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Solar Type IIIb Radio Bursts as Tracers for Electron Density Fluctuations in the Corona

V. Mugundhan[1] · K. Hariharan[2] · R. Ramesh[1]

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Abstract We present an estimation of the electron density modulation index ($\frac{\delta N_e}{N_e}$) for the first time using solar type IIIb radio burst observations. The mean value of $\frac{\delta N_e}{N_e}$ is calculated to be $\approx 0.006 \pm 0.002$ over the heliocentric distance range $r \approx 1.6-2.2$ $R_\odot$. The estimated $\frac{\delta N_e}{N_e}$ shows a power law dependence on r with a power law index $\approx 0.31 \pm 0.10$. The wavenumber (k) spectrum for the electron density fluctuation $(\frac{\delta N_e}{N_e})^2$ values shows a Kolmogorov-like behavior. Using $\frac{\delta N_e}{N_e}$ and the Kolmogorov turbulence index, we estimated the amplitude of density turbulence $[C_n^2(r)]$ in the aforementioned range of r.

Keywords Corona, radio emission · Radio bursts, type III · Turbulence

1. Introduction

Inhomogeneities in the solar corona and the solar wind lead to turbulent density fluctuations. Study of the latter is important to understand the low values of observed radio brightness temperature of the "undisturbed" Sun and the angular broadening/location of compact solar radio sources (Aubier, Leblanc, and Boischot, 1971; Bastian, 1994; Sastry, 1994; Thejappa and Kundu, 1994; Ramesh, 2000; Ramesh and Sastry, 2000; Ramesh, Subramanian, and Sastry, 2000; Kathiravan and Ramesh, 2004; Subramanian, 2004; Ramesh *et al.*, 2006, 2010b,

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✉ V. Mugundhan
mugundhan@iiap.res.in

✉ K. Hariharan
hara@ncra.tifr.res.in

✉ R. Ramesh
ramesh@iiap.res.in

[1] Indian Institute of Astrophysics, 2nd Block, Koramangala, Bangalore 560034, India

[2] NCRA-TIFR, Pune University Campus, Ganeshkhind P.O., Pune 411007, India

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2012b; Subramanian and Cairns, 2011; Morosan *et al.*, 2014, 2015; Mercier and Chambe, 2015). Measurements of density fluctuations have been carried out over large heliocentric distances from 10 $R_\odot$ up to 215 $R_\odot$ (Bavassano and Bruno, 1995; Woo *et al.*, 1995; Ramesh, Kathiravan, and Sastry, 2001; Spangler, 2002; Tokumaru, Kojima, and Fujiki, 2012; Bisoi *et al.*, 2014; Sasikumar Raja *et al.*, 2016). However, such measurements below 10 $R_\odot$ have not been possible to date due to various technical difficulties. Cairns *et al.* (2009) have suggested that observations of transient radio emission over the frequency range 30 – 300 MHz may be used to probe the density profile of the solar corona corresponding to $r \leq 2\ R_\odot$.

Type III solar radio bursts are thought to be generated through plasma oscillations induced by energetic electron streams traveling along open magnetic field-lines (Ginzburg and Zhelezniakov, 1958; Sasikumar Raja and Ramesh, 2013; Reid and Ratcliffe, 2014). They appear as individual or a group (of 10 or more) fast drifting ($\delta f/\delta t \approx 100$ MHz s^{-1}) enhanced features in the dynamic spectral records during the impulsive phase of flares (see *e.g.* Nindos *et al.*, 2011) with a duration of a few tens of seconds. Occasionally, however, they appear when there is little (*e.g.* Alissandrakis *et al.*, 2015) or no associated activity at other wavelengths.

