Simulation of Wind Profile Perturbations for Launch Vehicle Design

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Nomenclature

PSD $\quad$ = $\quad$ power spectrum density $(m^2/s^2)/(1/m)$

NPSD $\quad$ = $\quad$ normalized PSD

MNPSD $\quad$ = $\quad$ mean normalized PSD

c $\quad$ = $\quad$ parameter in empirical model for MNPSD

n $\quad$ = $\quad$ wave number (1/m)

F_j $\quad$ = $\quad$ Fourier series $\quad$ ($\sqrt{(m^2/s^2)/(m/s)}$)

A_j, B_j $\quad$ = $\quad$ components of F_j

$r1_j, r2_j$ $\quad$ = $\quad$ random number sequences that are tangents of "j" uniformly distributed random phase

$\quad$ angles in the interval from $-\pi/2$ to $+\pi/2$

β and γ $\quad$ = $\quad$ parameters of a Gamma distribution (s/m) and (dimensionless)

b $\quad$ = $\quad$ parameter for biasing an empirical Gamma distribution (m/s)

σ $\quad$ = $\quad$ standard deviation of high pass filtered wind profile (m/s)

E $\quad$ = $\quad$ variance coefficient of PSD model (m^2/s^2)

EVR $\quad$ = $\quad$ effective vertical resolution (m)

u and v $\quad$ = $\quad$ eastward and northward wind components, respectively (m/s)

z $\quad$ = $\quad$ altitude (km)

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Introduction

Ideally, a statistically representative sample of measured high-resolution wind profiles with wavelengths as small as tens of meters is required in design studies to establish aerodynamic load indicator dispersions and vehicle control system capability [1,8]. At most potential launch sites, high-resolution wind profiles may not exist. Representative samples of Rawinsonde wind profiles to altitudes of 30 km are more likely to be available from the extensive network of measurement sites established for routine sampling in support of weather observing and forecasting activity. Such a sample, large enough to be statistically representative of relatively large wavelength perturbations, would be inadequate for launch vehicle design assessments because the Rawinsonde system accurately measures wind perturbations with wavelengths no smaller than 2000 m (1000 m altitude increment). The Kennedy Space Center (KSC) Jimsphere [2,3,6] wind profiles (150/month and seasonal 2 and 3.5-hr pairs) are the only adequate samples of high resolution profiles (~150 to 300 m effective resolution, but over-sampled at 25 m intervals) that have been used extensively for launch vehicle design assessments. Therefore, a simulation process has been developed for enhancement of measured low-resolution Rawinsonde profiles that would be applicable in preliminary launch vehicle design studies at launch sites other than KSC.

Simulation Process

The simulation process is based on a power spectrum density (PSD) model for wind profile perturbations derived from samples of high-resolution KSC Jimsphere wind profiles. The magnitude of the simulated perturbations is established by assignment of the total perturbation energy to the simulated perturbation profile from a model based on KSC Winter season perturbation data that tend to be more severe than in the other seasons. Quantitative geographical and seasonal dependent differences in wind perturbation severity are not addressed in this note. The model for the normalized PSD (NPSD) for wind component profile perturbations is of the form

$$NPSD(n) \propto n^c \qquad (1)$$

Where, n is wave number (1/m). Normalization with respect to the variance produces a PSD that integrates to unity over the applicable wavelength range. The value of c (-2.62) is derived from the mean NPSD (MNPSD) of the each wind component (Fig.1) calculated from 518 high-pass filtered KSC Winter Jimsphere profiles. The high-pass filtered wind profile is the inverse transform of the truncated Fourier transform of the wind profile; harmonics for wavelengths greater than 2000 m are set equal to zero. A high-pass filtered Jimsphere profile is illustrated in Fig.1. The wavelength range of the high-pass filtered Jimsphere wind component profiles is 50 to 2000 m. The lines with slope minus 2.62 illustrated in Fig.2 represent the form of the PSD model (Eq.1), which is a very good fit to the mean normalized PSD (ragged data in Fig.2) for wave number as large as 0.007 m^{-1} (~150 m wavelength) for the eastward wind component, u, and 0.0050m^{-1} (~200 m wavelength) for the northward wind component, v; the effective vertical resolution (EVR) of the Jimsphere system is defined by these wavelengths. The degradation of the Jimsphere system signal to noise ratio at higher wave numbers (inverse wavelength) is evidenced by the deviation of the MNPSD from the minus 2.62 slope illustrated in Fig.2. These values of effective vertical resolution based on analysis over the entire altitude range are in general agreement with other studies[3,6]. If segmented profiles are examined the EVR can be as large as 300 m. This is because the ROSE data processing scheme of the Jimsphere system adjusts the data-smoothing interval as a function of detected noise level, which tends to be larger at high altitudes and large slant ranges (Ref.3).

