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Height measurements of OI(557.7 nm) gravity wave structure over the Hawaiian Islands during ALOHA-93

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Abstract. During the ALOHA-93 campaign simultaneous observations of gravity wave structure in the OI(557.7 nm) nightglow emission were made using two all-sky CCD imagers; one located near the summit of Haleakala Crater, Maui and the other at Mauna Loa Observatory, Hawaii. On 19 October a set of bright, planar, monochromatic waves was imaged by both systems as it progressed rapidly over the Hawaiian Islands. Triangulation on these wave forms indicates a mean altitude of 95 ± 2 km in good agreement with previous rocket soundings at mid-latitudes. Two methods of triangulation were employed, both achieving similar results.

Introduction

Since the early photographic observations of noctilucent clouds (NLC) by Jesse [1896] and "ionospheric structure" by Götz [1948] triangulation techniques have been used on a number of occasions to help identify atmospheric phenomena by determining the altitudes at which they originate. In particular, height measurements were essential for associating structure photographed in the near infrared (NIR) night sky emission [Peterson and Kieffaber, 1973] with the OH Meinel band emissions, which originate from a layer in the upper mesosphere at ~87 km altitude. These measurements were made using basic triangulation methods applied to pairs of long exposure photographs (5-15 min) taken from two widely separated sites (~65 km). More recently height measurements of the visible and NIR wavelength nightglow emissions have been made from satellites such as the Upper Atmosphere Research Satellite (UARS) using limb scanning techniques to investigate height variability on a global scale. However, these observations are insensitive to local height changes (due to the large path length of the limb measurements) and cannot be used to investigate the effects of short period gravity waves on the nightglow emissions.

Taylor et al., [1984] have developed a technique for determining the height of NLC bands and billows to an accuracy of typically ±2 km and have applied this method to measurements of faint wave structure imaged in the NIR OH emission [Taylor, 1986]. However, height determinations of structure in the visible wavelength nightglow emissions are extremely rare.

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During the ALOHA-93 campaign the opportunity arose to make a unique two station study of gravity waves imaged in the lower thermospheric OI(557.7 nm) nightglow emission using sensitive CCD cameras located on the islands of Maui and Hawaii. In this letter we describe height measurements of a single well-defined gravity wave event imaged on 19 October.

Observations

During the ALOHA-93 campaign two all-sky (180°) CCD imagers were operated from high altitude sites at Haleakala Crater, Maui (20.8°N, 156.2 W, 2970m) (Utah State University) and at Mauna Loa Observatory (19.5°N, 155.6°W, 3040m) (Lockheed Research Labs). The base line for these measurements was ~150 km and the azimuth from Haleakala ~152°N. A short description of each camera system is given in Taylor et al. [1995a] and in Swenson and Mende [1994]. The Lockheed System was filtered to image structure in the OI(557.7 nm) emission using an integration time of 60s and a cycle time of ~3 min. The image format was 341x341 pixels. The Utah State University System recorded structure sequentially in NIR OH and O_2 (0,1) At bands and visible wavelength OI(557.7 nm) and Na(589.2 nm) line emissions with a cycle time of 4-5 min for the OI and ~9 min for the other emissions. The integration time for the OI data was 90s and the image format was 512x512 pixels. Joint observations were made during the new moon period 6-23 October and several distinct wave displays were identified in both data sets suitable for height analysis. For these measurements we have chosen an unusual morphology wave display that progressed rapidly over Maui and then over the Big Island of Hawaii on a SSW heading.

19 October Wave Event

On this night a well-defined, monochromatic wave display, consisting of 3-4 wave crests with a prominent leading edge was detected by both instruments. This disturbance was first registered by the Haleakala imager around 08:30 UT at low elevation to the NNE appearing as an elongated band in all four nightglow emissions. By 09:00 UT the disturbance was resolved into a limited set of 3-4 planar waves extending from high elevations in the W down to the limits of the camera field in the E. This pattern passed through the zenith at Haleakala at ~09:10 UT and was overhead at Mauna Loa by 09:40 UT. Figure 1 shows three pairs of OI(557.7 nm) images illustrating this wave pattern as recorded at each station during the period 09:08 to 09:45 UT. In the first image pair the wave front is quite distinct and appears