At times, a chain of short duration narrow-band bursts have been observed to occur with an overall envelope having a drift rate similar to that of type III bursts and are called type IIIb bursts (Ellis and McCulloch, 1967; de La Noe and Boischot, 1972). The spectral fragmentations within the type IIIb bursts are sometimes referred to as "striae" (de La Noe and Boischot, 1972). Individual stria have been observed to have an average bandwidth and duration of ≈ 50 kHz and ≈ 1.2 s, respectively. Takakura and Yousef (1975) have suggested that stria-like features in type IIIb bursts could be caused by density inhomogeneities along the path of the electron beams (Smith and de La Noe, 1976; Tun Beltran, Cutchin, and White, 2015). This has been verified subsequently through numerical modeling (Kontar, 2001; Li, Cairns, and Robinson, 2011a,b, 2012; Loi, Cairns, and Li, 2014). It has also been suggested by Loi, Cairns, and Li (2014) that the aforementioned properties of type IIIb bursts can be used to probe the density inhomogeneities in the solar corona and the solar wind.

To address the above, we present and analyze here the spectral observations of solar type IIIb radio bursts in the frequency range of 80 – 40 MHz from the Gauribidanur Radio Observatory located about 100 km north of Bangalore in India (Ramesh, 2011). The radio emission from the Sun corresponding to the above frequency interval typically originates in the distance range $r \approx 1.6$ – 2.2 $R_\odot$ in the solar corona.

2. Observations

The observations reported in this work were obtained with the *Gauribidanur Low Frequency Solar Spectrograph* (GLOSS; Ebenezer *et al.*, 2001, 2007; Kishore *et al.*, 2014) array. GLOSS is a phased-array of 8 log-periodic dipole antenna elements aligned along the north–south direction with the dipole arms along the east-west (EW) direction. The response pattern of the GLOSS in the EW direction is $\approx 90^\circ$ and this ensures that Sun is within the array field of view for 6 hours every day. A new digital *Fast Fourier Transform Spectrometer* (FFTS) configured on field-programmable gate array (FPGA) hardware was used as the back-end receiver for the GLOSS. The FFTS offers a spectral and temporal resolution of ≈ 24 kHz and ≈ 5 ms, respectively. Further technical details of the FFTS back-end will be presented elsewhere (Hariharan, Mugundhan, and Ramesh, in preparation). Preliminary observations were performed with the GLOSS-FFTS system over the frequency range 40 – 80 MHz during the period July–October, 2016.

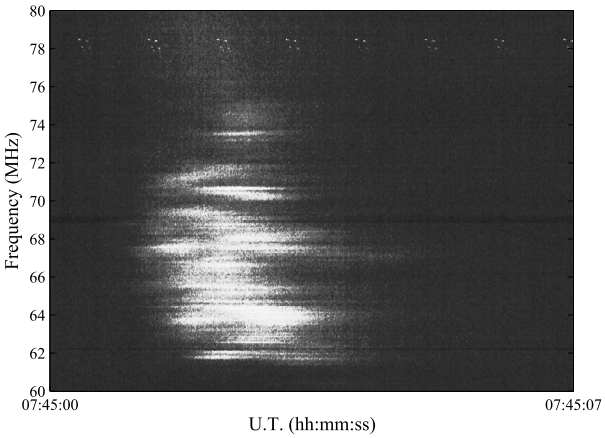

Figure 1 Type IIIb radio burst event recorded on 20 July 2016. The narrow-band features are striae which constitute the type IIIb burst.

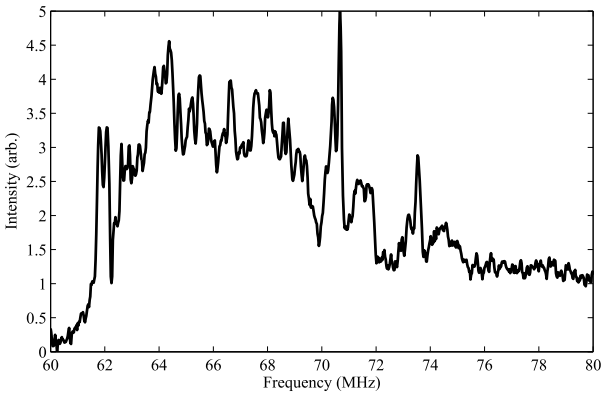

Figure 2 Spectral profile of the type IIIb radio burst event shown in Figure 1.

