

A vertical parallax technique for determining the peak altitude of the radiowave absorption layer using imaging riometers

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Abstract. The riometry technique of observing rapid variations in the level of absorption of cosmic radio noise as a proxy for ionospheric density fluctuations, is limited by its inability to directly determine the altitude at which the radiowave absorption occurs. We describe here a technique based on the simple vertical parallax principle, which enables direct measurements of this altitude to be made. The technique utilises the overlapping beams of two closely spaced imaging riometers in Antarctica. In this paper, peak absorption heights are presented for all suitable absorption events over a three month period. The altitude determination of both a 'classical' absorption event occurring in the D-region as well as one occurring in the F-region near 200km altitude are presented in more detail. The identification of an F-region event using the parallax technique confirms earlier findings that radiowave absorption in the F-region is a potentially significant contributor to the Cosmic Noise Absorption (CNA) measured by riometers. Finally, an event with multiple absorption enhancements is studied showing a significant variation in peak absorption altitude over short time scales closely correlated to the amplitude of the observed absorption. This new technique enables a simple and repeatable ground-based measurement of the peak altitude of the CNA layer.

Introduction

The absorption of cosmic radio noise in the ionosphere as measured by a riometer can result from a wide range of ionospheric and magnetospheric phenomena, and it is often difficult to distinguish between the 'type' of Cosmic Noise Absorption (CNA) event on an individual event basis.

From consideration of the characteristics of each type of absorption event it is clear that the diagnostic capabilities of riometers can be significantly improved by distinguishing between types of CNA on the basis of altitude. For example, it is well established that 'classical' D-region absorption due to energetic particle precipitation occurs near 90km altitude, absorption due to E-region heating processes near 120km (Stauning et al, 1984), and absorption due to dense F-region patches above ~ 180km (Rosenberg et al, 1993). Absorption altitudes have in the past been indirectly inferred from coordinated multi-instrument studies (eg Rosenberg et al, 1993; Stauning et al, 1994; Nishino et al, 1998). However a direct ground-based technique for determining absorption altitudes on an event basis has to date not been developed.

The development of the imaging riometer in 1988 (Detrick and Rosenberg, 1990) made possible the imaging of CNA over a wide area at ionospheric altitudes, compared to the single broad-beam measurements of earlier riometers. Due to their oblique beams however, interpretation of data from these instruments requires an assumption of the altitude at which the peak absorption layer occurs.

Riometry work to date has generally assumed that for discrete CNA events the absorption peak is located at 90km, following earlier modelling results (Penman et al, 1979; Osepian and Smirnova, 1997), ground-based observations (eg Hargreaves, 1980), and rocket experiments (Hargreaves, 1969; Friedrich and Torkar, 1983). With the unique proximal location of the Southern Hemisphere Imaging Riometer Experiment (SHIRE) at Davis, Antarctica, (74.61°S, 102.30°E magnetic) and the NIPR/STELab imaging riometer at Zhongshan, Antarctica (ZHS; 74.70°S, 98.60°E magnetic) only 109km away, we were able to employ simple vertical parallax principles to test the validity of this assumption.

The Vertical Parallax Technique

In the context of riometry, vertical parallax measurements involve the observation of a common absorption event by spaced riometers with beams inclined to intersect at the altitude of the event. The technique described here builds on this basic idea by employing the multiple inclined beams of two closely-spaced imaging riometers, intersecting at a wide range of altitudes to provide a more accurate determination of absorption altitude.

The method requires narrow, high-directivity beams for the best results (Hargreaves, 1969), for which the innermost beams of imaging riometers are ideal.

The time lag T , between observing an absorption event in a single beam of one imaging riometer, and the same event in an intersecting beam of the second imaging riometer, is given by

$$T = \left(\frac{H - Z}{Z} \right) \cdot \frac{L}{V} \quad (1)$$

where V is the component of event velocity in the direction of separation of the two instruments, H is the altitude of the event, Z is the altitude at which the two beams intersect, and L is the horizontal distance between the two imaging riometers.

This geometry is demonstrated in Figure 1 which shows three idealised absorption events (A, B and C), differentiated only by the relative altitude of the event with respect to the intersection altitude of the two beams. The relative responses of the two imaging riometer beams are also shown. Event A (C) which is below (above) the beam intersection altitude gives a negative (positive) time lag between the response of ZHS and SHIRE. Event B which occurs at the beam intersection altitude, registers coincidentally in the two beams.