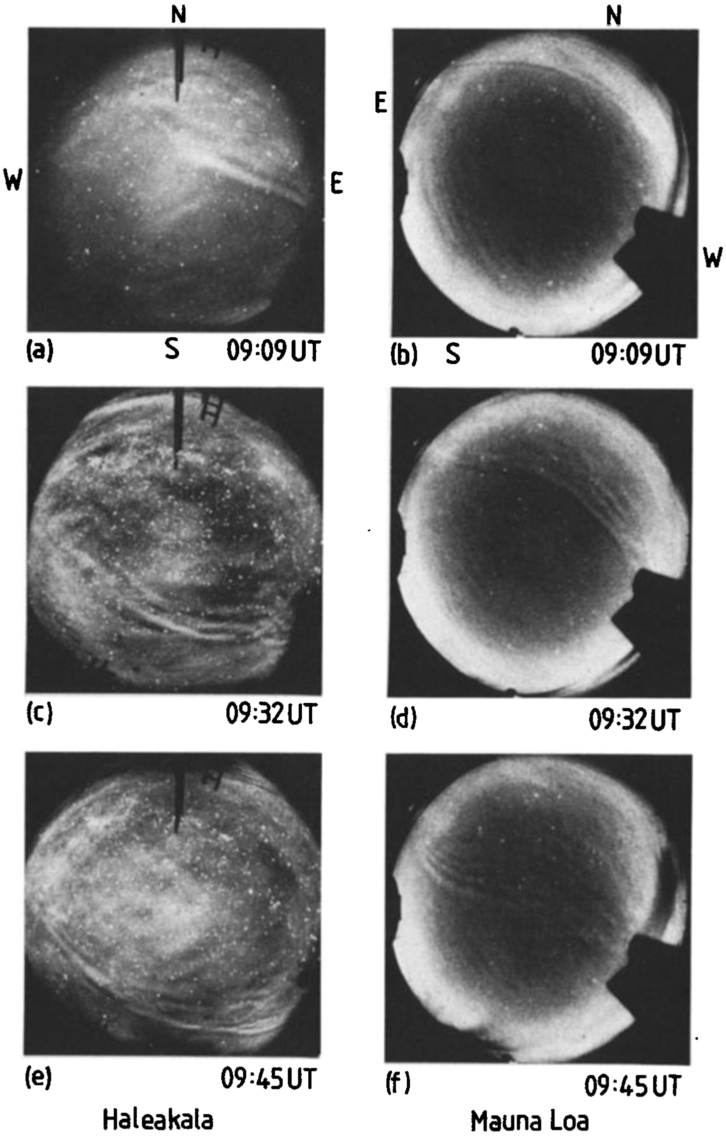

Figure 1. Three pairs of OI (557.7 nm) images recorded from Haleakala and Mauna Loa showing the transit of the wave pattern over the Hawaiian Islands during the interval 09:00-09:45 UT on 19 October, 1993.

planar. In the second pair the Haleakala data show a "kink" in the wave field at low elevation to the E. This appears as a distortion in the wave front of the Mauna Loa data which was better situated to observe this phenomena. In the final image pair the distortion is well developed appearing as an inflection in the wave field as it transited over the Mauna Loa site. This unusual wave morphology was also detected in the Na, O_2 and OH nightglow emissions recorded by the Haleakala imager indicating that the wave field was distorted throughout the 80-100 km region. Further examples of these data in the NIR OH and Na emissions are given in Taylor et al., [1995b].

Measurements of this wave event using both OI data sets reveal a horizontal wavelength of ~14 km and a horizontal phase speed of ~60 ms^{-1} (at an azimuth of ~200°N) indicating a very short apparent wave period of ~4 min. The disturbance was observed for over three hours as it progressed towards the SSW and showed no obvious signs of dissipation as it exited the Mauna Loa field of view. This display was superimposed on a prevailing southward wave motion that was evident for several hours in the Mauna Loa data (from 04:30 to 13:00 UT).

Height Measurements

Two techniques have been used to estimate the height of the wave structure imaged in the OI emission.

Azimuth Scan Map

Figure 2 shows three projections of the OI emission signal recorded by each imager in the plane defined by the two stations. The star field was used to calibrate the number of degrees per pixel, the aspect angles of both images and their central pixels. The Mauna Loa image (341x341 pixels) was then processed and expanded to pixel match the angular resolution of the Haleakala image (512x512 pixels). The zenith and azimuth of each pixel was then found and the signal versus zenith angle extrapolated for each image along the baseline connecting the two sites. This signal was then projected onto a surface defined by a plane between the two sites and the center of the earth for an assumed altitude 'H' of the emission. Spherical geometry was used with no correction for the viewing angle through the layer. Each plot in Figure 2 shows signal

