Wind and Gravity Wave Observations with ERWIN-II

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Introduction
The E-Region Wind Interferometer (ERWIN-II) is a Michelson interferometer that measures the mesospheric wind (~90 km) by determining the Doppler shift of airglow emissions. Airglow is the emission of light as a result of chemiluminescence; the airglow emissions of interest to us are the green line (557.7 nm) at a height of ~97 km, O₂ (866.0 nm) at a height of ~94 km, and the OH (843.0 nm) at a height of ~87 km emissions.

ERWIN-II measures five directions simultaneously (north, south, east, west, and zenith) through the use of a quad mirror; this results in an observation cadence of approximately 3 minutes for observations of all three emissions in all five directions. ERWIN-II is currently located at the PEARL observatory in Eureka, Nu.

Wind Calculations
The line of sight winds are determined by converting the interferogram phase to a wind using

\[ \Delta u = \frac{c \phi}{2 \pi \Delta \phi} \]

where \( \Delta \phi \) is the effective path difference of the Michelson interferometer, \( \phi \) is the wavenumber of the emission, and \( c \) is the speed of light. The vertical wind is simply equal to the LOS wind direction, and the horizontal winds, determined using the line of sight winds taken at an elevation of 38.7° (as shown in Figure 1), are

\[ u = \frac{\Delta OS \cos \alpha}{2 \cos \alpha} \quad \text{and} \quad \nu = \frac{\Delta OS}{2 \cos \alpha} \]

where \( \Delta OS \) is the difference in the vertical wavenumber of the emissions taken at the same elevation. The standard error for each wind measurement is ~1-2 m/s (as shown in Figure 2). The second data plotted on each graph (the red dots) are the errors as determined from the Schott noise and the visibility

\[ \sigma = \frac{c \lambda}{4 \pi \Delta \phi} \sqrt{\frac{I}{UV}} \]

where \( \lambda \) is the wavelength of the emission, \( I \) is the intensity, and \( UV \) is the product of instrumental and line visibilities, respectively.

Gravity Wave Theory
Gravity waves are perturbations of the atmosphere from the basic state. It can be assumed that these perturbations are simple harmonic motions:

\[ u' = u_0 e^{i\omega (t - \phi)} \]

where the prime denotes that this is a perturbation, \( u_0 \) is the amplitude of the perturbation parameter, \( \omega \) is the wave vector, \( \phi \) is the amplitude of the perturbation parameter, \( \omega \) is the angular frequency, \( t \) is the position, \( t \) is time, and \( \phi_0 \) is the phase offset.

Figure 4 shows a schematic of a gravity wave with the thin arrows being the wind direction, and the thick arrows are the direction of propagation of the phase fronts (which are orthogonal to wind direction).

Gravity Wave Analysis
Gravity waves are observed in the irradiance measurements, and isolated using a Butterworth filter (Figure 5). By determining the phase differences between the filtered irradiances of the three airglow layers, the vertical wavenumber of this wave is determined from the slope of the relative phases vs the relative layer heights (see Figure 6). This 10.3 cpd wave has a vertical wavelength of ~286.2 m⁻¹. By using a similar approach with the cardinal directions and zenith irradiances, the horizontal wavenumbers were determined to be:

\[ k = 4.49 \times 10^{-6} \text{ m}^{-1} \quad \text{and} \quad l = -7.19 \times 10^{-6} \text{ m}^{-1} \]

Therefore, this wave is propagating at an elevation of ~88° from the horizontal, and ~58° south of east.

Figure 7 is a filtered (10.3 cpd) all-sky image which shows the gravity wave present across the sky. The red arrow shows the direction of propagation determined using the ERWIN irradiances (~58°). This shows that the direction of propagation is orthogonal to the phase fronts, which is consistent with the gravity wave theory.

Conclusion
ERWIN is accurately observing polar mesospheric winds, with a precision of ~1-2 m/s. Gravity wave signatures have been observed using ERWIN, with results that are consistent with the theory. Comparisons of the vertical wind and zenith intensity show that these are correlated, with a phase shift of 90°, consistent with linear gravity wave theory.

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References

Figures:
Figure 1: ERWIN-II viewing geometry.
Figure 2: Plot of a) measured standard error and theoretical error, b) observed airglow intensity, and c) airglow visibility.
Figure 3: Plot of green line, O₂, and OH a) meridional and b) zonal winds.
Figure 4: Schematic of a latitudinal cross-section of a gravity wave. The thin arrows denote the wind direction, thick arrows show the direction of propagation, the lines denote warm and cold fronts, and the shaded areas are regions of high pressure.
Figure 5: Filtered (using a Butterworth filter) zenith irradiance of the green line (blue), O₂ (red), and OH (black) airglow emissions.
Figure 6: a) and b) are the cross-correlations between green line and O₂ airglow irradiances, and green line and OH airglow irradiances, respectively. C) is the plot of the phase relative to the green line irradiance with respect to the nominal airglow layer heights. The slope of c) (2.86e-2 m⁻¹) is the vertical wavenumber.
Figure 7: Filter all-sky image to extract the 10.3 cpd gravity wave signature. The black arrows denote the orientation of the image, and the red arrow shows the direction of the horizontal wave vector, which is orthogonal to the phase fronts.
Figure 8: Plot of the vertical wind (positive is downward motion) and the zenith irradiance for the green line the raw data and Figure 9 shows the data filtered with a Butterworth filter. Since the irradiance is related to the height (lower emission will result in higher intensity), these plots, to a first approximation, show a comparison between the velocity of the airglow layer, and its height. From this plot, it is observed that there is a 90 degree phase shift for many of the peaks, such that a downward vertical wind is followed by a decrease in the height (increase in the irradiance) of the emission.
Figure 9: Plots of the Butterworth filtered vertical wind (blue) and zenith irradiance (green) line airglow emission: a) 5.5 cpd, b) 10.8 cpd, c) 13 cpd, and d) 23.5 cpd. The lowest three frequencies show a n/2 phase shift between the vertical wind and the zenith irradiance which is consistent with the expected results due to linear gravity wave theory.