A modified von Karman model for the spectra and the spatial correlations of the offshore wind field

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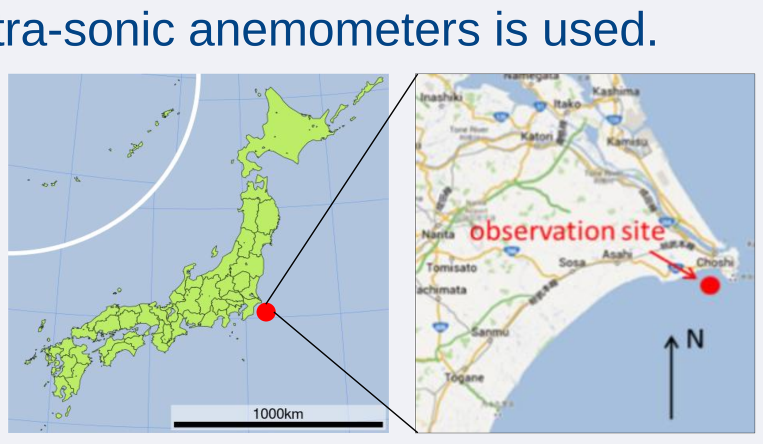
Abstracts

The dynamic response of wind turbines is strongly affected by the turbulence structure of wind field. As life time estimation and damage detection are expected to lead to cost reduction, the accuracy of dynamic analysis required in these techniques should be achieved through the accurate modelling of the three-dimensional wind field. Wind field is modeled in both spectrum and correlation form. While the former is commonly used in design, the latter is applicable for wind field generation using Auto-Regression model, which can include measurement data and thus improve the accuracy.

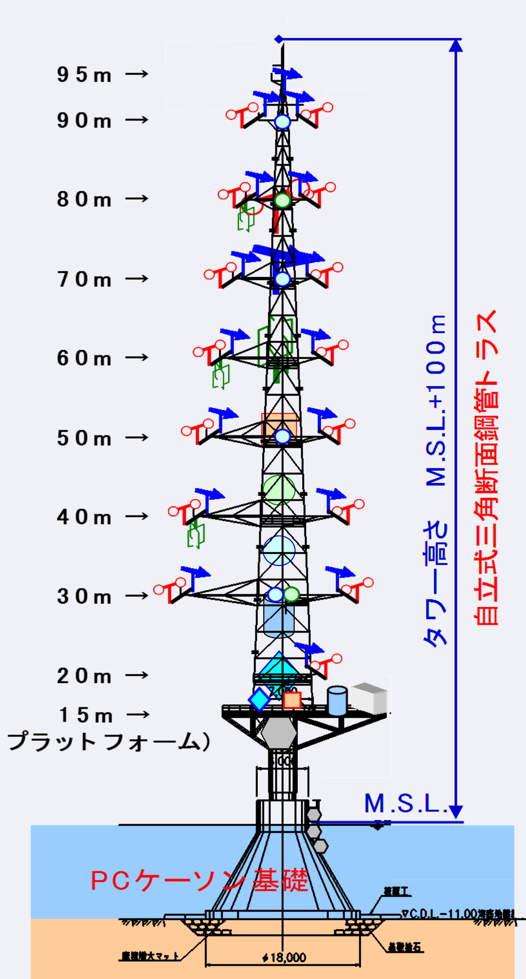
In this study the von Karman model is chosen for modelling of the wind field because of its ability to analytically formulate both spectrum and correlation and to adjust length scales of auto-spectra and spatial co-spectra for three components separately.. The auto-spectrum, auto-correlation, spatial co-spectrum and spatial cross-correlation of the von Karman model are compared to measurement data from offshore ultra-sonic anemometer, and a modified von Karman model is proposed for auto-spectrum and auto-correlation to correct the difference for lateral and vertical components which have been pointed out by previous studies to be the problem of the model. Finally, the turbulence scale parameters are evaluated and compared to the values in the design codes.

