a More General Radar Equation to Wind Profiler Data

D. Matthew Coleman
University of Virginia: Senior

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Science Research Mentor: Leslie M. Hartten
Writing and Communication Mentor: Amy J. Stevermer
Community Mentor: Jack Fellows
Peer Mentor: Maribel Martinez

ABSTRACT

Data collected by the Galápagos Islands’ Doppler wind profiler using 100- and 500-m pulse lengths do not yield the same wind profiles. The longer 500-m pulse length profiles are displaced in height from those of the shorter 100-m pulse. The standard radar equation used to assign heights to measured winds assumes that the reflectivity in the atmospheric scattering volume is constant and the range of the scattering volume is much longer than the profiler pulse length. These assumptions are often violated, producing substantial differences in 500-m height assignments.

This study adjusted 500-m pulse wind height assignments using a more general radar equation. The more general equation takes into account that the reflectivity in the scattering volume can be non-constant and the range of the scattering volume can be of similar length to the profiler pulse length.

Height corrections were applied to El Niño, La Niña, and normal 10-day case studies. Applying the more general radar equation reduced the mean absolute difference between the wind speed and direction profiles for all cases at heights above 750 m. The results implied that height corrections could be applicable during different atmospheric conditions.

The results of this research could allow profiles collected with different pulse lengths to be merged into one product, thereby improving data quality. Further research is needed to determine the statistical significance of the improvement and the equation’s applicability to other time periods in the Galápagos and other wind profiler data around the world.

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INTRODUCTION

Currently, there is room for improving the quality of wind profiler data. By modifying two assumptions made by the standard radar equation, it is possible that height assignments for measured winds can be refined. The standard equation assumes that the reflectivity in an atmospheric scattering volume is constant and the range of the scattering volume is much larger than the profiler pulse length. When these assumptions are violated, heights from long pulse lengths are often displaced from those collected by shorter pulse lengths. In an attempt to answer this problem, the standard radar equation was modified (Johnston et al., 2001) into a more general radar equation. The more general equation accounts for situations when the standard equation’s assumptions are violated, thereby reassigning high mode wind speed and direction heights.

The goal of this project was to examine the effects of applying a more general radar equation to wind height calculations from the Galápagos Islands’ 915-MHz wind profiler. If the wind profile differences were reduced, then data quality could be improved to benefit climate researchers, atmospheric dynamics analysts, and operational forecasters. Once improved data is available, significant developments can be made in understanding the past, present, and future states of the atmosphere. If the wind profile differences were not reduced using this method, fellow researchers could then proceed to develop a new approach to reducing the difference between high and low mode wind profiles.

The NOAA Aeronomy Laboratory deployed 915-MHz wind profilers at several sites in the tropical Pacific as a part of the Tropical Ocean Global Atmosphere (TOGA) program. The TOGA program lasted from 1985 until 1995, but the profilers continue to operate. The laboratory’s profiler at San Cristóbal in the Galápagos Islands has been measuring winds since 1994.

The Galápagos profiler is of particular importance for two reasons. First, it is located in the Eastern Pacific cold tongue, which is a highly variable atmospheric region. Second, its data document wind speed and direction changes in the Niño 1+2 region during El Niño and La Niña events. The data show how wind speed and direction vary with height, allowing better study of the dynamics of the tropical Pacific during different atmospheric conditions. A graphic of the Galápagos Islands and the tropical Pacific region is shown in Figure 1.
Figure 1. Map of the Galápagos Islands and a 1993 SST map of the Tropical Pacific. SST map obtained from the TAO Project Office/PMEL/NOAA. Galápagos map obtained from United Nations, Dept. of Public Info., Cartographic Section, Map No. 3878.
A wind profiler is a Doppler radar that measures wind velocities and wind directions. It measures these wind characteristics by transmitting variable-length pulses from an antenna. The radar detects Doppler shifts of pulse echoes that occur from turbulent irregularities in a parcel of atmosphere. The shifted pulse returns to the antenna, allowing us to infer wind speed and direction.

The wind profiler in the Galápagos (Figure 2) collects wind data in two modes. The low mode operates at a 100-m pulse. It gives a higher resolution of data within the lower troposphere. The high mode operates at a 500-m pulse. It has a coarser resolution, but is able to observe higher into the troposphere, providing lower- and mid-tropospheric wind profiles.

