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# Retrieving characteristics of IGW parameters with least uncertainties using hodograph method

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**Abstract.** We have analyzed time series of wind velocities measured with high resolution GPS-radiosonde ascents continuously for 120 h from Hyderabad with an interval of 6 h. Hodograph method has been used to retrieve the IGW parameters. Background winds are removed from the time series by detrending whereas polynomials of different orders are removed to get the fluctuations from individual profiles. Butterworth filter is used to extract monochromatic IGW component. Another filter FIR1 is tried in a similar manner to test the effects of filters in estimating IGW characteristics. Results reveal that the fluctuation profiles differ with the change of polynomial orders, but the IGW parameters remain same when Butterworth filter is chosen to extract the monochromatic wave component. FIR1 filter also produces acceptable results with a broader range. The direction of wave propagation is confirmed with additional temperature information which needs a large number of hodographs for statistical significance.

## 1 Introduction

It is well documented that gravity waves of different scales play an important role in maintaining the large-scale circulation of the middle atmosphere. A large number of studies have been carried out to characterize these waves by using different techniques. A very common, established and standard procedure of characterizing Inertia Gravity Waves (IGW) with frequencies close to Coriolis frequency is by hodograph method (Guest et al., 2000; Ogino et al., 2006; Niranjan Kumar et al., 2011). Radiosonde data of horizontal winds and temperature have been extensively used to study these waves (Tsuda et al., 2004; Vincent and Alexander, 2000; Gong et al., 2008; Chane-Ming et al., 2010, 2014; Murphy et al., 2014; Kramer et al., 2015). Nastrom and VanZandt (1982) reported good accuracy in gravity wave parameters derived using balloon measurements since balloons have good aerodynamic responses. In a simulation study Wei and Zhang (2014) have demonstrated that gravity waves with different frequencies and generated by different sources like jet-imbalance and convection can coexist together. The popular hodograph method demands the presence of a single coherent wave in the fluctuation profiles and does not yield good result when a mixture of various frequencies are present. The gravity wave parameters extracted by hodograph method might also be inaccurate when multiple waves are present in the data (Eckermann and Hocking, 1989).

Hodograph method is based on linear theory of gravity waves whereas the dynamics of the flow is more complex and non-linear which introduces some uncertainties in the interpretation. There are several sources of errors in this method which have been described in Zhang et al., (2004). These authors compared the gravity wave characteristics obtained using hodograph method with the values derived from 4D output of their simulation study. A narrow bandwidth filter used by them to extract the fluctuations of a near-monochromatic wave resulted in large uncertainties in the horizontal wavelength which got reduced for waves with shorter vertical wavelengths. Even the spatial variations of the wave characteristics were found to be large. Moreover, since the hodographs are quite variable, a large number of hodographs (profiles) are required to get accurate results of gravity wave parameters with some statistical significance (Hall et al., 1995). This defeats the very advantage of the hodograph method which is capable of retrieving GW parameters from a single set of vertical profiles of zonal and meridional winds.

The present paper attempts to overcome the inconsistency of hodograph method in delineating the characteristics of IGW from velocity fluctuations obtained with radiosonde measurements.

## 2 Experiment and Data

An intensive campaign with high resolution (i-Met, USA) GPS–radiosonde flights was carried out from the campus of India Meteorological Department (IMD), Hyderabad (17.4 ºN, 78.5 ºE) with four flights a day at an interval of 6 h for 5 consecutive days (20 flights) between 30 April and 4 May, 2012 to study the characteristics of IGW. The timings of the flights were 05:30, 11:30, 17:30 and 23:30 LT. The accuracy of wind and temperature measurements provided by the manufacturer is ±1 $ms^{-1}$ and ± 0.2 K respectively. There was one data gap at 11:30 LT on 4 May, 2012 which was linearly interpolated to get continuous time series of wind velocities. High resolution (~4 – 10 m) wind data obtained directly from balloon flights were first sorted in ascending order of height since the balloons occasionally drift downwards by a few meters. Wind profiles were visually inspected for outliers and such outliers, if any, were removed. The gaps were filled up by linear interpolations. The wind profiles were then interpolated vertically to have a constant height resolution of 50 m. This method is useful to smooth the profiles and to maintain a good resolution in height.