Wind Field Measurement

Wind field measurement is carried out at a meteorological mast located 3 km offshore Choshi, Japan. The mast is equipped with meteorological measurement devices listed below. In this study, data from 3 ultra-sonic anemometers is used.



Outline of offshore wind field measurement site



Devices	Number
Cup anemometer	22(22)
Vane anemoscope	23(23)
Ultra-sonic anemometer	3(12)
Barometers	1(1)
Hygrothermograph	3(6)
Differential temparature meter	4(4)
Rain gauge	1(1)
Visibility meter	1(1)
Water temparature gauge	3(3)

Outline of offshore meteorological mast

The mean properties of measurement data used in this study is shown below. Length scales for auto-spectra are calculated from spectra at 0 Hz assuming Taylor's hypothesis, and those for spatial co-spectra are calculated with least square method to fit the von Karman model. Measurement data are properly de-trended.

Mean properties of data used in this study

	U (m/s)	Iu (%)	σv/σu	σw/σu	xLu (m)
2013/3/13	17.4	5.8	0.88	0.69	108.9
2013/4/3	15.0	12.2	0.84	0.65	147.6
2013/4/7	18.0	7.3	0.81	0.62	178.8

Turbulence Models

The forms of auto-spectrum, auto-correlation, spatial cross-correlation and spatial co-spectra of von Karman series are shown for u, v, and w component below. In the original von Karman model, auto-spectrum for v, w component is delivered from u component using isotropy. In this study, the same form is proposed to be used for all three components with length scales in each direction.

Auto-spectrum

＜Proposed u,v,w＞

$$\frac{fS_i(f)}{\sigma_i^2} = \frac{4(fL_i/U)}{(1+70.8(fL_i/U)^2)^{5/6}}$$

＜Original von Karman v,w＞

$$\frac{fS_i(f)}{\sigma_i^2} = \frac{2(fL_i/U)(1+188.8(fL_i/U)^2)}{(1+70.8(fL_i/U)^2)^{11/6}}$$

Auto-correlation

$$\alpha_1 \approx 0.593$$
$$a_1 = 0.747/L_i$$

＜Proposed u,v,w＞

$$R_u(U\tau) = f(U\tau) = \alpha_1|a_1U\tau|^{1/3}K_{1/3}(|a_1U\tau|)$$

＜Original von Karman v,w＞

$$R_{v,w}(U\tau) = g(U\tau) = \alpha_1|a_1U\tau|^{1/3}K_{1/3}(|a_1U\tau|) - \frac{|a_1r|}{2}K_{2/3}(|a_1U\tau|)$$

Spatial cross-correlation

$$R_{jk} = (f(\mathbf{r}) - g(\mathbf{r}))\frac{r_jr_k}{r} + g(\mathbf{r})\delta_{jk}$$

