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Intermittency on simultaneous observations of riometer at several Antarctic locations

E.M. Ovalle [a,*], A.J. Foppiano [a], M.V. Stepanova [b], A.T. Weatherwax [c]

[a] Departamento de Geofísica, Universidad de Concepción, Casilla 160-C, Concepción, Chile
[b] Departamento de Física, Universidad de Santiago de Chile, Av. Ecuador 3493, Santiago, Chile
[c] School of Science and Engineering, Merrimack College, North Andover, MA 01845, USA

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Abstract

It is well known that auroral radio wave absorption, as measured by riometers, consists of periods of relative quiescence which are interrupted by short bursts of activity. Such patterns in activity are observed in systems ranging from the stock market to turbulence, i.e. they exhibit intermittency. In the case of the auroral absorption it has also been found that intermittency strongly depends on the magnetic local time, being largest in the night-time sector. This can be interpreted as indicating that the precipitating particles responsible of the absorption exhibit intermittency, especially near the substorm eye, where the level of turbulence increases. Here, we analyse simultaneous observations of riometer absorption at seven Antarctic locations, to determine whether they exhibit intermittency. We determine the Probability Distribution Functions of the fluctuations of riometer absorption for absorption events larger than 0.1 dB, as well as those for the time-intervals between absorption events. Observations are for locations within the austral auroral absorption zone and on the polar cap. It is found that the parameters of a power law used to describe the calculated PDFs are consistent with the formation of coherent structures being more frequent within the auroral zone, as a manifestation of intermittency.
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Keywords: Intermittency; Riometer radio-wave absorption

1. Introduction

Intermittency in fluid turbulence can be shown through the analysis of Probability Distribution Functions (PDF) of velocity and density fluctuations (Sorriso-Valvo et al., 2001). In particular, the statistics of a series of values u can be characterised by the PDF's of the values differences $u_\tau = u(t+\tau) - u(t)$ for several time-scales τ (Frisch, 1995). In general, for a small τ, the PDF is approximately Gaussian, but, as τ increases, the wings of the distribution become increasingly stretched, so that large departures from the Gaussian distribution are evident. This is a statistical description.

On the other hand, from an experimental point of view, a phenomenon is said to present intermittency when in a time series the signal is amplified by short time periods, as with the appearance of gusts in a wind field. To illustrate this, a synthetic random series was built such that the deviations from the mean value produce a Gaussian PDF (Fig. 1, upper panel). Then, the series was modified, amplifying the signal at some intervals to emulate the presence of bursts. The new PDF is thus modified clearly showing stretched "wings" (Fig. 1, lower panel).

Therefore, the intermittency of a phenomenon can be described by the PDF analysis of the amplitude changes (bursts) of the time series of a given variable, or alternatively,

* Corresponding author. Tel.: +56 41 2203153/+56 41 220 4136.
E-mail address: eo@dgeo.udec.cl (E.M. Ovalle).