Application of the PSD model for simulation of wind profile perturbations in the wavelength range requires real and imaginary components, A and B, of a Fourier series, F, to be uniquely defined for each simulation.

$$F_j = A_j + B_j i \qquad (2)$$

In Eq.2 j is the Fourier series harmonic index (1-400) and $i = \sqrt{-1}$. The values for A_j and B_j are calculated from

$$A_j = \frac{\sqrt{PSD_j}}{\sqrt{1+rl_j^2}} \frac{rl_j}{|rl_j|} \quad B_j = \frac{\sqrt{PSD_j}}{\sqrt{\frac{1+rl_j^2}{rl_j^2}}} \frac{r2_j}{|r2_j|} \qquad (3)$$

where the PSD, of each wind component is

$$PSD_j = A_j^2 + B_j^2 , \qquad (4)$$

and, rl_j is a random number sequence that is the tangent of "j" uniformly distributed random phase angles in the interval from $-\pi/2$ to $+\pi/2$. The random number $r2_j$ is also uniformly distributed within equal intervals on either side of zero. The quantities $rl_j/|rl_j|$ and $r2_j/|r2_j|$ ensure that the random phase at each harmonic can be in any quadrant. A unique set of "j" values of r1 and r2 are generated for each simulated wind profile. Thus, each simulated wind perturbation profile is uniquely determined by its unique random phase distribution. The phase distribution determines how the Fourier components combine to produce a unique simulated time series, for an invariant PSD at each harmonic. Note that the PSD in Eqs.3 and 4 is not normalized, i.e. it is of the form

$$PSD(n) = En^c \qquad (5)$$

Parameter E is set such that a desired value of the variance is obtained when the PSD function is integrated over the wave number range $(1/2000-1/50 \text{ m}^{-1})$. The units of PSD are variance per spatial frequency interval, which for this study is $\{(m^2/s^2)/(1/m)\}$. The final step in the simulation process is to generate the simulated time series by calculating the inverse Fourier transform of F_j. Two sets of values for the series F_j, calculated from A_j and B_j (Eqs.2 and 3) are required; one set for each wind component. The variance of each simulated wind component perturbation profile is adjusted to a value obtained by random selection from an empirical gamma probability distribution of

standard deviation, σ_n (square root of variance) derived from the 518 KSC winter high-pass wind component profiles. The gamma probability density functions in the 50 to 2000 m- wavelength range are of the form:

$$\sigma(\beta,\gamma) = \frac{\beta^\gamma}{\Gamma(\gamma)}(y-b)^{\gamma-1}\exp\left[-\beta(y-b)\right] \quad (6)$$

Where, β and γ are estimated from sample statistics of σ for each wind component and b is an empirically derived truncation parameter that ensures the best fit to the observed distribution.

$$\gamma = \left(\frac{\text{mean}(\sigma)}{\text{stdev}(\sigma)}\right)^2 \quad \beta = \frac{\gamma}{\text{mean}(\sigma)} \quad (7)$$

The values for β, γ and b are listed in Table 1. The observed and theoretical cumulative probability functions (CPFs) for wind component standard deviation (50-2000 m wavelength-band) are illustrated in Fig.3. The theoretical CPF is derived by integration of Eq.6 from a lower limit of zero to any desired value "y" for σ.

Table 1. Parameters β\{m/s\}, γ\{dimensionless\} and b\{s/m\} of gamma distributions for u and v wind component perturbation standard deviation, σ.