## 3 Analysis and Discussion

Experiments were carried out for five days with a view to getting continuous horizontal wind velocities for 120 h with a regular interval of 6 h keeping in mind that the IGW period over the site is ~40 h. The continuous zonal and meridional wind datasets are detrended (linear trend removed) to obtain time series of fluctuations. A third order Butterworth filter with a band-pass between 36 and 44 h is applied to the wind perturbations to retrieve the IGW fluctuations with zero phase distortion. The sufficiently wide band of the time filter is helpful to reduce the Doppler shift of IGW frequency (Niranjan Kumar et al., 2011). Ehard et al., (2015) also recommended the usage of Butterworth filter in extracting gravity waves over a wide range of periods from temperature perturbations measured by lidar. The filtered horizontal winds at particular heights are depicted in Fig. 1a – 1d which show the presence of IGW with a period of ~ 40 h. FFT analyses carried out with filtered wind data also reveal the presence of a clear monochromatic wave of the same period (Fig. 1e – 1h) which satisfies the requirement of hodograph method.

Hodographs plotted with this time-wise filtered zonal and meridional wind perturbations (u′, v′) are quite noisy and it is difficult to identify proper closings. The fluctuation profiles are, therefore, further band-pass filtered with a cut-off at 1.5 – 4 km which produced proper elliptic hodographs. The number of proper hodographs obtained from 20 pairs of vertical profiles of u′ and v′ are 124. A few IGW parameters have been extracted assuming linear dispersion relations (Cho, 1995; Tsuda et al., 1994). The intrinsic wave frequency (ω) is calculated from the ratio of minor to major axes of the ellipse.

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$$\frac{v'}{u'} = -i\left(\frac{f}{\omega}\right), \quad (1)$$

where $f$ is the inertial frequency and $v', u'$are the meridional and zonal wind fluctuations respectively. $f$ is computed as

$$f = \frac{\sin}{{}^{1}/_{2}day} \quad (2)$$

where $\varphi$ is the latitude of the place. The horizontal wave number k is found using the relation

$$k = m\omega/N \quad (3)$$

$N$ being the Brunt – Väisalä frequency and m is vertical wave number.

Intrinsic periods of IGW obtained from hodographs range between 20 – 28 h. The vertical and horizontal wavelengths inferred from the hodographs are between 2.0 to 2.8 km and between 493 – 846 km respectively. The direction of horizontal wave propagation is parallel to the major axis of the ellipse which is uncertain by 180°. This uncertainty can be removed with the help of additional temperature information. Temperature perturbation profiles are obtained by removing 5$^{th}$ order polynomial fits from the simultaneous temperature profiles and filtering them height-wise with a band-pass Butterworth filter between 1.5 and 4 km. Hodographs of u′ – v′ and u′ – t′ are capable of deciding the final directions of propagation of the wave (Hu et al., 2002). The unambiguous direction of propagation of IGW is observed to be south-east (62%) in this analysis.

Next we chose a different filter FIR1 of order 6 to test the effect of filtering on hodograph method since the vertical wavelength and intrinsic frequency are reported to be highly vulnerable to the filter used (Zhang et al., 2004). We followed the same procedure to delineate the IGW parameters as described before using Butterworth filter. The detrended and time-wise filtered horizontal wind profiles at a few heights and the corresponding FFT peaks are illustrated in Fig. 2a – 2d and 2e – 2h respectively. Both the time variation of wind fluctuations and the FFT peaks do not show distinct IGW periods. The frequency responses of Butterworth filter of 3$^{rd}$ order and FIR1 of 6$^{th}$ order are shown in Fig. 3. The Butterworth filter shows a sharp cut-off and also has the advantage of producing good result with a much lower filter order than the corresponding FIR1 filter. A few hodographs plotted with horizontal wind perturbations using both the filters are displayed in Fig. 4a – 4d. The IGW parameters derived from these hodographs are listed in Table 1. The ranges of horizontal wavelength, vertical wavelength and intrinsic period are observed to be broader using FIR1 filter compared to those obtained using Butterworth filter.