Spatial co-spectrum

＜u component＞

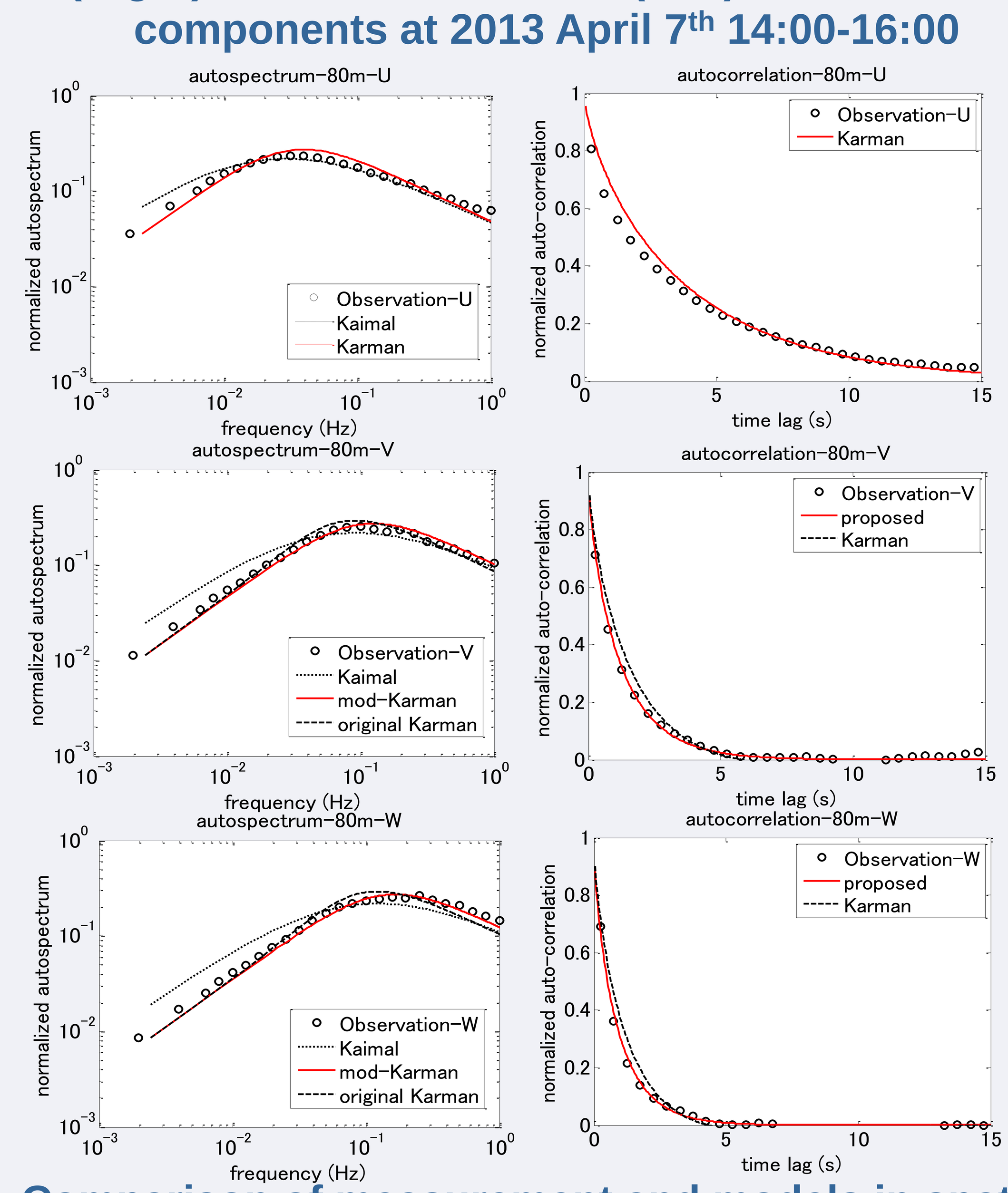
$$C_{ii}(f,\Delta r) = 0.994\left[\theta^{5/6}K_{5/6}(\theta) - 1/2\theta^{5/3}(\theta^{1/6}K_{1/6}(\theta))\right] \quad \theta = \sqrt{\left(\frac{0.747\Delta r}{L}\right)^2 + \left(\frac{2\pi f\Delta r}{U}\right)^2}$$