Component	β	γ	b
u	12.13	12.43	0.42
v	6.89	5.31	0.90

The simulated wind component perturbation profiles are adjusted such that the variation of component standard deviation as a function of altitude observed in the original sample of 518 high-pass filtered Jimsphere wind component profiles is reproduced in the simulated profiles. This

behavior is illustrated in Fig.4. The smooth curves are fourth order polynomial functions of altitude z(km) fitted to the standard deviations of the original data, 3-16 km.

$$\sigma_u\{z\} = 1.486 - 0.120z + 1.931 \times 10^{-4}z^2 + 1.489 \times 10^{-3}z^3 - 5.319 \times 10^{-5}z^4$$
$$\sigma_v\{z\} = 1.912 - 0.232z + 0.011z^2 + 1.348 \times 10^{-3}z^3 - 5.860 \times 10^{-5}z^4 \qquad (8)$$

These functions are normalized with respect to their values at z = 0. Multiplication of each simulated profile by the normalized function produces the desired variation with respect to altitude. The profiles are then re-adjusted such that the standard deviation over the altitude range is equivalent to the original standard deviation. These operations are expressed by Eqs.9-12,

$$\sigma'_u\{z\} = \sigma_u\{z\}/\sigma_u\{0\} \qquad (9a)$$
$$\sigma'_v\{z\} = \sigma_v\{z\}/\sigma_v\{0\} \qquad (9b)$$
$$u'\{z\} = u\{z\}\sigma'_u\{z\} \qquad v'\{z\} = v\{z\}\sigma'_v\{z\} \qquad (10)$$
$$ru = sd(u')/sd(u) \qquad rv = sd(v')/sd(v) \qquad (11)$$
$$u''\{z\} = u\{z\}/ru \qquad v''\{z\} = v\{z\}/rv \qquad (12)$$

Note that: $\sigma\{z\}$ and $\sigma'\{z\}$ are the standard deviations (original and normalized) for the entire Jimsphere data base at each altitude, whereas "sd" in Eqs. 11 and 12 are the standard deviations of each wind component profile.

To address a concern that the high-pass filtered wind component standard deviation illustrated in Fig.4 may be unduly influenced at high altitudes by Jimsphere tracking system noise and data gaps, the standard deviations were also calculated from a sample of 26 high-resolution AMPS wind profiles[4,5]. The AMPS (Automated Meteorological Profiling System) wind measurement error is not sensitive to balloon azimuth and altitude because it is based on GPS tracking for determination of balloon position and calculation of wind vectors along the balloon trajectory. The standard deviations from this relatively small sample of AMPS profiles obtained during a 5-month period exhibit the same behavior derived from the larger Jimsphere winter sample. The empirical function derived from the Jimsphere sample also fits the AMPS variation.

Enhancement of Rawinsonde Profiles

Enhancement is accomplished by adding a unique simulated wind component perturbation profile to each Rawinsonde wind component profile that has been cubic-spline interpolated to the same altitude interval (25 m) as the simulated profile. An original and enhanced Rawinsonde profile is illustrated in Fig.5.

Conclusion

Detailed wind profiles that are statistically representative at a selected launch site are a critical requirement in design studies to establish vehicle structural integrity and program risk for vehicle operations within the range of detailed wind profile variability. A methodology has been developed for simulation of wind profile perturbations in a prescribed wavelength band. These perturbation profiles to wavelengths as small as 10's of meters are appended to statistically representative low-resolution Rawinsonde wind profile databases that are likely to be available at or near candidate launch sites.. The simulation process is based on the inverse transform of the Fourier series having random components that define the PSD and the uniformly distributed phase angles of the Fourier harmonics. The PSD model for wind profile perturbations is derived from a large sample (518) of Jimsphere detailed wind profiles. Profiles so derived are a reasonable choice for initial launch vehicle design studies. Once a launch site is selected it would be prudent to establish a wind profile measurement program based on Jimsphere or its equivalent aimed to obtain a statistically representative sample of detailed wind profiles. As the development process continues toward commitment to hardware production, the vehicle design originally based on enhanced Rawinsonde profiles could be assessed with the launch site high-resolution wind profiles.

References

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Figures

Fig. 1 High-pass filtered wind components of a Jimsphere profile.

Fig. 2 Mean normalized PSD of 518 winter Jimsphere u and v-component wind profiles and PSD model.

Fig. 3 Observed and gamma cumulative probability of wind profile perturbation standard deviation, wavelength range, 50 to 2000 m.

Fig. 4 Standard deviation of wind components as a function of altitude calculated from 518 high-pass filtered (50 to 2000 m) Jimsphere profiles KSC, winter.