During the aforementioned observing period, type IIIb radio bursts were detected on four different days. Figure 1 shows a typical type IIIb radio burst observed with the GLOSS-FFTS on 20 July 2016, around 07:45 UT. The burst was not particularly associated with any flare at the time of occurrence,[1] although a SF class Hα and a B6.6 class X-ray flare during 08:16 – 08:25 UT were reported from the active region AR 12565 located at the heliographic coordinates N01W34. We note that during the time of observation of the type IIIb bursts no particular flares at other wavelengths were reported. These bursts probably belong to the category of weak energy releases (Ramesh *et al.*, 2010a, 2013; Suresh *et al.*, 2017). A total of 19 type IIIb bursts were recorded with our instrument, each with a typical duration and bandwidth of ≈ 3 s and ≈ 15 MHz, respectively (refer to Table 1). Each of the type IIIb events were found to be composed of $\approx 15 - 60$ stria within the bandwidth of the burst. Figure 2 shows the instantaneous spectral profile of the type IIIb burst shown in Figure 1. The amplitude variations seen in the spectral-cut correspond to the striae within the type IIIb event. The individual stria were found to have a spectral width between 24 – 100 kHz with a duration of ≈ 1 s and did not show any significant drift in frequency. These are consistent with previously reported observations of type IIIb bursts (de La Noe and Boischot, 1972; Krishan, Subramanian, and Sastry, 1980; Melnik *et al.*, 2009, 2011).

[1] See http://www.swpc.noaa.gov/.

Table 1 List of type IIIb bursts recorded with FFTS.

Date	Time UT (hh:mm:ss)	Duration (s)	Frequency range (MHz)
20 July 2016	07:45:02	3	75 – 60
13 August 2016	05:37:14	3	68 – 54
	05:37:34	2	71 – 55
	05:38:04	4	72 – 54
	06:37:45	5	87 – 52
	08:58:02	2	80 – 55
10 October 2016	05:38:36	5	70 – 48
	06:15:21	4	65 – 48
	06:58:22	4	68 – 45
12 October 2016	06:03:57	3	59 – 47
	06:04:14	4	60 – 46
	06:05:11	2	58 – 47
	06:05:14	3	6 – 47
	06:05:40	3	62 – 48
	08:39:18	4	65 – 50
	08:39:23	2	70 – 55
	08:39:25	3	68 – 53
	08:39:30	2	70 – 48
	08:40:39	3	58 – 43

3. Analysis and Results

3.1. Estimation of $\frac{\delta N_e}{N_e}$

For the present work we have considered only the single individual stria bursts within the type IIIb events (see Table 1) for analysis in order to avoid ambiguities. The choice of the striae were constrained as follows: i) the striae are bright enough to be distinguishable from the smooth type III background; ii) the striae remain stationary in frequency with no noticeable frequency drift. From the spectral profile we marked and noted the upper (f_u), lower (f_l) and central (f_c) frequencies corresponding to the spectral width of the striae. The above values were then used to estimate $\frac{\delta N_e}{N_e}$ by applying Equations 1 and 2:

$$f_p = 8980\sqrt{N_e}\ \text{Hz} \tag{1}$$

where N_e is in units of cm^{-3}, and

$$\frac{\delta N_e}{N_e} = \frac{f_u^2 - f_l^2}{f_c^2}. \tag{2}$$

The above analysis was carried out for each of the individual stria selected from all the type IIIb events reported in Table 1. Figure 3 shows the histogram distribution of the estimated values of $\frac{\delta N_e}{N_e}$ from all the type IIIb bursts listed in Table 1. It can be noted that the most frequent value of $\frac{\delta N_e}{N_e}$ is found to be $\approx 0.006 \pm 0.002$. This is consistent with the values of $\frac{\delta N_e}{N_e}$ at distances < 1 AU reported in the literature (Woo *et al.*, 1995; Bavassano and Bruno, 1995; Huddleston, Woo, and Neugebauer, 1995; Bisoi *et al.*, 2014).