＜v,w component＞

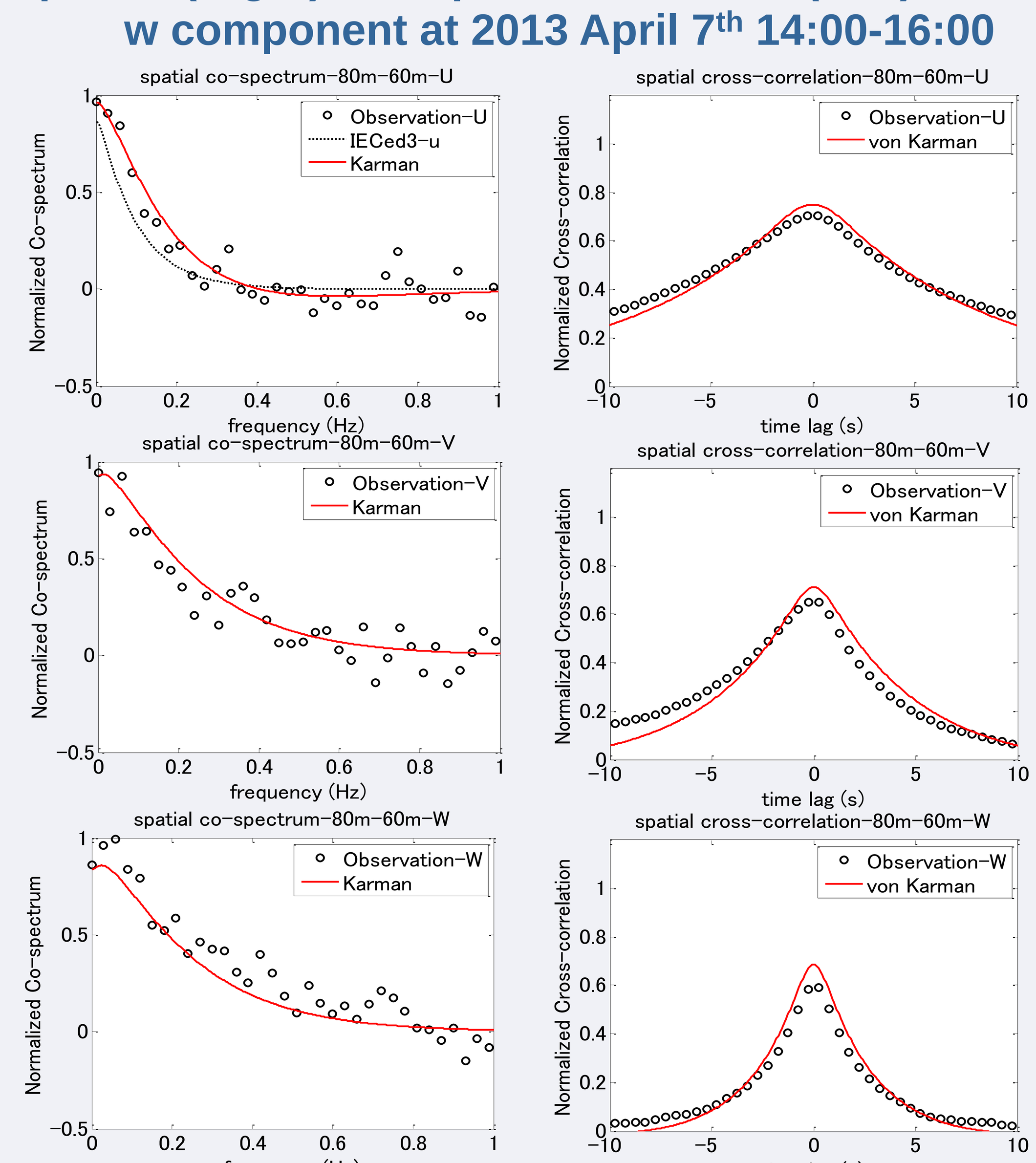
$$C_{ii}(f,\Delta r) = \frac{0.597}{\{2.869\theta^2/(\Delta r/L)^2\}-1}\left[\frac{4.781\theta^2}{(\Delta r/L)^2}\theta^{5/6}K_{5/6}(\theta) - \theta^{11/6}K_{11/6}(\theta)\right]$$

Spectra and Correlations

Comparison of measurement and models in auto-spectra (Right) and auto-correlation(Left) for u, v and w components at 2013 April 7th 14:00-16:00



Comparison of measurement and models in spatial cospectra (Right) and spatial correlation(Left) of u, v, and w component at 2013 April 7th 14:00-16:00



Length Scales

Length scales in turbulence model have large effect in accuracy, and thus need to be properly modeled. In this study, length scale are defined with the equation below using correlations, and the three components in three directions are modeled based on observation. Values suggested in IEC are larger compared with proposed models. Note that horizontal length scales are assumed to be the same with vertical, which needs further investigation.