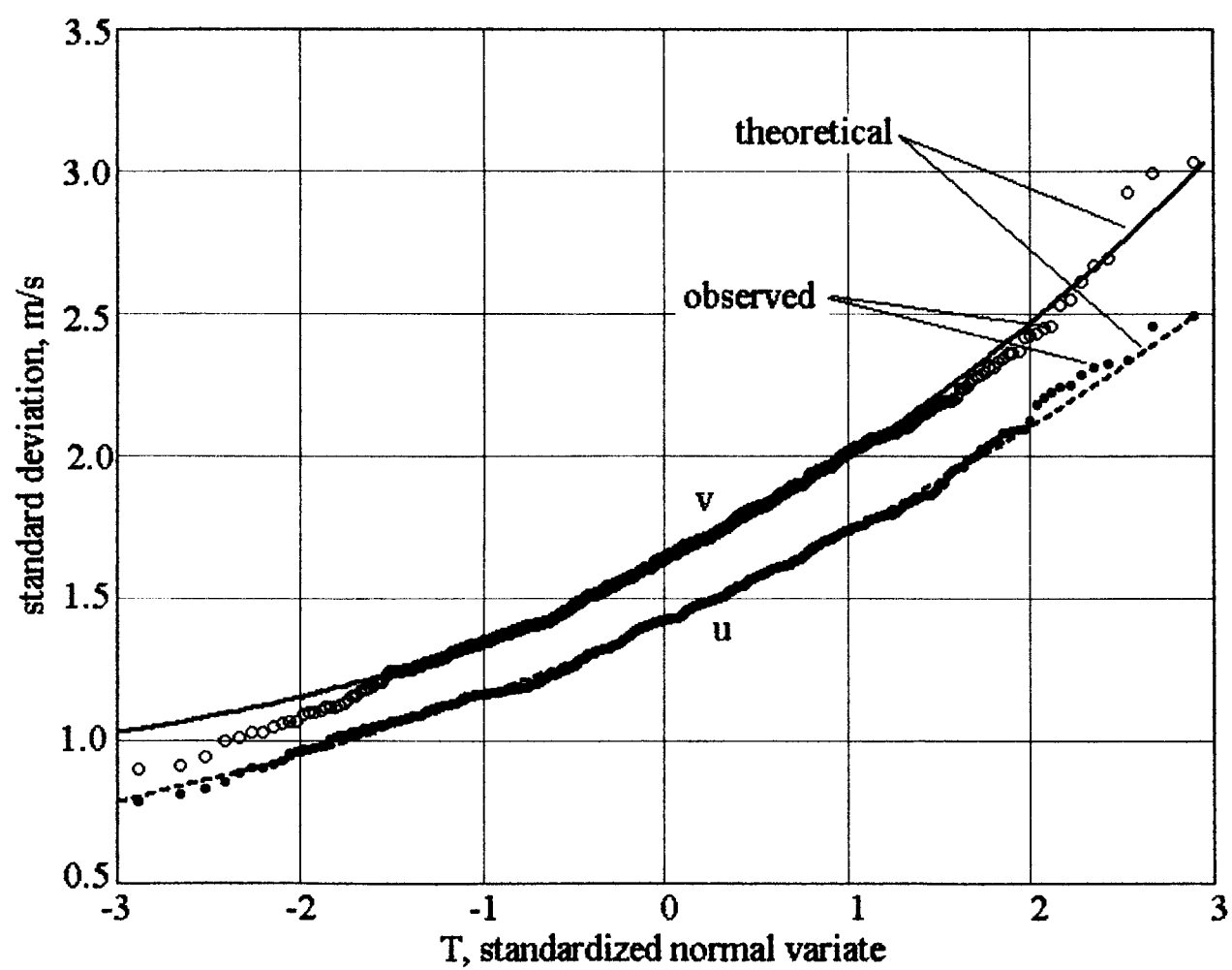Fig. 5 Original (smooth curve) and enhanced Rawinsonde