Figure 1 shows only the case for one intersecting beam pair. However, between the SHIRE and ZHS instruments, there are ~ 100 intersecting beam combinations with a wide range of intersecting altitudes. This enables the generation of an altitude profile of time lag as the event moves across the two arrays. The time lag for each intersecting SHIRE-ZHS beam pair is determined by cross-correlation over the event interval, and the intersection altitude from the known azimuth and zenith angle of the two beams. From the time-lag/altitude profile, both the event altitude and the event velocity can be accurately determined by fitting a function of the form in equation (1).

The SHIRE and ZHS imaging riometers are uniquely placed to perform vertical parallax measurements. A ground-spacing of only 109km results in the overlap of a significant number of beams of the two instruments (Figure 2). The beams shown in Figure 2 are those that were used for the vertical parallax measurements. The more oblique edge beams of both SHIRE and ZHS (omitted from the figure) have larger solid angles and, in the case of ZHS, derive a considerable fraction of their total power from side lobes making them unsuitable for parallax studies of this kind. This includes all edge beams of ZHS and twelve corner beams of SHIRE. Beam intersections between the two instruments are distributed over a range of altitudes from ~ 40 km to ~ 400 km, peaking between 80 and 90km. ZHS is situated to the invariant west of SHIRE.

Observations and Results

We now consider results for two illustrative riometer absorption events, followed by the statistical distribution of a sample of events.

Example CNA Events

The first event presented is a classical absorption event that occurred at 0725UT (0935MLT) on 02 May 1998. Vertical parallax measurements (Figure 3) establish it was associated with an absorption layer at 96km. The second is an absorption event that occurred at 2251UT (2026 MLT) on 11 April 1998, associated with an absorption layer at 194km (Figure 4). Both figures show the individual beam pair cross-correlations (marked by '+' signs), and the fitted curve (solid line) of the form (1) from which the unknown parameters, altitude and E-W velocity, were calculated.

Although the event altitude can be determined from Figures 3 and 4 by the point at which the observed time-lag equals zero (i.e. event coincidental in both SHIRE and ZHS beams), a more accurate method is to use an iterative function fitting routine to fit a function of the form (1) from which the unknown parameters can be determined. The function fitting routine uses a gradient-expansion algorithm to iteratively compute a non-linear least squares fit to the function. Only those beam-pair cross correlations with a correlation coefficient above 0.8 were used when fitting the model curve. The correlation coefficients for each beam pair were used as weightings for the least-squares fit to favour those beam pairs with a good correlation.

For confirmation of the above results, data from the two instruments in the form of spatially interpolated images were overlaid at a range of assumed altitudes. Figure 5 shows the results of the projection of absorption data to 90km (LH panel) and 194km (RH panel) for the event in Figure 4. The open and filled contours represent SHIRE and ZHS data, respectively. The approximate fields of view of the two instruments are depicted by dashed lines. The overlaid data clearly has a better match when projected to 194km, qualitatively supporting the parallax altitude determination.

Statistical Absorption Altitude

For the statistical study, 70 discrete absorption events were identified in SHIRE data on days when useable data were available from both instruments. Coincident data covered the period 25 March to 30 June 1998. Of these, 33 events produced an unambiguous result when calculating absorption altitude using the parallax technique. The reduced number is a consequence of the requirement of the parallax technique for roughly linear motion of the event across the two arrays, and an east-west component of motion in the range of ~ 0.1 -10 km/s. This is related to the east-west separation of the two instruments where the event must transit first one array and then the other in order to create a measurable time lag between the two instruments.

The right hand panel of Figure 6 shows a frequency histogram of the altitude at which the 33 absorption events occurred. The data are binned into 3km bins with a cut-off at 120km. Only one event was observed to occur above 120km (see Figures 4 and 5). The distribution has a peak in the range 87 - 90km. However, an interesting feature is the skew of the distribution toward higher altitudes, resulting in a median altitude of 92.5km.

The diurnal distribution of absorption altitude with local time (LT) is shown in the left hand panel of Figure 6. The events occurred primarily around local magnetic midnight, with a few events just prior to local magnetic noon and none in the afternoon. The altitude at which the events occurred shows no obvious dependence on LT.