![Wind profiler](image)

*Figure 2. The Galápagos 915-MHz wind profiler. Graphic obtained from P. E. Johnston (2002, personal communication).*

Theoretically, the high and low mode pulse lengths should provide the same wind profiles at low altitudes because they are both traveling upward into the same region of space. However, this is not the case. When analyzing three years of Galápagos wind profiler data, Hartten and Gage (2000) noted that there was often a discrepancy between the wind speed and direction profiles obtained from the different pulses. Wind speed minima and direction shifts were offset by as much as 500 m (Figure 3). The same problem has been observed in wind profiler data examined over different averaging periods from other stations around the world.
Johnston et al. (2001) analyzed this problem and proposed that part of it could be associated with the height assignments that result from using the standard radar equation. Currently, measured winds are assigned to a height located at the center of the scanned atmospheric volume. This height assignment comes about mathematically because of two assumptions made by the standard radar equation. The standard equation assumes that the reflectivity in the scanned volume is constant and the range of the scanned volume is much longer in length than the pulse length.

Johnston et al. (2001) modified the standard equation into a more general radar equation that accounts for the fact that the standard equation’s assumptions are not always valid for wind profilers. The general equation takes into account that:

1. the reflectivity in the atmospheric scattering volume can vary with height, and
2. the range of the volume can be of similar length to the profiler pulse length.

The more general equation used in this research accounts for non-constant reflectivity by utilizing an exponentially decaying reflectivity profile instead of one that is constant. The decaying reflectivity profile is based on worldwide National Bureau of Standards reflectivity measurements.

This paper documents the effects of applying the more general radar equation to data obtained from the Galápagos wind profiler. In the following section, the experimental methods are documented. Next, the results are stated and discussed. In the final section, major conclusions are drawn and future scientific implications are considered.

METHODS
Instrumentation and data set description

The Galápagos 915-MHz wind profiler is a UHF-band profiler, which can be used to monitor clear air turbulence at a high resolution. It sends low mode (100-m pulse length) and high mode (500-m pulse length) pulses vertically into the atmosphere as well as at 21° from the
vertical. The low mode can observe an altitude of five or six km into the troposphere while the high mode observes as high as 12 or 13 km (Carter et al., 1995).

The wind profiler data studied for this project were collected in the Galápagos Islands between the years 1994 and 2001. The 915-MHz wind profiler gathered the wind data continuously in both the high mode and the low mode. The data were then post-processed as described by Riddle et al. (1996) into half-hourly profiles.

Case selection

Eight cases were chosen and each case consisted of 10 consecutive days of high and low mode data. Two cases were chosen during El Niño events, two during La Niña events, and four during "normal" conditions. Standard Sea Surface Temperature anomaly (SST') data for the Niño 1+2 region (in which the Galápagos are located, see Figure 1) were used to classify the cases. The anomalies were departures (in °C) from a particular month's 30-year mean (1971-2000) temperature. The anomalies were studied by examining a plot of SST' (Figure 4). Emphasis was placed on studying the SST' data and plot during the 1994 to 2001 period, when the wind profiler data were available. Conditions were defined as follows:

- SST' ≥ 1°C corresponds to El Niño
- SST' ≤ -1°C corresponds to La Niña

-1°C < SST' < 1°C corresponds to normal

The cases chosen are shown in Table 1.

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**Figure 4.** Plot of Niño 1+2 SST' from 1990 to 2000. Data obtained from http://www.cpc.noaa.gov/index.html.
Table 1. Case numbers, dates, Julian Days and SST’ of El Niño, La Niña, and Normal cases.

<table>
<thead>
<tr>
<th>Case</th>
<th>Date</th>
<th>Julian Days</th>
<th>SST’ (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2 10-19 July 1997</td>
<td>10-19</td>
<td>3.80</td>
</tr>
<tr>
<td>La Niña</td>
<td>3 10-19 December 1996</td>
<td>345-354</td>
<td>-1.18</td>
</tr>
<tr>
<td></td>
<td>4 10-19 July 1998</td>
<td>191-200</td>
<td>-1.36</td>
</tr>
<tr>
<td>Normal</td>
<td>5 10-19 December 1994</td>
<td>344-353</td>
<td>0.82</td>
</tr>
<tr>
<td></td>
<td>6 10-19 March 1995</td>
<td>69-78</td>
<td>-0.25</td>
</tr>
<tr>
<td></td>
<td>7 10-19 June 1995</td>
<td>161-170</td>
<td>-0.50</td>
</tr>
<tr>
<td></td>
<td>8 21-30 August 1995</td>
<td>233-242</td>
<td>-0.77</td>
</tr>
</tbody>
</table>