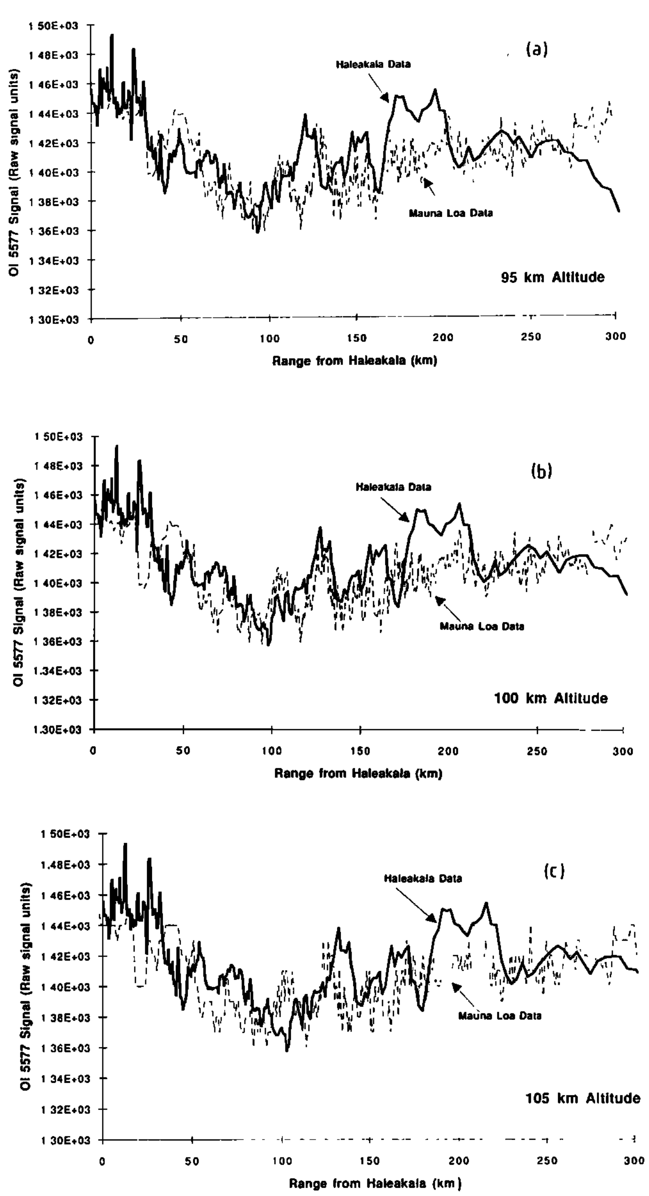

Figure 2. OI (557.7 nm) signal intensity versus range for the 09:45 UT image pair for projections on a radial surface of (a) 95 km, (b) 100 km and (c) 105 km altitude in a plane defined by the two stations and center of the earth.

intensity corrected in this manner as a function of range from Haleakala. By varying H the relative positions of prominent features in these traces can be compared for best visual fit. In this case the last image pair of Figure 1 (09:45 UT) were used and the best fit was found to be ~95 km except for the wave crest at ~135 km range which exhibits a best fit near 100 km.

Surface Projection

This technique is very well suited for height measurements of faint features in the nightglow emissions [Taylor, 1986]. Unlike triangulation on a single point this method utilizes the two-dimensional morphology of the features present in each image to determine a best fit height of many points and can be used to investigate height differences across the field of view [Gadsden and Taylor, 1994]. For the all-sky data available here, the method has been modified to determine height by the following iterative process. After first calibrating each image with respect to the star background an array of points delineating the waves as they appeared in Figure 1 from the Haleakala site was generated and converted into geographical coordinates assuming an emission height 'H' for the OI structure. The same process was then repeated for the image data as recorded at the Mauna Loa site to determine a second ground map of the wave forms for the same assumed height. Comparison of the maps for different altitudes (incremented in 1 km steps over the range 90-105 km in this case) was then used to visually determine a best fit to the two data sets. Due to the relatively high elevation of these measurements (>15°) the effects of refraction were minimal and have been ignored [Gadsden and Taylor, 1994].

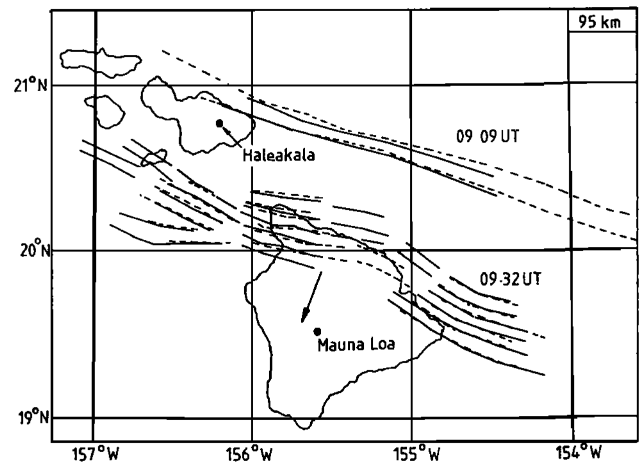

Figure 3. Composite ground map showing the relative locations of the most prominent OI wave forms present in the first (09:09 UT) and second (09:32 UT) image pairs of Figure 1. The solid lines delineate the waves as imaged at Haleakala and the dashed lines their positions as determined from the Mauna Loa data for an assumed height of 95 km.