wind components.
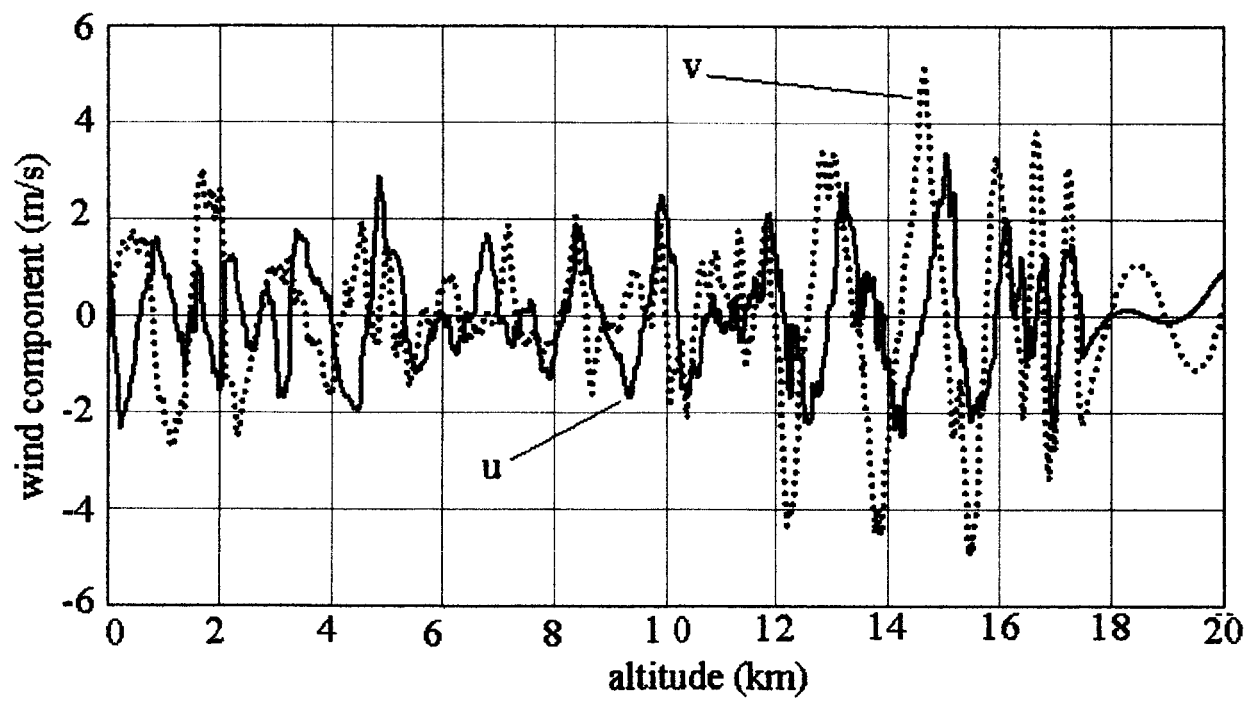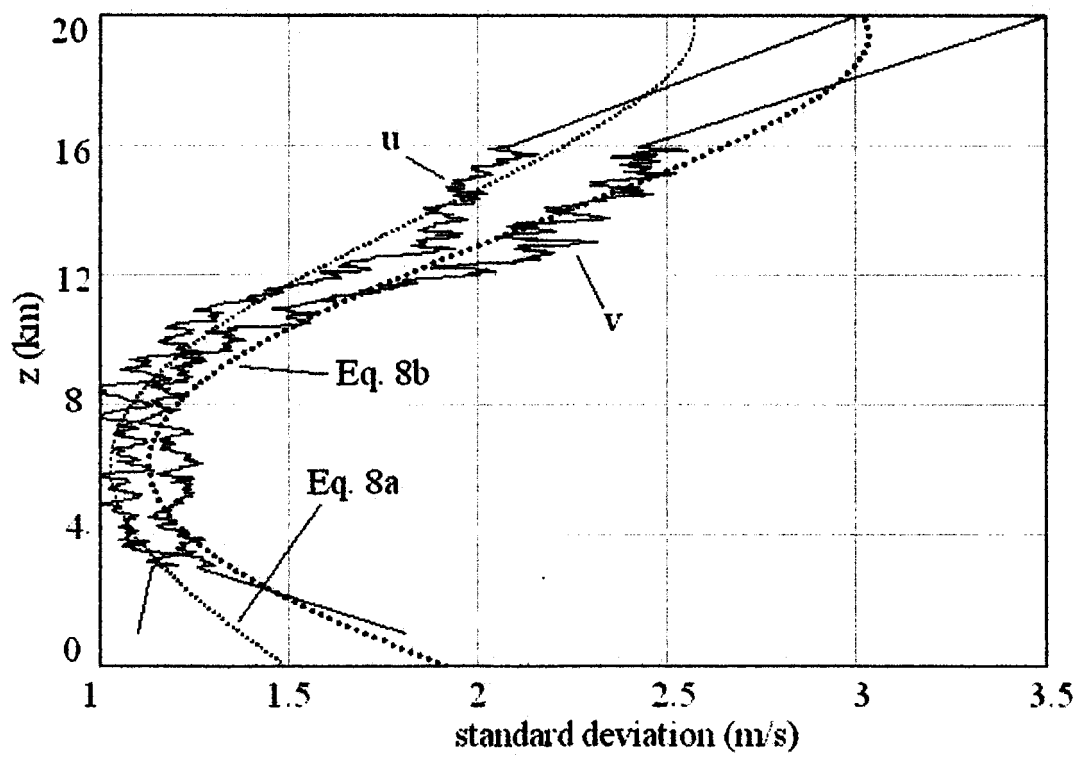