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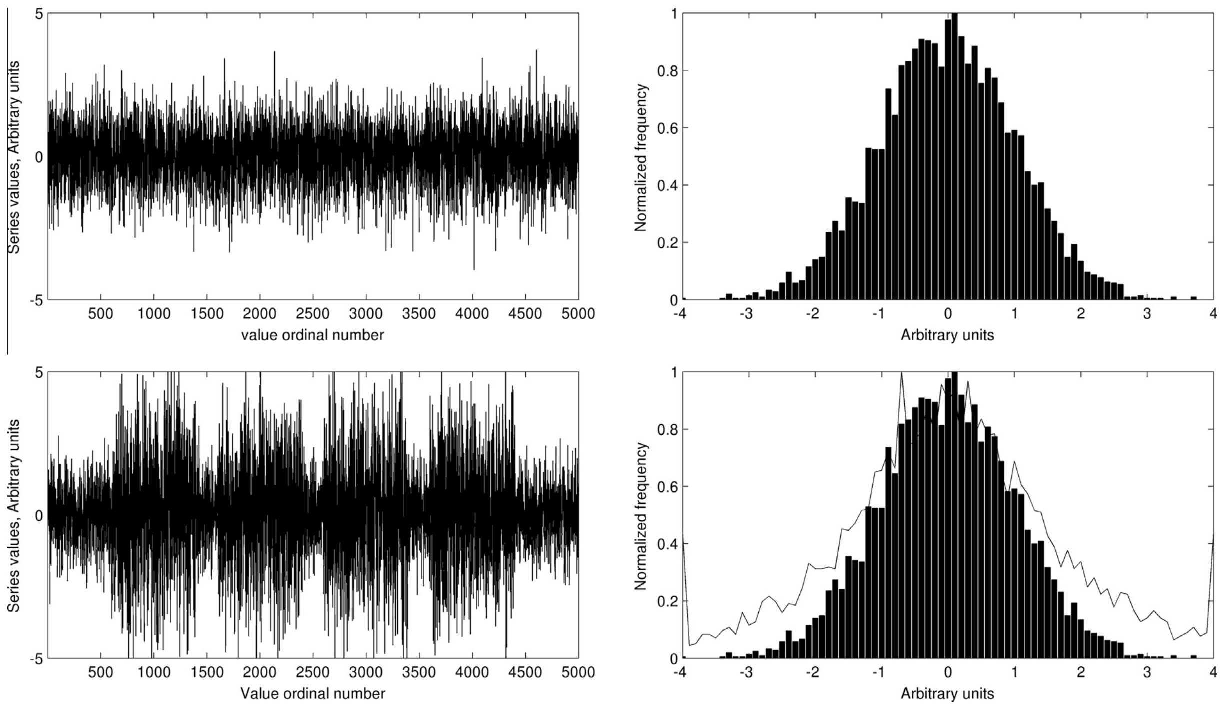

Fig. 1. Time series and their Probability Distribution Functions (PDF's). (top) Random synthetic series. (bottom) Modified random synthetic series by bursts like amplitude changes.

by the analysis of the time series of the intervals between bursts.

As our understanding of the space environment progresses, it increasingly becomes incontrovertibly evident that a tight coupling exists among various space plasma regions in the Sun–Earth system. Also, that the dynamic processes in these regions exhibit disturbances over a wide range of scales both in time and space. The relationship between the phenomenon of intermittency and the deviation from Gaussian PDF's is explained by Chang et al. (2006). In his words, complex dynamical systems exhibit global nonlinear stochastic behaviour due to the strong nonlinear interaction between formed coherent structures having a multitude of different scale sizes. Thus, their behaviour is vastly different from the one that could be surmised from the original elemental dynamical equations.

In a MHD plasma embedded in a dominant background magnetic field, magnetised coherent structures are usually in the form field-aligned flux tubes. When such coherent magnetic flux tubes with the same polarity migrate toward each other, strong local magnetic shears are created and sporadic non-propagating fluctuations will generally migrate toward the strong local shear region. Eventually, the mean local energies of the coherent structures will be dissipated into these concentrated fluctuations in the coarse-grained sense and would induce reconfigurations of the magnetic field geometry. Then, the complexity of creation and dissipation of coherent structures in a plasma is similar to the occurrence of avalanches; both have associated non-Gaussian fluctuations PDF distributions. The phenomena of intermittency have been observed in the solar wind (Bruno et al., 2001) and in the plasma sheet (Consolini et al., 2005).

Here, observations of riometer auroral radio-wave absorption over a latitude range on the southern hemisphere absorption zone are analysed for intermittent behaviour. For all purposes the present paper is a follow up of the one by Stepanova et al. (2005). These two analyses can be thought of as alternatives to previous studies of the structure and spatial coherence spectra of absorption (e.g. Hargreaves and Berry (1976)).

2. Data analysis

2.1. Absorption determination

Radio-wave absorption has been determined at several manned Antarctic stations for many years from observations made by different types of riometers (relative ionospheric opacity metre, Little and Leinbach (1959)) and associated antennas, using various techniques to derive the absorption values (see Hargreaves (1969), for a review on early riometry). In the previous quoted study (Stepanova et al., 2005) 38.2 MHz cosmic noise intensities received at South Pole by a riometer using a broad-beam antenna (Rosenberg et al., 1991) were used. The analyzed absorption values were those routinely derived using the so-called 'inflection point' method to determine a reference 'quiet day curve' (QDC) as reported by Krishnaswamy et al. (1985). In this method, a distribution of received cosmic noise intensities for a short time interval (say a minute) at the same sidereal time for typically a month is first calculated. Then an analytical function is fitted to the distribution. The received intensity corresponding to the slope change on the lower intensities side of the distribution is regarded as the reference intensity to derive absorption values for the corresponding sidereal time. Reference intensities for all hours thus define the QDC.