Variation of absorption altitude for multiple-peak absorption event

An absorption event with multiple enhancements was studied in detail using the parallax technique. The multiple enhancements over a short time scale provided a means of studying the altitude variation of an absorption event in response to changes in the particle precipitation spectrum, as distinct from changes in local ionospheric conditions. The event chosen for this study was a large absorption event that occurred at approximately solar noon at Davis (06:20–07:45 UT; 08:30–09:55 MLT) on the 2nd May, 1998 and consisted of a series of local absorption enhancements associated with a common disturbance. The event was related to a substorm on the nightside arising from a Sudden Commencement a few hours prior. Nine individual enhancements were identified in SHIRE imaging riometer data over the period of the event. These are labelled ‘a’ – ‘i’ in Figure 7 which shows the absorption amplitude as measured by the central beams of the SHIRE imaging riometer, as a function of time (lower trace). The absorption event has the form of a slowly varying base level of absorption with a series of stronger absorption peaks superimposed. Large negative deflections in the magnetometer H component (not shown) are coincident with each of the absorption enhancements suggesting strong azimuthal currents/conductivity enhancements associated with each event. Each enhancement in this event has a significant component of motion in the magnetic invariant west-east direction enabling use of the vertical parallax technique to determine the peak absorption altitude of each enhancement. The results are also shown in Figure 7 (upper trace with error bars). The figure shows the variation of the altitude of the absorption layer over the sequence of nine absorption enhancements, in relation to the amplitude of the absorption event. Generally, the altitude of these enhancements is well above the median of all events in this study, with six out of the nine enhancements occurring above 100km. There is a significant variation of the altitude at which each enhancement occurred, strongly correlated to the amplitude of the event. Note the altitude scale (R.H axis) is reversed so that the higher altitudes are towards the bottom of the plot. This correlation suggests a hardening of the precipitation spectrum for the larger absorption events, resulting in precipitation to lower altitudes characterised by higher collision frequencies. The event appears to be an SVA-type absorption event resulting from the drizzle of trapped substorm electrons, with a superimposed modulated precipitation. IMF data (not shown) shows a modulation closely matching that of the precipitation suggesting the IMF played a role in modulating the superimposed precipitation.

Discussion

Statistical Absorption Altitude

The statistical results do not constitute a comprehensive survey of absorption altitude, as the vertical parallax technique requires a significant E-W component of motion. This may have resulted in the preselection of events favouring substorm-related precipitation travelling away from the midnight sector and auroral absorption events moving in a similar manner. All events occurred over a three-month interval between southern hemisphere autumn equinox and winter.

With the above caveats, the results do provide a number of points of interest. Firstly, they indicate a preference for cosmic radio wave absorption to peak in the altitude range 87–90km. This is consistent with previous observations and modelling (e.g. rocket based studies by Hargreaves, (1969); the modelling results of Penman et al (1979) and Osepian and Smirnova (1997); and the observational results of Hargreaves (1980) and Friedrich and Torkar (1983)). However, the surprising result is the number of absorption events peaking at higher altitudes. The median altitude of the distribution is 92.5km. There is a sharp cut-off in events below the peak in the distribution at 87–90km, resulting in less than 15% of events below 87km. However more than 50% of events peaked above 90km, indicating the peak of the absorption layer is often somewhat higher than is commonly assumed.

There was a clear relationship between the amplitude of absorption events and the altitude at which they occurred with the larger absorption events peaking lower in the ionosphere. The decreasing number of absorption events at higher altitudes may thus be related to the sensitivity of the imaging riometer with the highest altitude absorption events being too weak to register in the imaging riometer.

The distribution of absorption event altitudes with local time (Figure 6) is also subject to the caveats detailed above. The diurnal distribution of events studied reflects the average diurnal variation of CNA (Hargreaves, 1969) with the events mostly clustered around local magnetic midnight where substorm-related precipitation peaks. A few events were seen just before local magnetic noon, close to the local time corresponding to the statistical peak of energetic particle precipitation (Hardy et al., 1987). There was a distinct paucity of events studied in the local post-noon sector. The distribution of altitudes appears to show no significant variation with local time; however a wider diurnal coverage would be required to confirm this. This is consistent with the modelling results of Osepian and Smirnova (1997) which shows minimal diurnal variation of the altitude of the peak of the absorption layer, but a shift of the lower edge of the absorption layer to higher altitudes in the dark ionosphere.