Hodographs are generally plotted with the fluctuations derived from data of individual sounding by removing polynomials of 1$^{st}$ or 2$^{nd}$ order. We treated the measured vertical profiles of zonal and meridional winds as single individual set (not time series) and approximated the backgrounds by polynomials of different (2 to 9) orders. Fig.5 depicts the different fits and the corresponding wind profiles. The fluctuation profiles obtained by removing polynomials of 4, 5 and 6 orders show close agreements whereas appreciable differences could be noticed for others (figure not shown). These profiles are then filtered with a 3$^{rd}$ order Butterworth filter height-wise to retain IGW oscillations with short vertical wavelengths (1.5 – 4 km). IGW parameters obtained from the hodographs plotted with these fluctuations match extremely well with those delineated from the previous computation where the background was removed from the time series by detrending and filtering was done both time-wise (36 – 44 h) and height-wise (1.5 – 4 km).

The individual profiles of winds and temperature are then analyzed in a similar manner using FIR1 filter with height instead of Butterworth filter. The perturbation profiles (after removing backgrounds with different orders) and the filtered fluctuation profiles using both Butterworth and FIR1 filters are shown in Fig. 6a – 6c and 6d – 6f for both the wind components, respectively. It is clearly observed that the Butterworth filter can extract the monochromatic IGW fluctuations very efficiently. The retrieved IGW parameters retain same numerical values (except after decimal points) irrespective of the background removals. Results obtained with FIR1 filter also belong to the same range but with a broader band which is illustrated in Table 2 for different orders. The direction of propagation of IGW inferred from different ways of computation is unambiguously south-east. This demands a large number of hodographs to finalize the direction with some statistical significance.

## 4 Summary

Balloon borne experiments have been conducted for five days with an interval of 6 h to characterize IGW using hodograph method. The method is helpful in identifying low-frequency IGW but suffers from several uncertainties. We have utilized the time series of wind fluctuations to extract IGW component by filtering and confirmed it with spectral analysis. Results obtained by using Butterworth and FIR1 filters are compared. A band-pass Butterworth filter with a sharp cut-off is found to isolate the monochromatic IGW component very efficiently. Backgrounds of individual wind profiles have been approximated with polynomials of different orders when the perturbation profiles show reasonable differences. The differences are observed to get reduced when Butterworth filter is used to isolate the IGW components, whereas differences still persist with FIR1 filter. IGW parameters delineated from the corresponding hodographs using the former filter agree extremely well for different order polynomial removal. Results obtained with FIR1 filter also show reasonable agreement but with a broader range. Filtering appears to be of great importance in removing uncertainties of hodograph method. The unambiguous direction of wave propagation can be ascertained using additional and simultaneous temperature information but a large number of hodographs are needed to confirm it with statistical significance.

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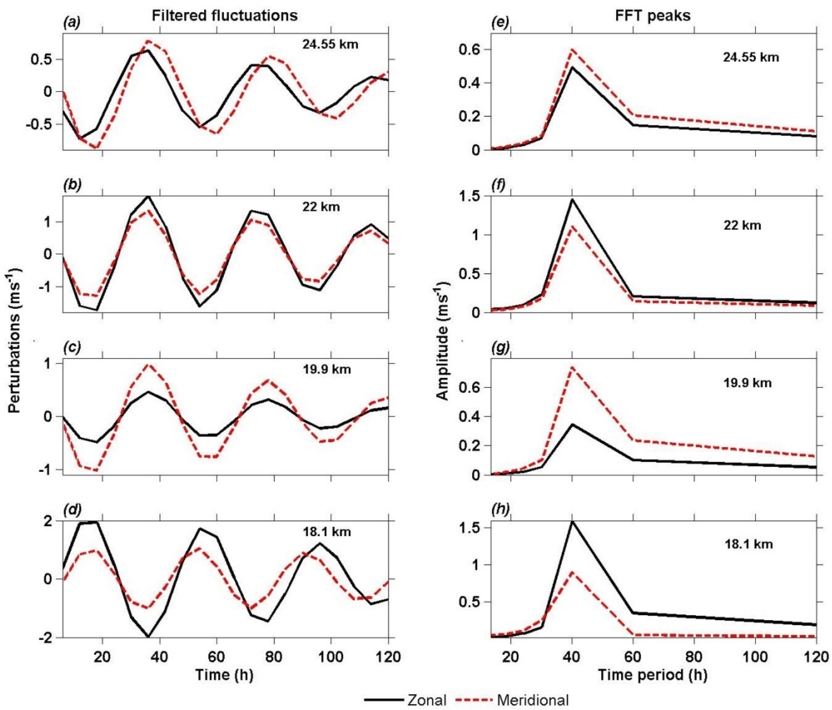


**Figure 1.** Time series of filtered (Butterworth filter) fluctuations (ms$^{-1}$) of zonal and meridional winds (a – d) and corresponding FFT spectra (e – f) at a few heights.