During the last decades at both manned stations and unmanned Automatic Geophysical Observatories (AGO's) scanning riometers coupled to antenna arrays have been deployed (Imaging Riometer for Ionospheric Studies (IRIS) systems, Detrick and Rosenberg (1988)). These allow absorption determinations for as many as 49 narrow beams covering similar lower ionosphere areas than the old broad-beam antenna riometers.

In the present paper IRIS auroral absorption values from the seven Antarctic locations during 1997–98 have been analysed. At an additional location a four fixed beam system is used. Locations coordinates and specific time intervals used are listed in Table 1 and their relative positions shown in Fig. 2. In all cases the 'inflection point' method was used. For South Pole, the absorption values were for a 7×7 beam IRIS, with a temporal resolution of 10 s. The mean of the central beams (3×3) during 1 min was computed. Similarly, for AGO's AP1, AP2, AP3, AP4 and AP5 values for a 4×4 beam IRIS, with a 12 s of temporal resolution were used. The computed mean was for central beams (2×2) during 1 min. In the case of Syowa an 8 beam IRIS, one second resolution was used, and again the mean of the central beams (2×2) during 1 min was calculated. Finally, for Halley Bay only the third fixed beam out of four was used, because for the other three beams large differences are found between reported QDC and original observed intensities. Sample diurnal variation of riometer auroral absorption during geomagnetic quiet and perturbed conditions at the eight locations considered are shown in Fig. 3, together with the corresponding variations of AU/AL indices.

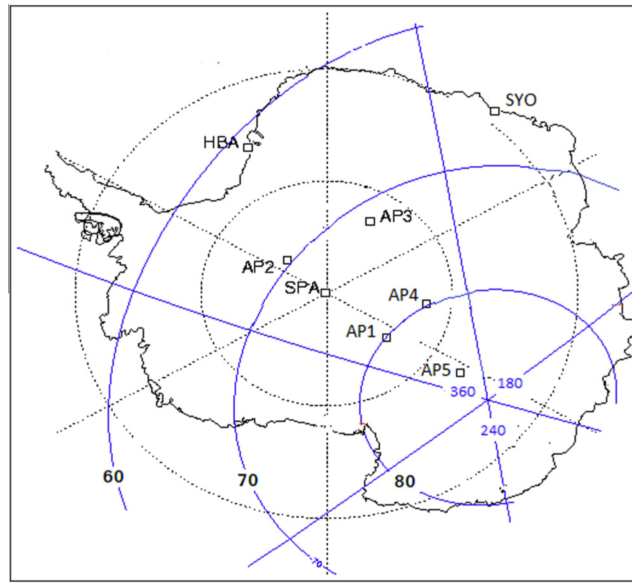

Fig. 2. Antarctic locations on two coordinate systems. (dotted black) Geographic. (full blue) Corrected geomagnetic. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2. Diurnal variations screening

First of all the diurnal variations of absorption for all days and locations determined as already indicated were checked visually. It was found that in many cases there were obviously spurious values and several clear offsets. For this reason a detailed screening was performed in two stages using some purpose build MATLAB code: (a) comparison of auroral absorption events with excursions of AU/AL and PC indices, spurious absorption values removal and setting negative values to zero, and (b) relocation of the daily reference level to avoid clear biases. The screening process is illustrated for South Pole in Fig. 4.

After the screening was finished, two time series for each location were assembled. One giving the absorption values

Table 1
Locations and time interval used.

