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金风科技

测风数据长期订正的算法对比及效果探究

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内容介绍

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- 算法归纳介绍
- 不同测风时长下各算法效果对比
- 算法特点对比及探究

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算法归纳

Algorithm Type	Abbrev.	Description
Linear Least Squares	LLS	The classisc least squares fit to the scatter plot of target and reference speeds
Total Least Squares	TLS	A slight modification of LLS that minimizes orthogonal distance to the best fit
Variance Ratio	VR	A simple linear mapping that aims to preserve the variance of the target data
Bulk Speed Ratio	BSR	The simplest possible algorithm, based on the ratio of mean wind speeds
Weibull Fit	WBL	A power law fit whose parameters derive from the Weibull parameters of the target and reference data
SpeedSort	SS	A linear fit to the relation ship between target and reference cumulative frequency distributions
Vertical Slice	VS	A piecewise linear fit tot the scatter plot of target and reference speeds
Matrix Time Series	MTS	An implementation of the classic matrix method that we modified to produce realistic time series data

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最小二乘线性回归

The 'Linear Least Squares' MCP algorithm is a method of correlating target and reference speed data based on a straightforward application of the linear least squares procedure to the scatter plot of target speed versus reference speed. The resulting linear curve fit is described with a slope and intercept value, i.e. as a relationship of the form $y = mx + b$.

Windographer uses the following equations to calculate the slope and intercept for the LLS algorithm:

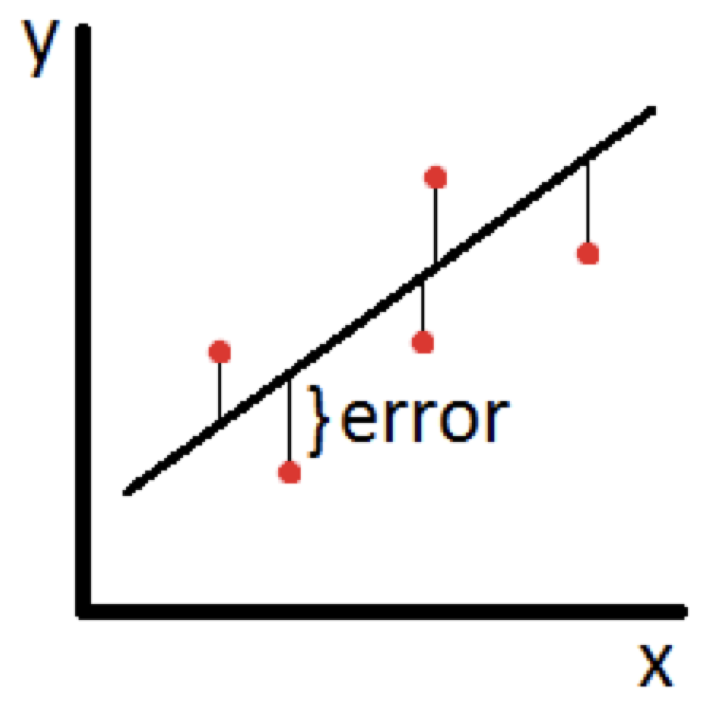
$$m = \frac{S_{xy}}{S_{xx}}$$

$$b = \bar{y} - m\bar{x}$$

Where S_{xx} and S_{xy} are given by the following equations:

$$S_{xx} = \sum_i (x_i - \overline{x})^2$$

$$S_{xy} = \sum_i (x_i - \overline{x})(y_i - \overline{y})$$



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整体最小二乘线性回归

The 'Total Least Squares' MCP algorithm, also known as 'orthogonal least squares', is a method of correlating target and reference speed data that minimizes the orthogonal distance to the line of best fit. The resulting linear curve fit is described with a slope and intercept value, i.e. as a relationship of the form $y = mx + b$.