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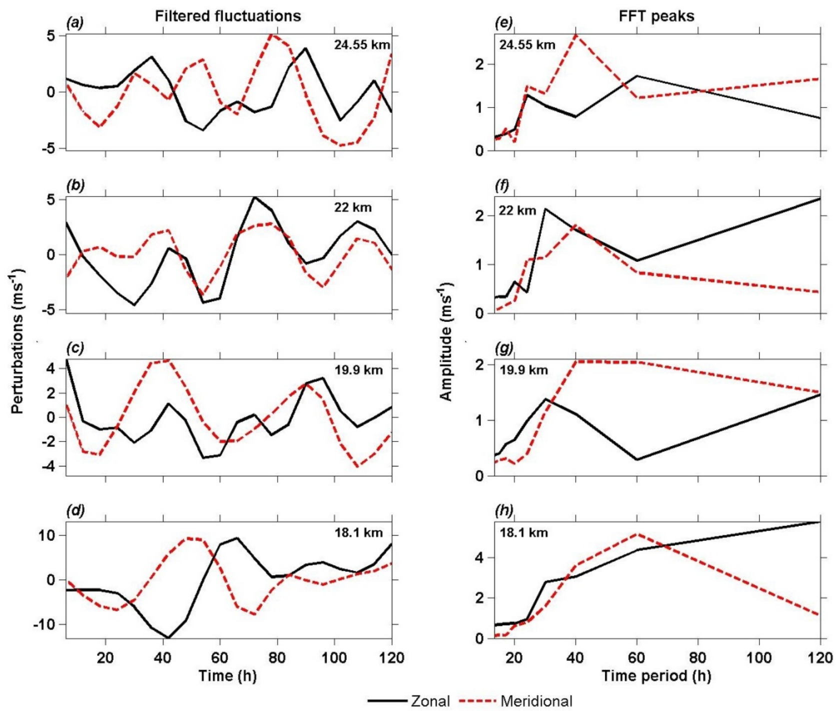



191
192 **Figure 2.** Same as in Figure 1 but with FIR1 filter.