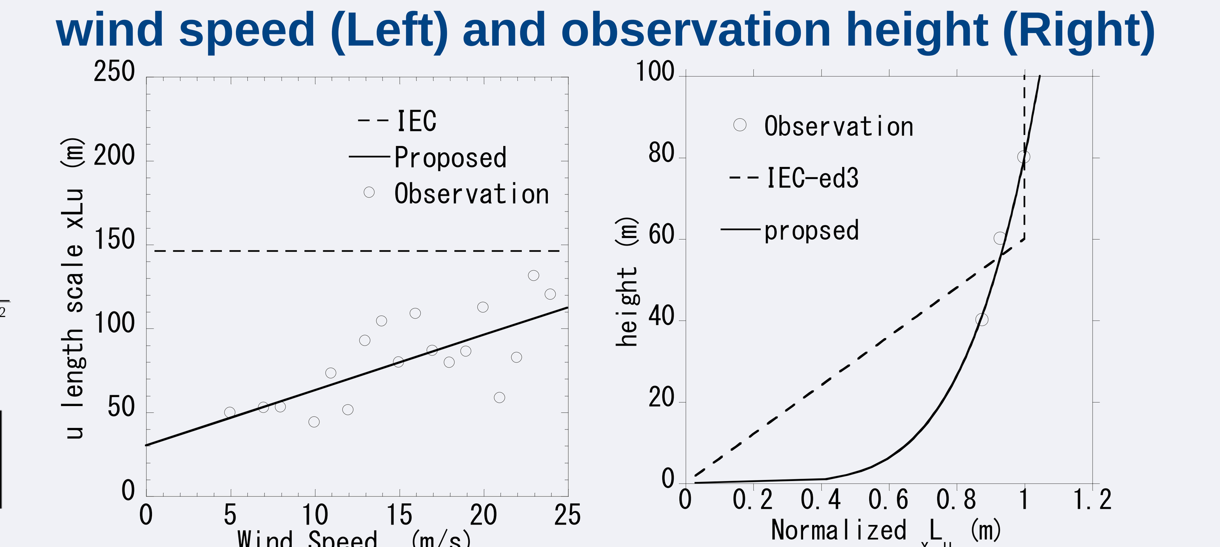
＜Definition of length scale for i-th component in r direction＞