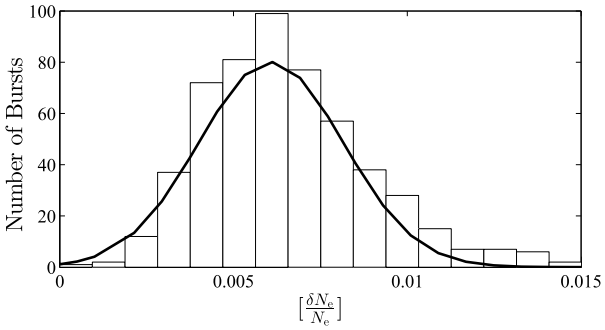

Figure 3 A histogram of $\frac{\delta N_e}{N_e}$ obtained from type-IIIb events. The *solid line* is a Gaussian fit to the distribution.

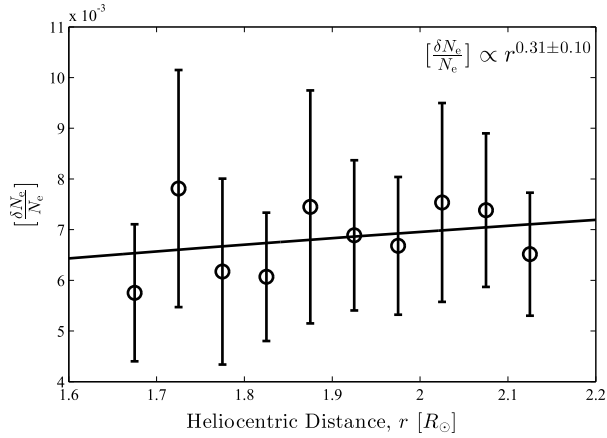

Figure 4 Distribution of mean $\frac{\delta N_e}{N_e}$ over $r \approx 1.6-2.2$ R$_\odot$. The *solid line* is a least-squares power law fit (refer to Table 2 for details). The *error bars* represent the spread in the data at the respective values of r.

We adopted the Baumbach–Allen electron density model (Baumbach, 1937; Allen, 1947) in order to study the radial dependence of $\frac{\delta N_e}{N_e}$. Assuming that the spectral fine structures in type IIIb bursts are due to density inhomogeneities along the path of the type III beam, we considered an enhancement factor of 10 similar to that considered in the simulation studies by Li, Cairns, and Robinson (2012) and Loi, Cairns, and Li (2014). Also, a 10× Baumbach–Allen model represents a reasonable estimate of electron density enhancement in the corona during times of activity (Maxwell and Thompson, 1962; Stewart, 1976; Dryer and Maxwell, 1979; Ramesh *et al.*, 2005). Thus, when using the above model, our observing frequency range of 40 – 80 MHz then translates to $r \approx 1.6-2.2$ R$_\odot$. The study on the radial dependence of $\frac{\delta N_e}{N_e}$ was carried out for all the events on individual days of observation and also for the combined dataset from all four days, the results of which are summarized in Table 2.

Figure 4 shows the distribution of $\frac{\delta N_e}{N_e}$ values over heliocentric distance obtained from the combined data of all four days. A least-squares power law fit ($\propto r^\beta$) to the data indicates that $\frac{\delta N_e}{N_e}$ shows a weak variation with heliocentric distance, with an index $\beta \approx 0.31 \pm 0.10$. When estimated separately for each day, the obtained β is found to lie in the range of 0.28 – 0.40. Further, we find that mean value of $\frac{\delta N_e}{N_e}$ obtained from our measurements when combined with those obtained through other methods (*viz.* Interplanetary Scintillation (IPS), Radio Source occultation, *Very Long Baseline Interferometry* (VLBI) and spacecraft observations), also show a power law variation with $\beta \approx 0.33$ over $r = 1.5-215$ R$_\odot$ (refer to Figure 5). Reid and Kontar (2010) also predicted similar variation of $\frac{\delta N_e}{N_e}$ ($\propto r^{0.25}$) up to 1 AU for