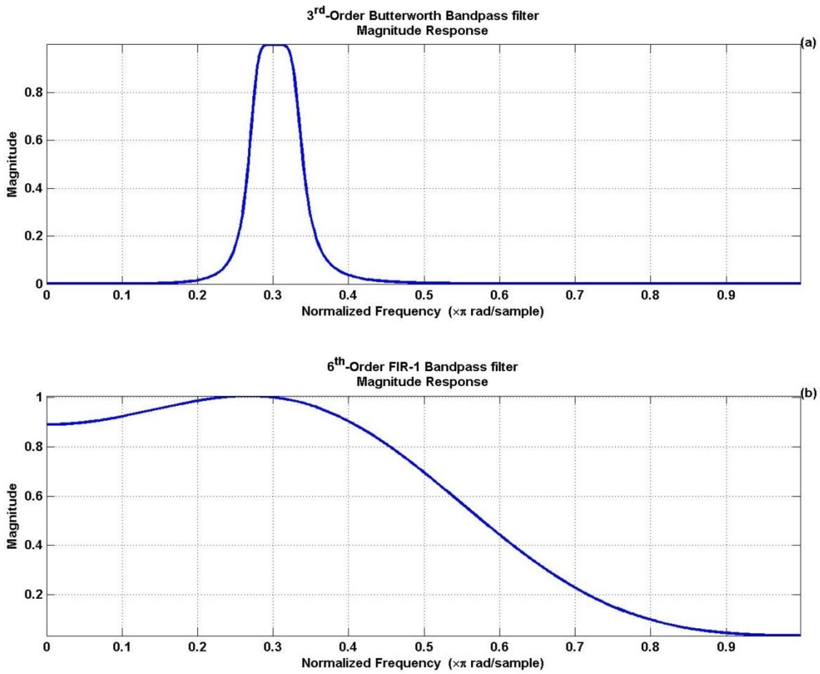



**Figure 3.** The filter responses of Butterworth (a) and FIR 1(b) filters.

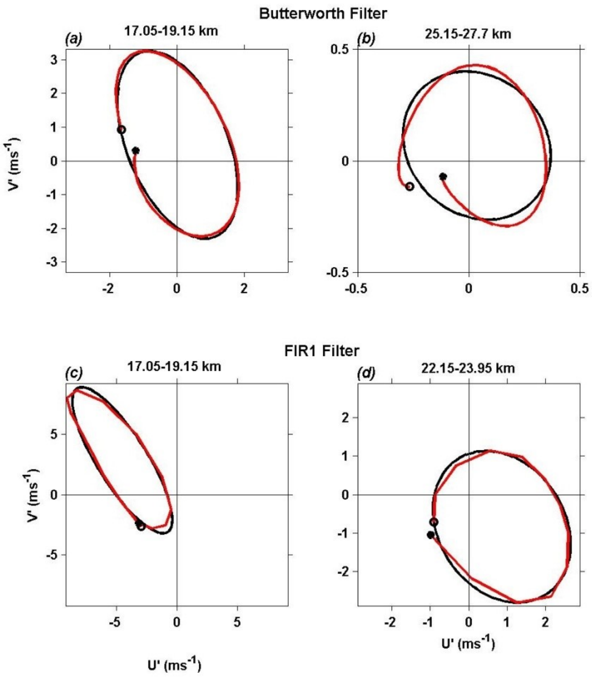
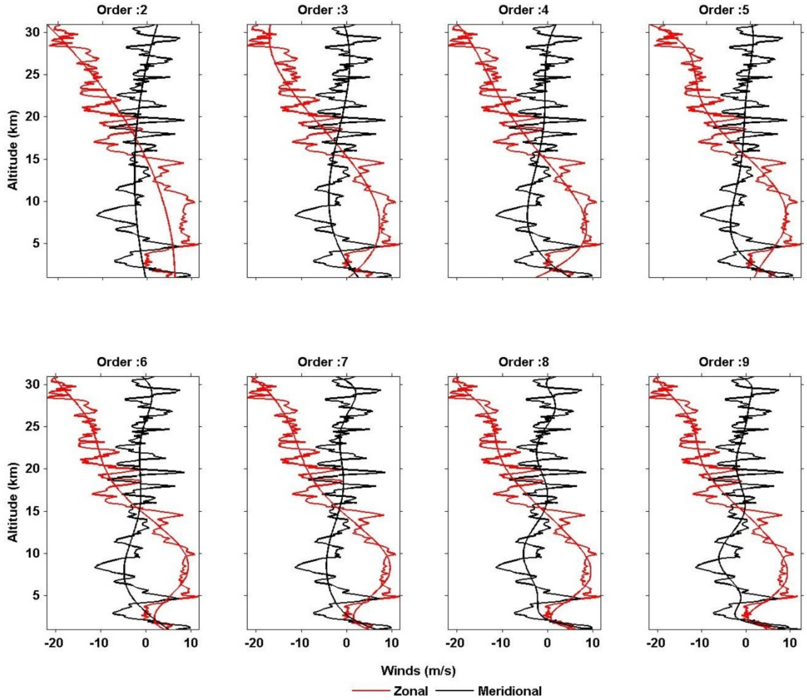



**Figure 4.** Hodographs of horizontal wind fluctuations (ms$^{-1}$) obtained using Butterworth (a, b) and FIR1 (c, d) filters. An open circle and a solid circle in each hodograph indicate the lowest and highest altitudes, respectively. The thin curves represent the elliptical fits.




199
200 **Figure 5.** Profiles of zonal and meridional winds ($ms^{-1}$) and their fits with different orders.