Figure 1
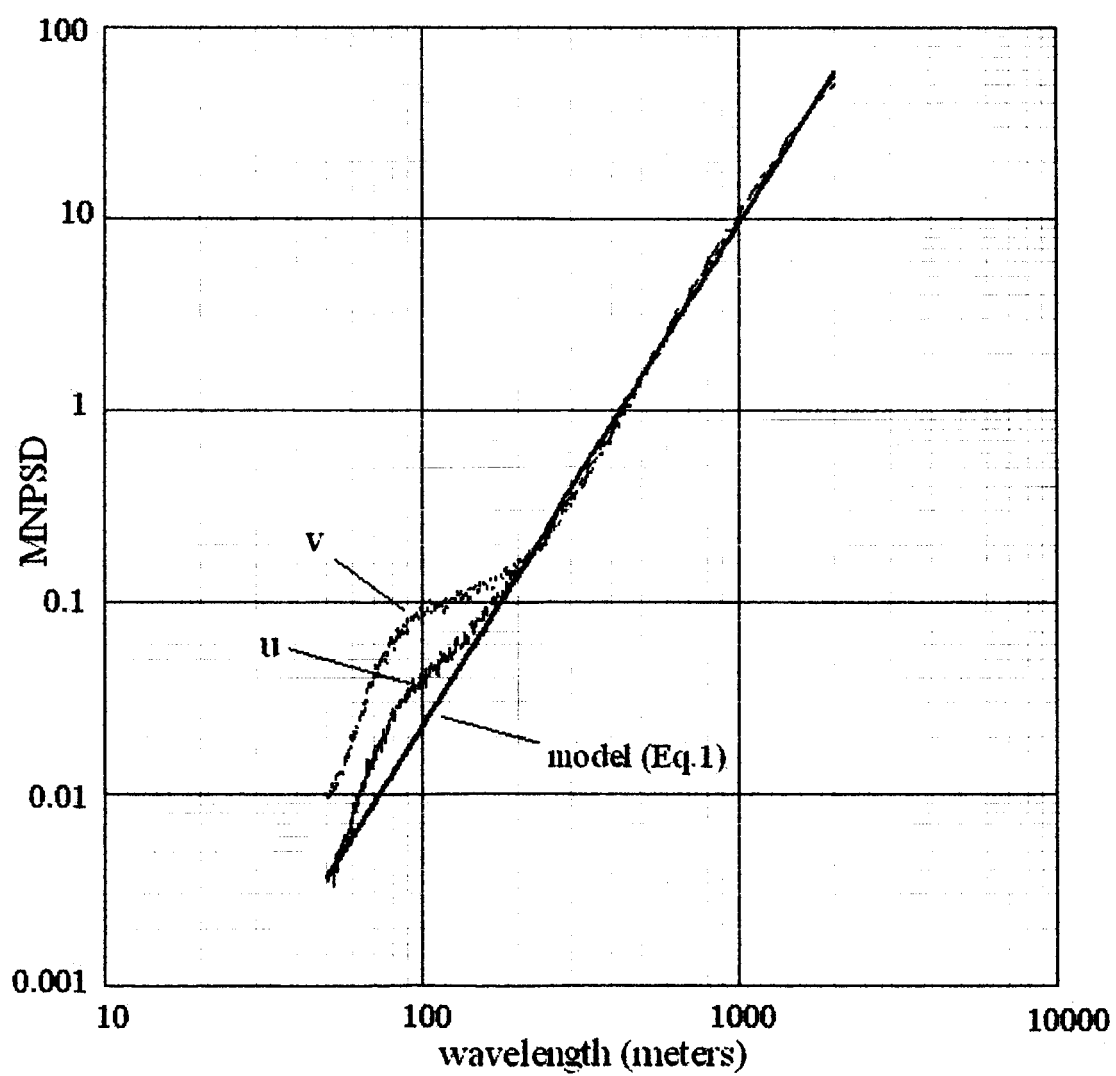
Figure 2

Figure 3

Figure 4

Figure 5