Extreme and normal event cases were divided seasonally. The extreme cases contained one 10-day data set during the austral summer and one during the winter. The normal cases extended through the course of a year and were separated into summer, fall, winter, and spring seasons. Seasonal divisions were used because the Galápagos Island region experiences much atmospheric variability throughout the course of a year. This variability allowed us to see exactly when the modified radar equation would be applicable to the data. Furthermore, seasonal divisions allowed us to compare profiles for the eight cases for both summer and winter conditions. All of the data were initially chosen during the middle of each month for consistency. It should be noted that the cases picked were constrained by data availability. Although the profiler operated from 1994 through 2001, there were large gaps present. Some desired extreme and normal events were not studied because there were insufficient profiler data at those times.

Height correction

The high mode heights were corrected using a more general radar equation suggested by Johnston et al. (2001). Corrections were made in hope of making them more closely resemble those of the low mode. The low mode data were taken as the reference because the shorter pulse length involves integration over a smaller volume for each observation (Johnston et al. 2001). The more general equation uses Galápagos system parameters and a median reflectivity gradient of –2.17 dB/km that was derived by Doviak and Zrnic (1993). The derivation utilized worldwide reflectivity data and an average reflectivity profile collected by the U.S. National Bureau of Standards (NBS).

The height corrections were largest for altitudes less than about 5000 m (Figure 5). The correction is larger below 5000 m because of varying reflectivity and because the range of the scattering volume is comparable to the pulse length. Above 5000 m the asymptote of range correction that is approached is due primarily to varying reflectivity. Once the corrected heights were calculated and provided by P. E. Johnston (2002, personal communication) in a lookup
table, L. M. Hartten (2002, personal communication) provided Fortran computer code that implemented the corrections for statistical purposes.

![Figure 5. Height correction used vs. original high mode height.](image)

**Gridding**

The original data obtained from the wind profiler were interpolated so all high and low mode data were on the same 100-meter vertical grid. This allowed the data to be compared statistically. The uncorrected data were interpolated using a cubic spline interpolation. The corrected data were interpolated using a linear interpolation because the corrected heights were not evenly spaced, a necessary condition for implementing the available cubic spline routine. Development of a cubic spline routine that works with unequally spaced data is still in progress. The Fortran code used for the gridding was provided by C. H. Love and L. M. Hartten (2002, personal communication). The routine read the original wind profiler wind heights and interpolated them onto the uniform vertical grid. Then, the original and interpolated results were sent to an output file for later use.

**Statistical analysis**

Statistical analysis was based on the 10-day mean and standard deviation of wind speed and direction for each of the eight cases for the low mode, the uncorrected high mode, and the corrected high mode. At each height, the time-mean zonal and meridional wind components were computed, together with their standard deviations. Also, the vector-mean speed and direction were calculated from the 10-day mean components. The number of observations available at each height was also documented.

Next, the mean and standard deviation difference statistics between the low mode and uncorrected high mode, and the low mode and corrected high mode were computed for all eight cases. At each height, the mean difference and absolute difference between the high and low mode wind components were calculated, as were their standard deviations. The mean and absolute differences between the high and low mode speed and direction were also corrected, together with their standard deviations. The number of observations available at each height was also documented.
RESULTS AND DISCUSSION

Many plots were obtained and analyzed for the uncorrected and corrected high modes and low mode. Focus was placed on the average speed and direction plots to obtain a qualitative description of the effects of applying the more general radar equation. Mean absolute difference plots were used to obtain a quantitative description of the height correction's effect.

Average wind and absolute difference profiles: Uncorrected high mode vs. low mode

During the Normal cases of December 1994, March 1995, June 1995, and August 1995 (Figures 6-9), there are discrepancies between the high and low mode average wind speed and direction profiles. There is a difference of 500 to 750 m between the high and low mode profiles for all of the cases, with the exception of March 1995. The wind speed minima for all cases occurs between 1000 m (low mode) and 2000 m (high mode). The wind directional change from low-level southerlies to upper-level easterlies occurs between 1000 m (low mode) and 2000 m (high mode) for all cases except March 1995. In the March 1995 case, the high and low mode profiles look very similar to each other because of warm sea surface temperatures. Speeds are nearly constant with height, and the winds change only slightly, from northeasterlies to southeasterlies aloft. The variability seen in all normal cases in the heights of wind speed minima and direction shifts reflect the annual cycle of the wind profiles. During the austral winter the low-level jet and wind speed minimum are lower in altitude and during the austral summer the features are higher in altitude (Hartten and Gage, 2000)

The mean absolute difference speed and direction plots for all cases show the largest differences between modes at heights between 750 m and 2000 m (Figures 6-9). In March 1995 the differences are smallest, increasing through August 1995. Below 750 m and above 2000 m, the differences taper off.