Location	Latitude, °	Longitude, °	C.G.Lat., °	C.G.Long., °	Time interval, DOY
HBA, Halley Bay	−75.50	−31.60	−61.61	29.06	1–365, 1997
SYO, Syowa	−69.00	39.35	−66.24	71.79	1–365, 1997
					60–90, 1998
AP2, AGO	−85.67	313.62	−69.88	19.35	1–70, 1997
					60–90, 1998
AP3, AGO	−82.75	28.59	−71.85	40.22	1–90, 1997
SPA, South Pole	−90.00	0.00	−74.08	18.44	1–90, 1997
					60–90, 1998
AP4, AGO	−82.01	96.76	−80.05	41.69	1–90, 1997
AP1, AGO	−83.86	120.61	−80.11	22.34	1–90, 1997
AP5, AGO	−77.24	123.52	−86.78	29.44	1–65, 1997
					60–90, 1998

AGO: Automatic Geophysical Observatory (Polar Experiment Network for Geospace Upper-atmosphere INvestigations (PENGUIn) project. Rosenberg and Doolittle (1994), Studying the polar ionosphere and magnetosphere with Automatic Geophysical Observatories: The United States program in Antarctica, *Antarctic Journal of the United States*, 29, 347–349).

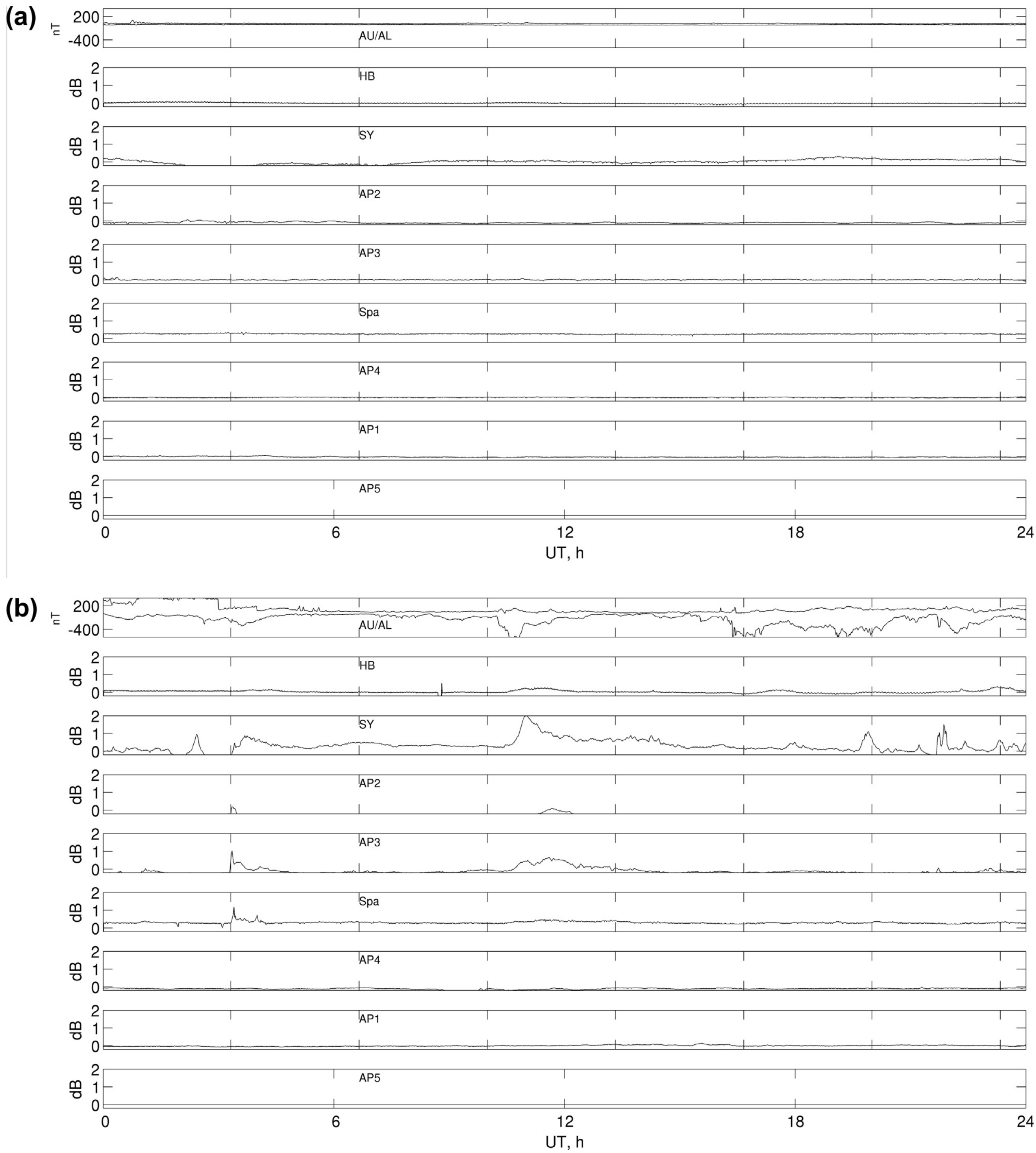

Fig. 3. Sample diurnal variations of riometer auroral absorption at eight Antarctic locations and corresponding AU/AL indices for two days in 1997. (a) Geomagnetic quiet conditions (9 March). (b) Geomagnetic disturbed conditions (27 January).