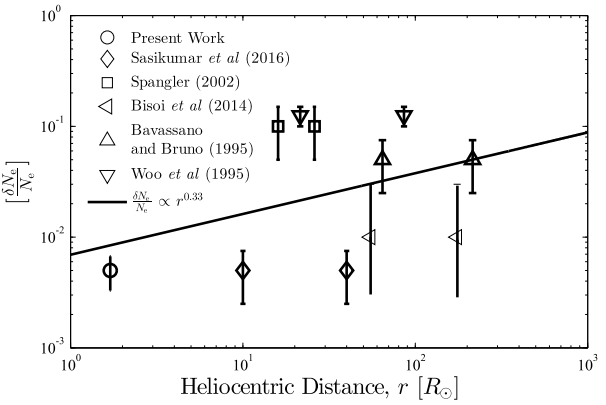

Figure 5 Distribution of Density modulation index ($\frac{\delta N_e}{N_e}$) over the heliocentric distance range from $\approx 1.5-215$ $R_\odot$ (1 AU). The axes are in log–log scale. The *error bars* represent the spread in the data at the respective values of r. The *solid line* represents a least-square power law fit to the data, with a power law index of ≈ 0.33.

Table 2 Summary of analysis.

Date	$\frac{\delta N_e}{N_e}$ (%)	Heliocentric distance (r) ($R_\odot$)	Power law index (β)
20 July 2016	0.5 ± 0.11	1.6 – 2.0	0.29 ± 0.13
13 August 2016	0.6 ± 0.19	1.6 – 2.1	0.40 ± 0.15
10 October 2016	0.5 ± 0.12	1.7 – 2.2	0.31 ± 0.10
12 October 2016	0.6 ± 0.23	1.7 – 2.2	0.28 ± 0.11
Overall	0.6 ± 0.20	1.6 – 2.2	0.31 ± 0.10

transport of type III electrons. This shows that the $\frac{\delta N_e}{N_e}$ ratio obtained here is consistent with previously reported values and follows the same trend in the inner corona as well.

3.2. Nature of Density Fluctuations

It has been suggested that the solar corona and solar wind follow a Kolmogorov-like power-law spectrum with wavenumber $k = 2\pi/l$, where l is the scale size involved in the turbulence cascade (Marsch, 1991; Goldstein, Roberts, and Matthaeus, 1995; Cranmer, 2007). Since we carried out spectral observations, the largest and smallest measurable scales depend on the observation bandwidth and frequency resolution, respectively. The scales are estimated using the density model assumed in the previous section. Since the spectral enhancements in the type IIIb burst could be due to local density inhomogeneities, the bandwidth of the striae at different frequencies correspond to the turbulence scale there (Loi, Cairns, and Li, 2014). Figure 6 shows the $(\frac{\delta N_e}{N_e})^2$ spectrum in log scale, where the small and intermediate scales correspond to the spectral width of the individual stria and their fluctuating background, respectively while the large scales correspond to the overall spectral extent of the type IIIb burst.

A fit to the data shows that the spectrum has an index $\alpha \approx -1.70 \pm 0.02$. This is in close agreement with the one-dimensional Kolmogorov spectral index $[\propto k^{-5/3}]$ (Reid and Kontar, 2010; Loi, Cairns, and Li, 2014). The minimum scale length estimated from our data corresponds to $l_{\min} \approx 520$ km. But even after reaching this scale, there is no evidence of spectral flattening which is expected beyond the inner scale. This suggests that the inner scale[2] (l_i) could be smaller than the minimum scale obtained from this dataset. Note that

[2]The scale beyond which turbulence cascade energy begins to dissipate.

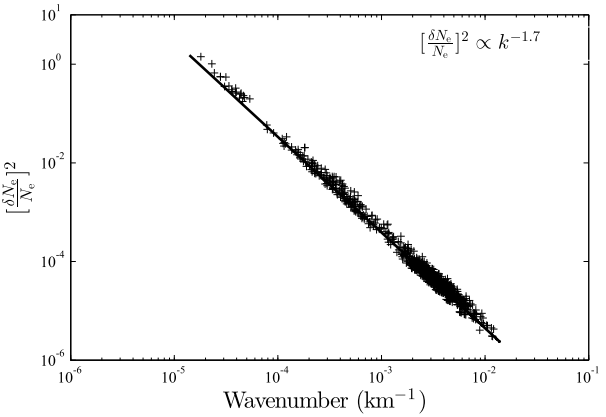

Figure 6 Spectrum of $(\frac{\delta N_e}{N_e})^2$ fluctuations. Both axes are plotted in log scale.

flattening of the spectrum ($\propto k^{-1.1}$) at distances ≤ 20 R$_\odot$ has been observed (Woo and Armstrong, 1979); The former has been reported to set in at shorter scales ($\approx 3-300$ km), shifting to larger k sunward (Coles *et al.*, 1991; Imamura *et al.*, 2005; Mullan, 1990).