$$sL_i = \int_0^\infty R_{ij}\{s,0\}ds$$

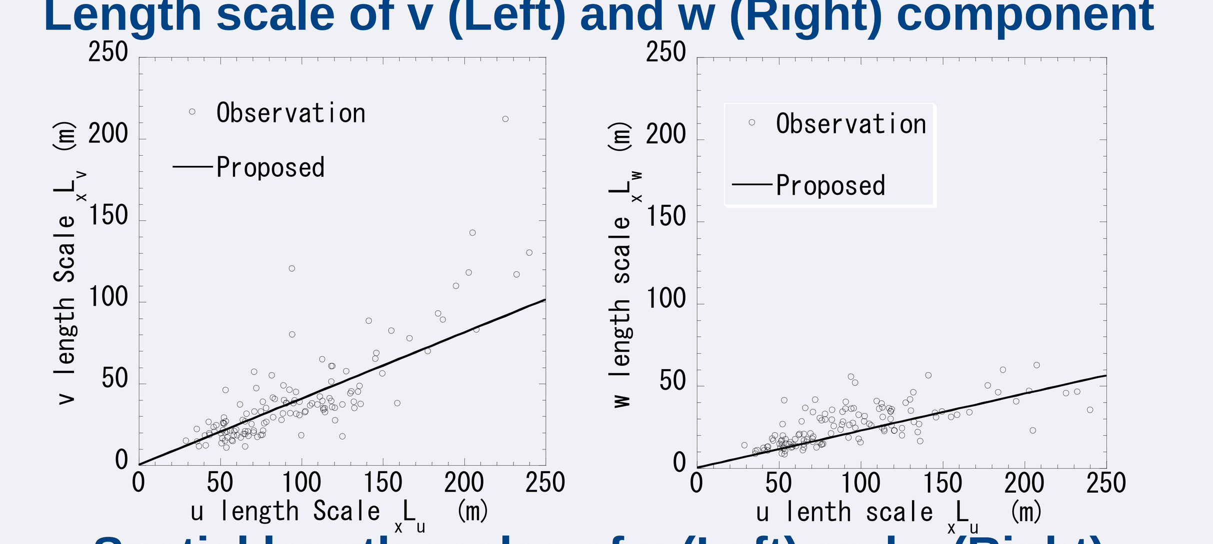
＜Proposed length scale model＞

$$\begin{pmatrix} xL_u & xL_v & xL_w \\ yL_u & yL_v & yL_w \\ zL_u & zL_v & zL_w \end{pmatrix} = xL_u\begin{pmatrix} 1 & 0.44 & 0.25 \\ 0.63 & 0.42 & 0.24 \\ 0.63 & 0.401 & 0.24 \end{pmatrix}, \qquad xL_u = 3.3U + 30$$

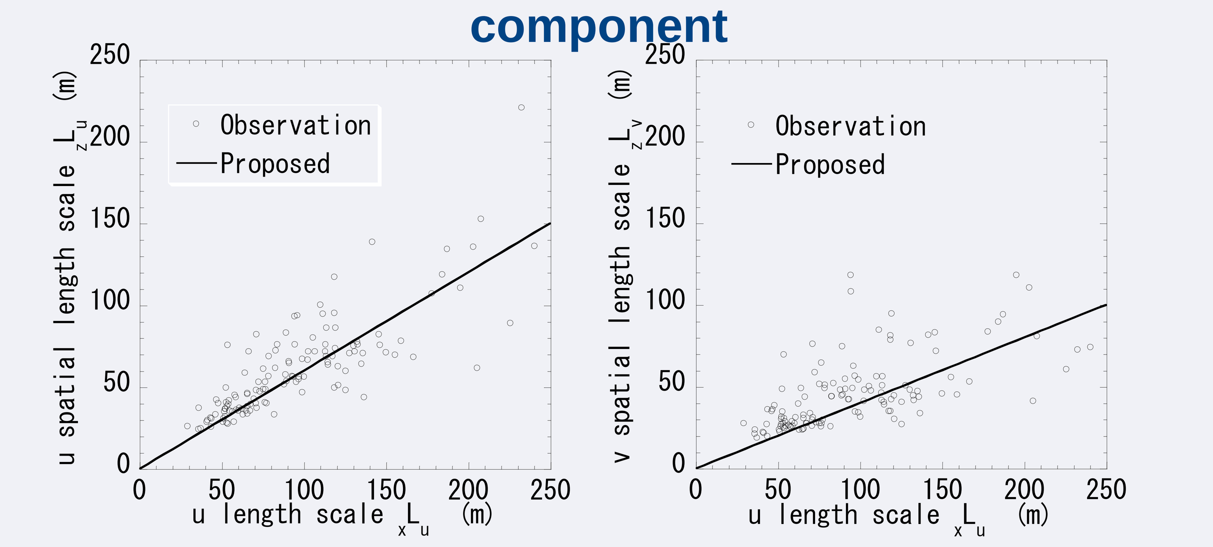
Length scale of u component with respect to wind speed (Left) and observation height (Right)



Length scale of v (Left) and w (Right) component



Spatial length scales of u (Left) and v (Right) component



Conclusions

Offshore wind field measurement using ultra-sonic anemometers is performed to validate the original and the modified von Karman model for auto-spectrum, auto-correlation, spatial co-spectrum and spatial cross-correlation. Modified von Karman model agreed well with measurement for auto-spectrum and auto-correlation. Validation of spatial models showed that the original von Karman model for spatial co-spectrum and cross-correlation gives good approximation of the results of offshore wind field measurement if length scales are identified properly. Finally length scales for each component are evaluated for offshore wind filed, which was smaller than the values suggested in IEC.

References

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