(in dB) for the sequence of auroral events (only values above 0.1 dB were selected) and the other giving the time intervals (in minutes) in between successive absorptions events.

2.3. Intermittency determination

Several methods have been proposed to estimate intermittency. Among them are the wavelet analysis (Farge, 1992) and statistical methods such as super statistics (Becka and Cohen, 2003) and extensive statistics (Tsallis, 1999). Assuming that the notion of self-similarity underlies the energy cascade process in turbulence, Castaning et al. (1990) and Vassilicos (1994) have introduced a model which characterises the behaviour of the PDFs of the fluctuations using a parameter describing how the shape of the PDF changes as the time-scale τ increases. Here the version by Stepanova et al. (2003) of the technique proposed by Castaning et al. (1990) is used. The PDF of the variable

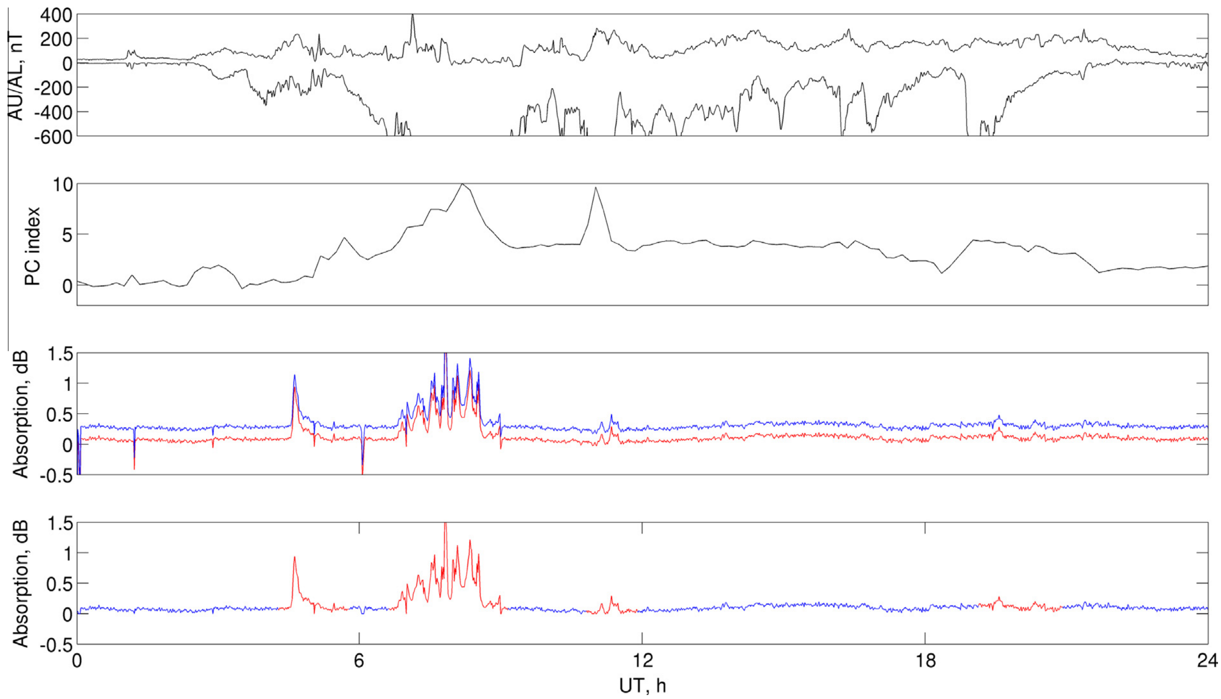

Fig. 4. Sample diurnal variation screening (South Pole, 10 January 1997). (top panel) AU/AL indices. (2nd panel) PC index. (3rd panel) Absorption with (blue) and without (red) bias. (bottom panel) Adopted absorption (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