3.3. Determination of $C_n^2(r)$

As a corollary, we used the estimated $\frac{\delta N_e}{N_e}$ and α to calculate the amplitude of density fluctuations, $C_n^2(r)$. To date, estimation of $C_n^2(r)$ has only been performed for $r = 10-60$ R$_\odot$, using *in situ* spacecraft and VLBI observations (refer to Section 1). Sasikumar Raja *et al.* (2016) used data from the occultation of the radio source 3C144 by the solar corona to obtain $C_n^2(r)$ for $r = 10-45$ R$_\odot$. They found a solar-cycle dependent power-law variation of $C_n^2(r)$ with r.

The relation between $(\frac{\delta N_e}{N_e})^2$, α and $C_n^2(r)$, for a one-dimensional turbulence spectrum at the inner scale usually is (Sasikumar Raja *et al.*, 2016; Subramanian and Cairns, 2011 and the references therein):

$$C_n^2(r) \propto \frac{[\frac{\delta N_e}{N_e}]^2 {N_e}^2}{4\pi k_i^{2-\alpha} e^{-1}}, \tag{3}$$

where the wavenumber at the inner scale (l_i) is $k_i = \frac{2\pi}{l_i}$. Note that for a three-dimensional turbulence spectrum k_i is raised to 3-α.

There has been considerable debate as to what the smallest scale is that is present in the corona and the solar wind (Mullan, 1990). Sasikumar Raja *et al.* (2016) have shown that scales of the order of 1.6 km exist at $r < 10$ R$_\odot$. In view of recent *in situ* spacecraft and IPS observations (Bale *et al.*, 2005; Alexandrova *et al.*, 2009, 2012; Bisoi *et al.*, 2014), it has been suggested that dissipation could occur down to proton and electron gyro-radii scales (ρ_p) (Chen *et al.*, 2014). The proton gyro-radius (ρ_p) is given by

$$\rho_p(r) = 102\sqrt{\mu T_i} B(r)^{-1} \quad [\text{cm}], \tag{4}$$

where μ is the ratio of the mass of ions to that of protons, which is ≈ 1, and where T_i is the proton temperature in eV, and $B(r)$ is the coronal magnetic field, which can be modeled as $B(r) = 0.5(r-1)^{-1.5}$ [G] with r in units of R$_\odot$ (Dulk and McLean, 1978; Ramesh, Kathiravan, and Sastry, 2010; Ramesh, Kathiravan, and Narayanan, 2011).

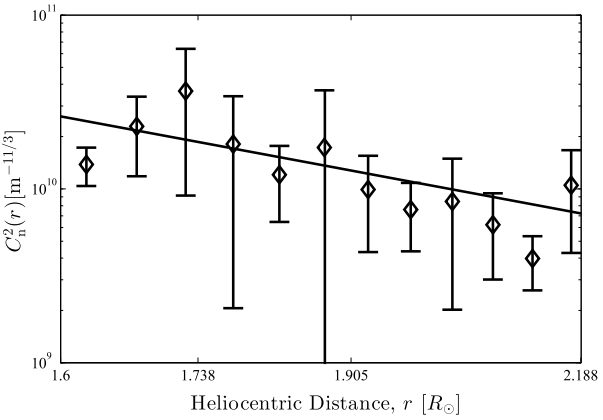

Figure 7 Log–log plot of $C_n^2(r)$ with r, for a spectrum with $\alpha \approx -1.7$ and inner scale as electron gyro-radius. The *solid line* is a power law fit of the form Ar^γ. The fitted values are $A = 1.8 \pm 1.0 \times 10^{11}$ m$^{-11/3}$ and $\gamma = -4.11 \pm 1.75$. The *error bars* represent the spread in the data at the respective values of r.