F-region Cosmic Noise Absorption

The observations presented in Figures 4 and 5 corroborate previous reports that F-region CNA is observable with imaging riometers. Most commonly, CNA measured by riometers is attributed to regions of increased electron density in the ionospheric D and E regions. The contribution of the F region to the total absorption is assumed, in most cases, to be negligible due to the relatively low electron collision frequency of that layer. However, it has been suggested that under certain ionospheric conditions F region absorption due to an increase in electron-ion collisions may contribute significantly to total absorption (Ramanathan et al., 1961; Abdu et al., 1967). Rosenberg et al (1993), and

later Wang et al (1994) and Nishino et al (1998), observed absorption events which they attributed to F-region absorption through analysis of coincident data from Incoherent Scatter Radar and ionosondes. The present results support the premise of these observations with a direct quantitative measurement of the altitude of an F-region CNA event.

The F-region event presented here occurred on the poleward edge of the nightside auroral oval following a geomagnetic substorm enhancement. Consistent with the previous observations, the event occurred during a period of significantly enhanced f_0F_2 (~8.3 MHz) and low, relatively steady local f_{\min} (~1.6MHz), which indicates an enhanced F-region density and minimal low-altitude absorption throughout the duration of the event. In addition, photometer data (not shown) showed a high 630:427.8nm ratio, supporting the above observations.

Importantly, the F-region event presented here showed no morphological difference in imaging riometer data to 'classical' CNA events, and was large enough (0.6dB) to register on a co-located broadband riometer.

Conclusions

A technique has been developed which uses simple parallax principles applied to two closely spaced imaging riometers to measure the altitude of the peak of the Cosmic Noise Absorption layer. The vertical parallax technique enables a quick measurement of altitude of riometer absorption events on an event basis without the uncertainty of theoretical or semi-empirical models of ionospheric chemistry, or the coordination of multiple instrument data sets. Importantly, distinction can be made between CNA events occurring in the ionospheric D, E and F-regions, which are often the signatures of very different particle precipitation and/or acceleration mechanisms. The technique is restricted to ~50% of discrete absorption events since it requires the absorption event to have a discernable motion in the direction of separation of the two instruments.

The vertical parallax technique has been used to carry out a limited statistical study on the peak altitude of discrete absorption events at cusp latitudes. Comparable to previous estimates, the results showed a strong peak in the altitude range 87-90km. However there were also a significant number of events that peaked at higher altitudes, above 90km. An absorption event which occurred in the ionospheric F-region near 200km was identified using vertical parallax, supporting earlier studies reporting the observation of CNA events attributed to the F-region. Finally, an absorption event with multiple absorption enhancements was studied in detail using the parallax technique. This study showed a significant variation in the altitude of each absorption enhancement closely correlated to the absorption amplitude suggesting a hardening of the precipitation spectrum for larger absorption events.

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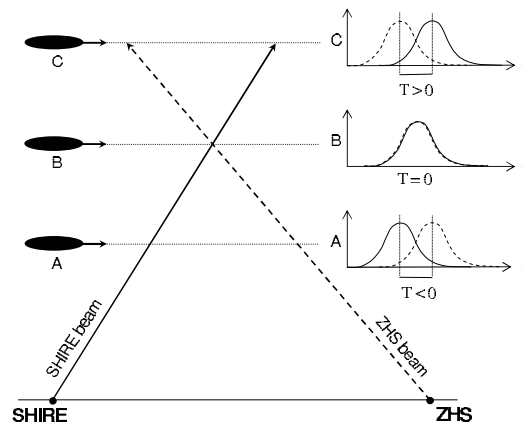


Figure 1. Schematic demonstrating the relative response of an individual SHIRE and ZHS beam to an absorption event passing over the two arrays (A) below; (B) at; and (C) above the beam intersection altitude.