fluctuations is expressed as the superposition of a Gaussian function and a log-normal distribution which describes the distributions of the variances σ,

$$P(\tau) = \frac{A}{2\pi\lambda}\int_0^\infty exp\left[\frac{-\tau^2}{2\sigma^2}\left(1 + a\frac{\tau/\sigma}{\sqrt{1+\tau^2/\sigma^2}}\right)\right] \times exp\left[\frac{-ln^2(\sigma/\sigma_0)}{2\lambda^2}\right]\frac{d\sigma}{\sigma^2}$$

where A is a normalisation factor, a is a skewness factor describing the asymmetry of PDF tails, σ_0 is the most probable variance and λ represents the log-norm variance of the Gaussian variances σ. Therefore, a $\lambda^2(\tau)$ function is a quantitative measure of intermittency. For a longer discussion of the Castaing model see Sorriso-Valvo et al. (2015).

For each time series (8 locations $\times$ 2 series types: absorptions events and time intervals between events) PDF's of fluctuations were determined corresponding to a range of values of τ. Then analytical PDF's were fitted to these observed PDF's using the Nelder–Mead algorithm, which is readily available in several statistical software packages.

In order to study the dependence of the PDFs on τ, a power law $\lambda^2(\tau) = \mu\tau^{-\alpha}$, was adjusted to the observed dependence as done by Stepanova et al. (2005), where μ is a measure of the magnitude of $\lambda^2(\tau)$ defined as the variance of the set of Gaussian variances σ corresponding to the different τ. The α parameter indicates the degree of change of the correlation between fluctuations for different τ, which increases as intermittency becomes larger.

In Fig. 5 intermediate results from the complete analysis are illustrated using a time series giving the absorption values for a specific sequence of auroral events: from the observed riometer auroral values to the fluctuations determination to the frequency distribution computation to the PDF determination and final power law fitting. This example corresponds to observations made at Halley Bay during 1997.

PDFs for $\tau = 2$, 4, 8, 32, 64 and 128 min (see Supplementary material) exhibit increasingly stretched “wings” as τ, increases. This is consistent with the fluctuations for events corresponding to larger τ being more likely to occur.

3. Results

Fig. 6 shows the latitudinal dependences of the parameters α and μ of the $\lambda^2(\tau)$ model. The latitudinal variation of α for absorption values seems to be consistent with the intermittency being more significant between about 65–75° corrected geomagnetic latitude (c.g.lat.), that is from the auroral absorption zone centre to the poleward fringe. In fact α is at least 5 times as large there than at Halley Bay (−61.61° c.g.lat.) and more than twice as large as at AP1(−80.11° c.g.lat.). It should be noted that the time series of observations at Halley Bay (−61.61° c.g.lat.), Syowa (−66.24° c.g.lat.) and South Pole (−74.08° c.g.lat.) are the longer ones. The α values for AP2 (−69.88° c.g. lat.) and AP3 (−71.85° c.g.lat.) are consistent with the indicated latitude dependence in spite of corresponding to rather short time series. In the case of AP4 (−80.05° c.g. lat., not shown), also for a short time series and located at a latitude similar to AP1 (−80.11° c.g.lat.), results are completely inconsistent. This is most likely due to the very different computed PDF's. α values for AP5 (−86.78° c.g.