Figure 6. December 1994 (Normal) wind speed, direction, and absolute difference profiles obtained from a 915-MHz wind profiler. Blue lines represent the low mode, green lines the uncorrected high mode, and solid black lines the absolute difference. A direction of 0° indicates a northerly wind, 90° indicates an easterly wind, etc.
Figure 7. March 1995 (Normal) wind speed, direction, and absolute difference profiles obtained from a 915-MHz wind profiler. Blue lines represent the low mode, green lines the uncorrected high mode, and solid black lines the absolute difference.

Figure 8. June 1995 (Normal) wind speed, direction, and absolute difference profiles obtained from a 915-MHz wind profiler. Blue lines represent the low mode, green lines the uncorrected high mode, and solid black lines the absolute difference.
Figure 9. August 1995 (Normal) wind speed, direction, and absolute difference profiles obtained from a 915-MHz wind profiler. Blue lines represent the low mode, green lines the uncorrected high mode, and solid black lines the absolute difference.

El Niño

During the El Niño period of January 1998 (Figure 10), the average high mode wind speed and direction profiles look very much like those of the low mode. There is little discrepancy between the high and low mode profiles. The January 1998 speed and direction profiles look very much like the March 1995 profiles due to similar warm conditions associated with the austral summer. During the El Niño period of July 1997 (Figure 11), there is a large ~300 m discrepancy between the high and low mode average wind speed and direction profiles (Figure 10). The wind speed minimum and direction shift occur at lower altitudes during the January 1998 case. Both modes’ wind directions change from northeasterly to southeasterly at about 1500 m.

The mean absolute differences in speed and direction for January 1998 (Figure 10) are quite small due to the annual cycle. The quantitative differences for July 1997 (Figure 11) are much greater than those of January 1998 because high and low mode profiles are much more different in the winter. The maximum speed and direction differences for the January 1998 and July 1997 cases are about 0.75 m s⁻¹ and 25°, and 2 m s⁻¹ and 50°, respectively.
Figure 10. January 1998 (El Niño) wind speed, direction, and absolute difference profiles obtained from a 915-MHz wind profiler. Blue lines represent the low mode, green lines the uncorrected high mode, and solid black lines the absolute difference.

Figure 11. July 1997 (El Niño) wind speed, direction, and absolute difference profiles obtained from a 915-MHz wind profiler. Blue lines represent the low mode, green lines the uncorrected high mode, and solid black lines the absolute difference.

La Niña

During the La Niña periods of December 1996 (Figure 12) and July 1999 (Figure 13), there is again much discrepancy between the high and low mode average wind speed and direction profiles. The wind speed minima occur between 1000 and 1500 m. The directional changes from southeasterly to easterly also occur between 1000 and 1500 m. The profiles look
like those of a normal austral summer: they are composed of lower altitude minima and directional changes.

The mean absolute differences in speed and direction for December 1996 (Figure 12) are smaller due to the warm season’s characteristics. The differences between modes for July 1999 (Figure 13) are much greater than those of December 1996 because high and low mode profiles are more similar in the summer. In December 1996, the largest differences of about 1.5 m s\(^{-1}\) and 30° occur between 1000 and 1500 m. In July 1999, the largest differences of about 1.5 m s\(^{-1}\) and 70° occur between 1000 and 2000 m.

![Figure 12. December 1996 (La Niña) wind speed, direction, and absolute difference profiles obtained from a 915-MHz wind profiler. Blue lines represent the low mode, green lines the uncorrected high mode, and solid black lines the absolute difference.](image)

![Figure 13. July 1999 (La Niña) wind speed, direction, and absolute difference profiles obtained from a 915-MHz wind profiler. Blue lines represent the low mode, green lines the uncorrected high mode, and solid black lines the absolute difference.](image)
**Average wind and absolute difference profiles: Corrected high mode vs. low mode**

**Normal**

In all normal cases (Figures 14-17), the corrected high mode average wind and direction profiles better approximate those of the low mode at heights greater than 750 m. The discrepancies between the wind speed minima and directional changes are now approximately 300 m, which is reduced from the earlier value of 400 m.