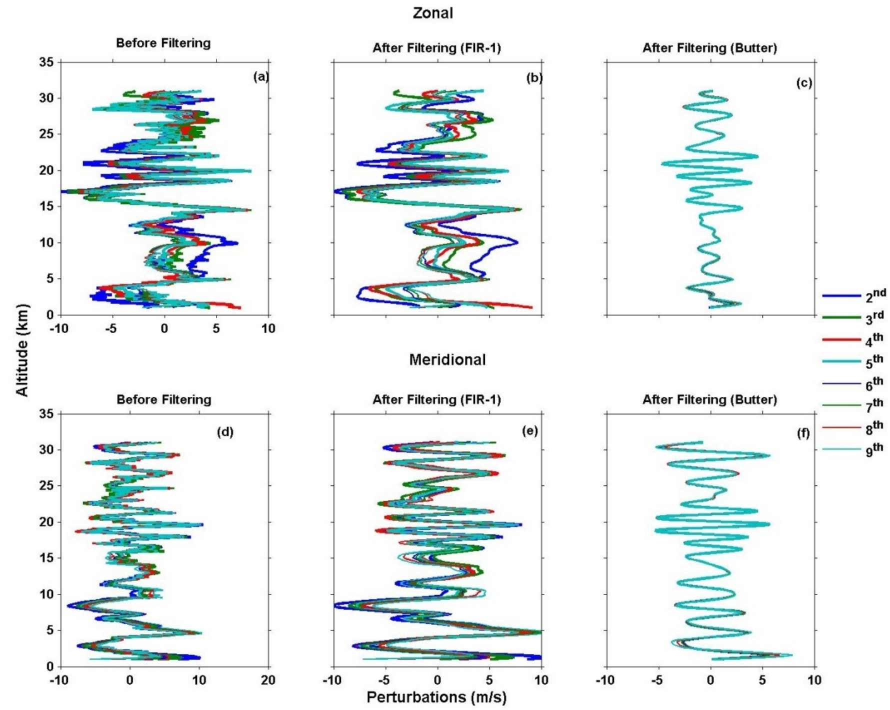



**Figure 6. Upper panel:** Vertical profiles of zonal wind fluctuations ($ms^{-1}$) after approximating the backgrounds with different order ($2^{nd}$ – $9^{th}$) polynomials (a) and filtering height-wise with Butterworth filter (b) and FIR1 filter (c). **Lower panel:** Same as upper panel but for meridional wind fluctuations.

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**Table 1:** Comparison of IGW parameters using detrended time series fluctuations and obtained with different filters

| Parameters | Butterworth filter | FIR1 filter |
|---|---|---|
| Horizontal wavelength (km) | 493 – 836 | 227 – 800 |
| Vertical wavelength (km) | 2.0 – 2.8 | 1.5 – 3.5 |
| Intrinsic Period (h) | 20 – 28 | 10 – 30 |
| Ratio of minor to major axis | 0.44 – 0.76 | 0.35 – 0.87 |
| Direction of propagation | South-East (62%) | South-East (63%) |

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**Table 2:** Comparison of IGW parameters using individual set of wind fluctuation profiles by removing the backgrounds with different order polynomial fits and using both the filters.

| **Parameters** | | **Horizontal wavelength (km)** | **Vertical wavelength (km)** | **Intrinsic Period (h)** | **Ratio of minor to major axis** | **Direction of propagation** |
|---|---|---|---|---|---|---|
| **Filter** | **Order number** | | | | | |
| **Butterworth** | **2 to 9** | 388-770 | 2.0-2.6 | 16.25 | 0.34-0.71 | South-East (52%) |
| **FIR1** | **2** | 300-722 | 1.7-4 | 15.23 | 0.34-0.71 | South-East (63%) |
| | **3** | 426-663 | 1.7-4 | 17.3-23.9 | 0.32-0.71 | South-East (65%) |
| | **4** | 371-683 | 1.7-3.2 | 15.8-23.5 | 0.32-0.71 | South-East (64%) |
| | **5** | 250-850 | 1.8-3.1 | 16-25 | 0.32-0.7 | South-East (60%) |
| | **6** | 332-712 | 1.7-4 | 15.8-24.7 | 0.3-0.69 | South-East (66%) |
| | **7** | 403-711 | 1.7-4 | 16.1-25.4 | 0.3-0.69 | South-East (65%) |
| | **8** | 330-685 | 1.8-3.1 | 16-25 | 0.32-0.68 | South-East (63%) |
| | **9** | 322-577 | 1.7-4 | 16.2-25 | 0.31-0.68 | South-East (66%) |