Figure 3 shows a composite ground map for the two first two image pairs of Figure 1. The waves are plotted assuming a height of 95 km. For the 09:09 UT data only the distinct leading edge was traced. At this altitude the fit to these data was very good along the entire length of the wave form. In the 09:32 UT data parts of several wave crests are plotted. The "kink" in the Haleakala data proved difficult to map accurately (probably due to line of sight effects) but the fit to the rest of the data was clearly very good. Maps plotted at 1 km intervals (not shown) confirm this result indicating that 95 km was the best fit esti-

Table 1. Mean times of coincident data for height measurements and the time difference between each image pair.

Haleakala	Mauna Loa	Δt (s)
08:59:23	08:58:34	49
09:08:22	09:08:28	6*
09:17:21	09:18:22	59
09:22:30	09:21:41	49
09:31:29	09:31:34	5*
09:35:20	09:34:52	28
09:40:29	09:41:28	59
09:44:19	09:44:46	27*

* Mapped

mate of the structure height for this period. These image pairs were chosen as the mean time difference between them was only a few seconds thereby offering the best opportunity for accurate measurements. Table 1 lists several other potential image pairs that may be used for further analysis of the wave height. These observations are in good agreement with the estimated height determined using the scan map technique (where the time difference was significant, ~27s) and show that on this occasion the OI(557.7 nm) layer was in close proximity to its mean level of ~96 km, as determined from numerous rocket soundings, primarily at mid-latitudes.

Discussion

This display represents only one of many wave motions recorded during the ALOHA-93 campaign. These will be analyzed to investigate altitude changes during the course of the campaign and to search for significant height variations in the wave structure that may exist across the all-sky field (~900 km diameter). The unusual shape of this wave pattern and its clarity were particularly useful for identifying the same feature in both images. The main errors associated with the height determination can be attributed to the finite integration time employed by the imagers (60-90s) and the timing difference between the two data sets, which were not synchronized for this study. These uncertainties are amplified in this case by the relatively fast horizontal phase motion (~60 ms^{-1}) resulting in an error in geographic position of about 2 km for the first two image pairs of Figure 1 and ~3.5 km for the last image pair (used in the scan map analysis). This compares with a horizontal displacement of ~2-6 km determined by varying the layer height from 93 to 97 km (using the surface analysis method). Thus, the mean height of the wave structure on this night was determined to be 95 ± 2 km.

The limited number of wave crests (3-4) and the very short observed wave period of ~4 min (close to the local Brunt-Väisälä period) exemplifies the unusual nature of this wave display [Taylor et al., 1995a]. The vertical coherence and rapid motion of this event is suggestive of a ducted rather than freely propagating gravity wave motion. This is significant as ducted waves may propagate considerable distances from the source region before they deposit their energy into the background medium, whereas, freely propagating short-period gravity waves of tropospheric origin are expected to travel only limited distances (depending upon the prevailing background winds) before they achieve mesospheric heights.

Unfortunately, there are insufficient data available for height measurements of the other nightglow emissions during this night. Observations from the UARS satellite were not made during most of the campaign. However, measurements of the O_2 emission (which is expected to occur in close proximity to the OI layer, but at a slightly lower altitude) were obtained on 26 October and indicate a height variation with latitude ranging from ~90 km at 20°S to ~96 km at 5-15°N [Wiens et al., 1995]. These authors also emphasize considerable height variability with time possibly due to tides. Thus our estimate of 95 km for the OI(557.7 nm) over the Hawaiian Islands appears to be in good agreement with the satellite observations.

Summary

These observations demonstrate the capability of high quality image data for accurate height measurements and provide a good benchmark for the OI(557.7 nm) measurements during the ALOHA-93 campaign. This result also provides a useful reference height for the other nightglow emissions which are expected to occur in close proximity to the OI layer but at lower altitudes. This work highlights the need for further, more detailed, height studies to quantify the altitudinal relationship between the nightglow emission layers and to investigate their variability. For example, using simultaneous height measurements of more than one nightglow emission it would be possible to interpret, with good confidence, the phase relationship between the wave motions at different altitudes and hence to investigate their propagation characteristics in exceptional detail.

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