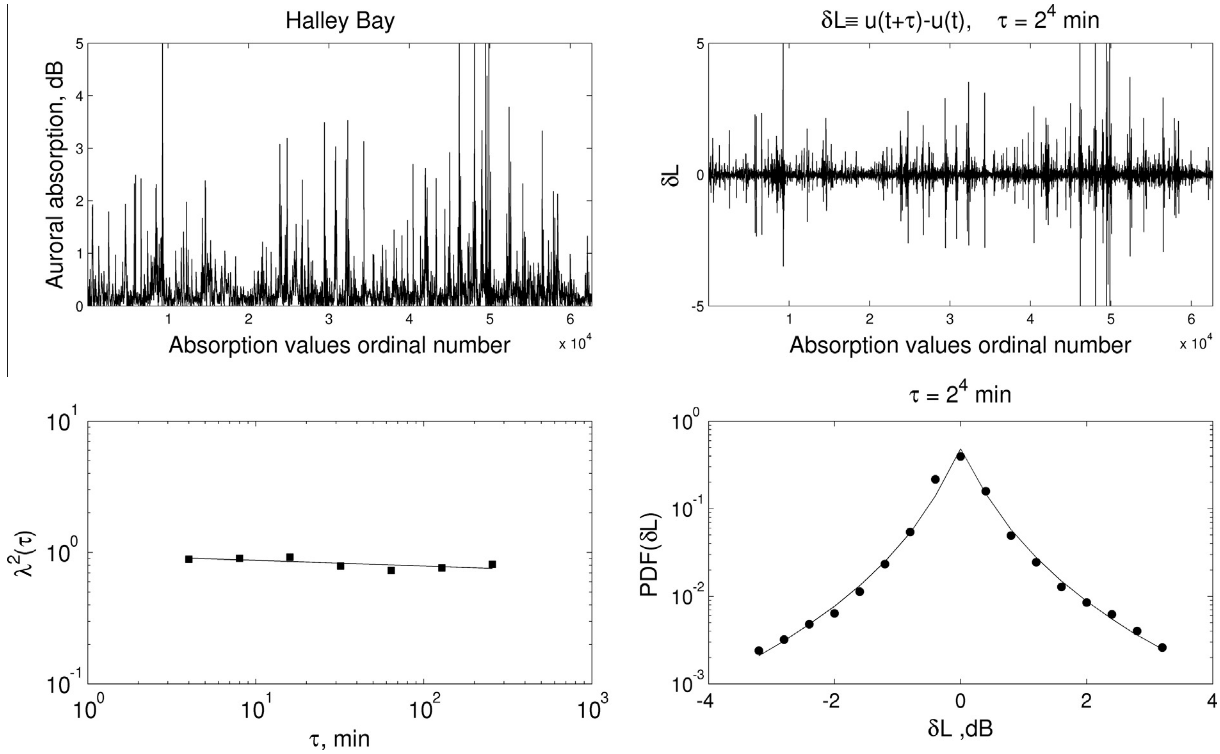

Fig. 5. Sample results of complete analysis. (Clockwise from top left). Observed absorption values, fluctuations, frequency distribution and PDF fitting, power law fitting.