The electron gyro-radius (ρ_e) is

$$\rho_e = 2.38\sqrt{T_e}B(r)^{-1} \quad [\mathrm{cm}]. \tag{5}$$

In this work, we consider both electron and proton gyro-radii as the inner scale for $C_n^2(r)$ estimation. We used Equation 3 to obtain the $C_n^2(r)$ values corresponding to $\frac{\delta N_e}{N_e}$ using α estimated earlier in this paper (see Section 3.2) for both inner scale estimates. The $C_n^2(r)$ calculated was binned to different solar radii and its scatter with respect to r was obtained. A least-squares power law of the form Ar^γ was fit to the data obtained for both inner scale considerations. We show a representative scatter of the behavior of $C_n^2(r)$ against r, considering $l_i = \rho_e$ in Figure 7. A similar fit with $l_i = \rho_p$ yielded the following fit parameters: A $\approx 4.79 \pm 1.50 \times 10^{11}$ m$^{-11/3}$ and $\gamma \approx -4.09 \pm 2.00$. However, the $C_n^2(r)$ estimates have to be treated with caution as these depend strongly on l_i, which is not yet precisely known.

4. Conclusion

We report the first estimate $\frac{\delta N_e}{N_e}$ and $C_n^2(r)$ for $r = 1.6$–2.2 R$_\odot$ from the observations of type IIIb solar radio bursts. $\frac{\delta N_e}{N_e}$ varies with r as a power law with index $\beta \approx 0.33$. Note that previous estimates of $\frac{\delta N_e}{N_e}$ through techniques like IPS, Radio Source occultation, VLBI and *in situ* spacecraft measurements were limited to $r \geq 10$ R$_\odot$ (Woo *et al.*, 1995; Bavassano and Bruno, 1995; Ramesh, Kathiravan, and Sastry, 2001; Spangler, 2002; Bisoi *et al.*, 2014; Sasikumar Raja *et al.*, 2016). It has been suggested by several authors (Takakura and Yousef, 1975; Smith and de La Noe, 1976; de La Noe and Boischot, 1972; Tun Beltran, Cutchin, and White, 2015) that striations in type IIIb radio burst emission can be due to electron density variations along the path the electron beams causing the type III bursts. Subsequent numerical modeling has shown that stria-like fine-structure emissions can indeed arise from density or temperature inhomogeneities along the path of the exciter and thus can be effective probes of the same (Kontar, 2001; Li, Cairns, and Robinson, 2011a,b, 2012; Loi, Cairns, and Li, 2014). We use the values of $(\frac{\delta N_e}{N_e})^2$ obtained from the data and determine that the density modulation index follows a Kolmogorov-like spectrum ($\propto k^{-1.7}$) for the range of values of r examined in this work.

As a corollary, we use the obtained values of $(\frac{\delta N_e}{N_e})^2$ and α to estimate the behavior of $C_n^2(r)$ with r. It is found that the former shows a power law variation radially with an index ≈ -4.2.

The results obtained in the present work are consistent with those obtained using other techniques *viz.* IPS, VLBI and occultation experiments. Studies like the one presented here are useful to understand scattering due to density fluctuations in the solar corona, and the spatial extent of the smallest observed compact sources there (Ramesh, Subramanian, and Sastry, 1999; Ramesh and Sastry, 2000; Ramesh and Ebenezer, 2001; Mercier *et al.*, 2006, 2015; Kathiravan *et al.*, 2011; Ramesh *et al.*, 2012a; Mugundhan *et al.*, 2016). We conclude by stating that observations of fine-structure/fragmented radio emission (Thejappa, Zlobec, and MacDowall, 2003; Pohjolainen, Pomoell, and Vainio, 2008; Tun Beltran, Cutchin, and White, 2015) with high spectro-temporal resolution (Hariharan *et al.*, 2016) can be used as a proxy for density turbulence measurements in the solar corona, particularly in the range $r < 10\ R_\odot$ which is presently unavailable.

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Disclosure of Potential Conflicts of interest We declare that there are no conflicts of interest for the work presented here.

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