The absolute difference profiles (Figures 14-17) give a quantitative description of the height correction effects. It is again evident that the discrepancies are reduced between the high and low modes. In all cases, one observes a decrease in the largest differences occurring between 1000 and 2000 m. An increase in differences occurred at altitudes less than 750 m.

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**Figure 14.** December 1994 (Normal) wind speed, direction, and absolute difference profiles obtained from a 915-MHz wind profiler. Blue lines represent the low mode, red lines the corrected high mode, and dashed black lines the absolute difference.
Figure 15. March 1995 (Normal) wind speed, direction, and absolute difference profiles obtained from a 915-MHz wind profiler. Blue lines represent the low mode, red lines the corrected high mode, and dashed black lines the absolute difference.

Figure 16. June 1995 (Normal) wind speed, direction, and absolute difference profiles obtained from a 915-MHz wind profiler. Blue lines represent the low mode, red lines the corrected high mode, and dashed black lines the absolute difference.
Figure 17. August 1995 (Normal) wind speed, direction, and absolute difference profiles obtained from a 915-MHz wind profiler. Blue lines represent the low mode, red lines the corrected high mode, and dashed black lines the absolute difference.

El Niño

In both El Niño cases (Figures 18-19), the discrepancies are again reduced at heights greater than 750 m. This improvement is especially evident between 1000 and 2000 m for both cases. However, it should be noted that the original January 1998 modes were already very similar and did not have much room for improvement. The wind speed minima and direction differences are lessened from ~300 m to ~250 m.

The absolute difference profiles (Figures 18-19) show quantitatively that the height correction is valid for the El Niño cases, again at heights above 750 m. Also, note the substantial improvement in wind speeds above 750 m for July 1997.
Figure 18. January 1998 (El Niño) wind speed, direction, and absolute difference profiles obtained from a 915-MHz wind profiler. Blue lines represent the low mode, red lines the corrected high mode, and dashed black lines the absolute difference.

Figure 19. July 1997 (El Niño) wind speed, direction, and absolute difference profiles obtained from a 915-MHz wind profiler. Blue lines represent the low mode, red lines the corrected high mode, and dashed black lines the absolute difference.

La Niña

In both La Niña cases (Figures 20-21), the discrepancies between the high and low mode speed and direction profiles are again reduced at heights greater than 750 m. The wind speed minima and direction differences are lessened from ~300 m to ~150 m.

The absolute difference profiles (Figures 20-21) again show that the height correction is valid for La Niña cases. Both cases have an overall decrease in speed and direction differences between 1000 and 2000 m.
Figure 20. December 1996 (La Niña) wind speed, direction, and absolute difference profiles obtained from a 915-MHz wind profiler. Blue lines represent the low mode, red lines the corrected high mode, and dashed black lines the absolute difference.

Figure 21. July 1999 (La Niña) wind speed, direction, and absolute difference profiles obtained from a 915-MHz wind profiler. Blue lines represent the low mode, red lines the corrected high mode, and dashed black lines the absolute difference.
Summary

Figure 22 shows the effect of the height corrections on the discrepancies between high and low mode profiles for all cases. The mean absolute differences in speed and direction were averaged at heights above 750 m (the region where the corrections were effective). This method allowed us to obtain an average difference for each case between the original high and low modes and the corrected high and low modes. Note that the corrected high mode differences are lower in all cases. Calculating the statistical significance of these differences remains a topic for future work.
Figure 22. Mean speed and direction absolute differences for all cases between high and low modes at altitudes > 750 m.
CONCLUSION

Applying a more general radar equation and its corresponding high mode height reassignments reduces the discrepancies between the high and low mode wind speed and direction profiles for all cases. The results indicate that the equation could be applied during different atmospheric conditions. The height corrections are most effective for altitudes greater than 750 m and when the uncorrected high and low mode profiles are not already very similar. The height correction does not work below 750 m because instrument limitations prevent effective gathering of high mode data (P. E. Johnston, personal communication). Below 750 m, researchers should use only low mode data, because they are integrated over a shorter atmospheric volume than the high mode. Furthermore, there are many low-mode observations available at heights less than 750 m.

Further research is necessary to calculate the statistical significance of the reduction in profile discrepancies to give a better idea of how well the differences were decreased. Also, the more general equation’s applicability during other Galápagos time periods as well as at other sites around the world needs to be explored.

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REFERENCES