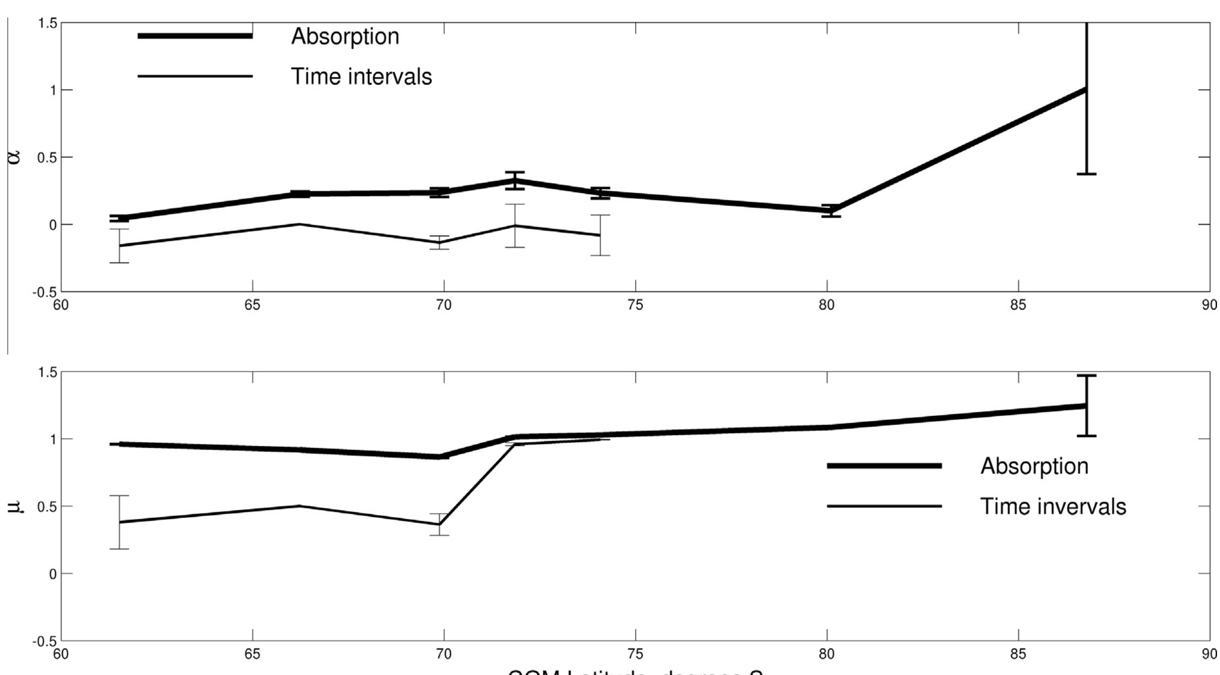

Fig. 6. Latitudinal dependence of power law fitting parameters to (thick line) absorption and (thin line) time intervals time series. (top) α. (bottom) μ.

lat.) are much larger as are uncertain, but they clearly correspond to the polar cap instead of the auroral absorption zone. They are related to quite different processes to the auroral ones.

Although the latitudinal variation of α for the time-intervals series exhibits the same pattern than that for the absorption values, absolute values for the auroral absorption zone fringes are larger than those for the zone centre, except for AP2 (−69.88° c.g.lat.) which is nearby AP3 latitude wise. No specific reason is offered for this result; perhaps a larger weight should be assigned to the results for the longer time series. Again values for AP4 (−80.05°

c.g.lat.) and AP5 (−86.78° c.g.lat.) and now also for AP1 (−80.11° c.g.lat.) are not consistent with the latitude dependence for the larger part of the latitude range.

The μ for absorption changes very little with latitude; it is between 0.96 and 1.07 times the value for the equatorial fringe of the auroral absorption zone and between 0.8 and 0.95 times that for the polar fringe. The latitude dependence for the time-intervals is different altogether. No suggestion as to this behaviour is offered.

4. Discussion and conclusions

It is recalled that previous results for South Pole (Stepanova et al., 2005) are for absorption values derived using riometers coupled to broad-beam antennas and correspond to a longer time series. This makes it possible to take into account local time differences. They find that α is less than 0.3 for all times-of-day except for 01:00–03:00 MLT. Values of μ were less than 1 from 04:00 to 11:00. On this basis Stepanova et al. (2005) suggested that intermittency sources are likely to be active during nighttime. Present results are for IRIS type systems, shorter time series and relate to all times-of-day combined. Nevertheless, the found values for α and μ at South Pole, 0.23 and 1.1, respectively, are considered quite consistent with those of Stepanova et al. (2005).

The present analysis leads to the following conclusions.

The found decreasing of the variance (λ^2) of the Gaussian variances (σ) of the fluctuations for increasing time-scale (τ) is larger within the absorption auroral zone (larger values of α). This is consistent with the formation of coherent structures being more frequent within the auroral zone, as a manifestation of intermittency. The decreasing is observed both for the absorption events and the time-intervals between events.

The parameter μ is found to be almost constant all along the latitude range analysed. This is so because μ is the variance of the Gaussian variances for fluctuations associated with events that are temporarily very close to each other ($\lambda^2 \to \mu$ for $\tau \to 0$), and thus is not strongly related to the intermittency, as it is indeed the variance for larger values of τ.

Longer time series are needed for definite conclusions to be derived. Unfortunately, it is hard to find long simultaneous observation intervals.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.asr.2015.08.038.

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