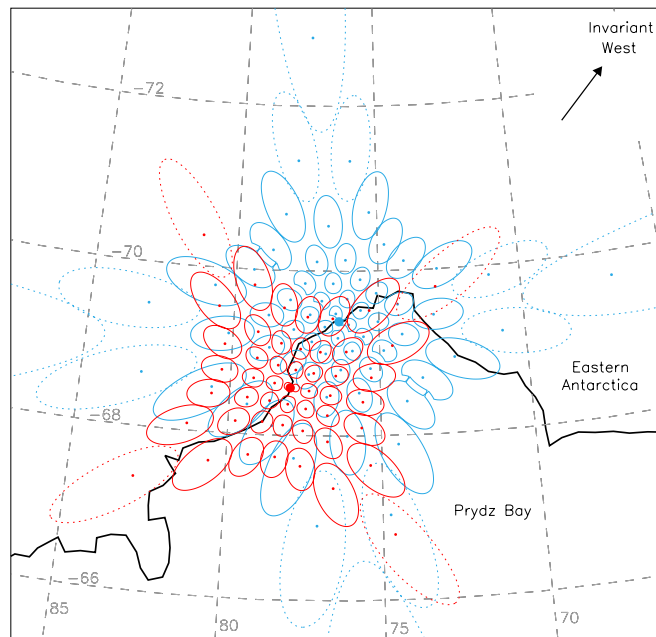


Figure 2. Projection of SHIRE (red contours) and ZHS (blue) beam patterns to the ionosphere at 90 km altitude. The contours represent the 3dB power level of the individual beams. Those beams used in vertical parallax measurements are depicted with solid lines. Coordinates are geographic (south to the top). Invariant west is also indicated. The Antarctic coastline (bold) is included for reference.

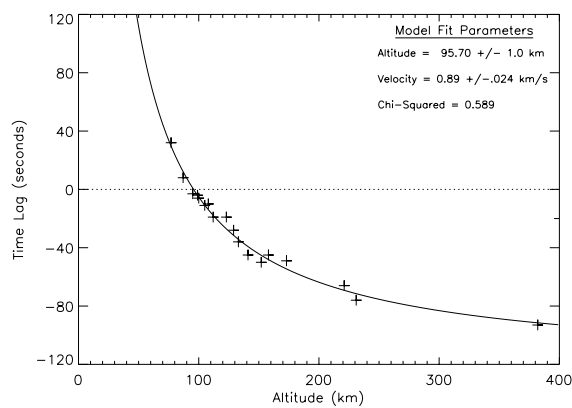


Figure 3. Parallax absorption altitude determination – D/lower E-region event. Fitted curve parameters: Altitude: 96km, Event velocity: 0.9km/s eastward

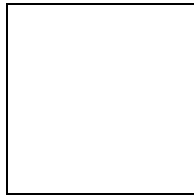


Figure 4. Parallax absorption altitude determination – F-region event. Fitted curve parameters: Altitude: 194km, Event velocity: 1.9km/s westward

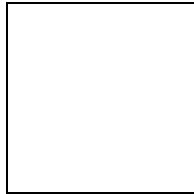


Figure 5. Overlay of imaging riometer data from SHIRE (open contours) and ZHS (filled contours) for the event in Fig 4 projected to both 90km (Left); and 194km (Right). The approximate fields of view of both instruments are dashed.

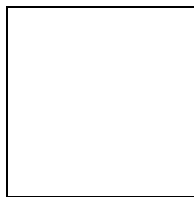
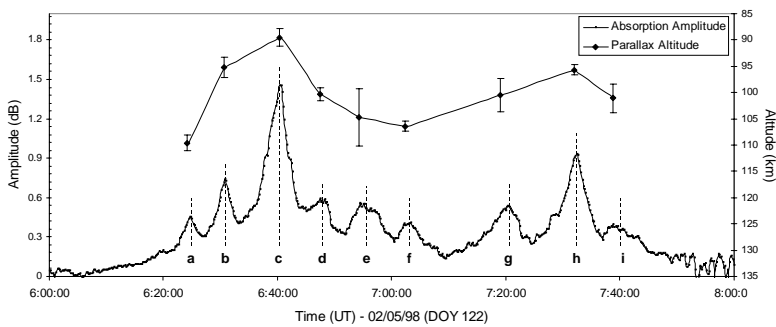


Figure 6. (Left) Variation of absorption event altitude with local time. Local solar noon is identified with a vertical line. Magnetic noon and midnight are identified with an open and closed triangle, respectively. **(Right)** Histogram of absorption event altitude (n=33, bin size=3km) from vertical parallax.



ms of the SHIRE array (lower curve) and the altitude of peak de scale on the right hand axis is reversed. The sequence of