Windographer uses the following equations to calculate the slope and intercept for the TLS algorithm:

$$m = \frac{S_{yy} - S_{xx} + \sqrt{(S_{yy} - S_{xx})^2 + 4S_{xy}^{\ 2}}}{2S_{xy}}$$

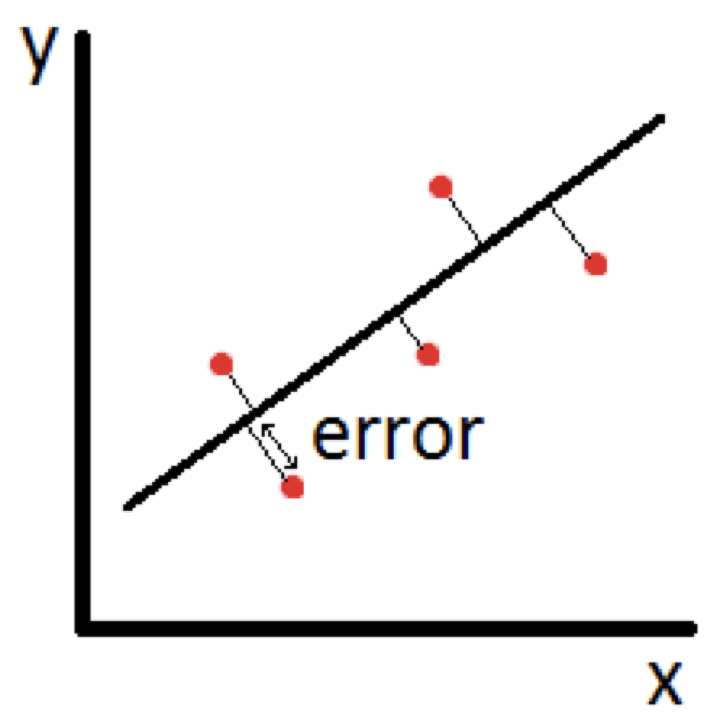
$$b = \overline{y} - m\overline{x}$$

Where S_{xx}, S_{xy}, and S_{yy} are given by the following equations:

$$S_{xx} = \sum_i (x_i - \overline{x})^2$$

$$S_{yy} = \sum_i (y_i - \overline{y})^2$$

$$S_{xy} = \sum_i (x_i - \overline{x})(y_i - \overline{y})$$



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方差比法

This article uses x to denote observed reference wind speeds, y to denote observed target wind speeds. Using that notation, a linear model to predict target wind speeds from observed reference wind speeds appears as follows:

$$\hat{y} = mx + b$$

The Variance Ratio algorithm aims for the variance of the predicted target wind speeds to equal that of the observed target wind speeds, so:

$$\sigma^2(y) = \sigma^2(\hat{y}) = \sigma^2(mx + b) = m^2\sigma^2(x)$$

So the square of the slope is equal to the 'variance ratio', meaning the ratio of the variance of the observed target wind speeds to the variance of the observed reference wind speeds:

$$m^2 = \frac{\sigma^2(y)}{\sigma^2(x)}$$

The slope itself is therefore equal to the ratio of the standard deviation of the observed target wind speeds to that of the observed reference wind speeds:

$$m = \frac{\sigma_y}{\sigma_x}$$

The Variance Ratio algorithm also aims for the mean of the predicted target wind speeds to equal the mean of the observed target wind speeds, so:

$$\bar{y} = \bar{\hat{y}} = m\bar{x} + b = \frac{\sigma_y}{\sigma_x}\bar{x} + b$$

Solving that for the intercept yields:

$$b = \bar{y} - \frac{\sigma_y}{\sigma_x}\bar{x}$$

where $\bar{x}$ is the mean of the observed reference wind speeds and $\bar{y}$ is the mean of the observed target wind speeds.

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Weibull拟合算法

The 'Weibull Fit' algorithm is an MCP algorithm proposed by **van Lieshout (2010)**. It uses a power law model of the form:

$$\hat{y} = \alpha x^{\beta}$$

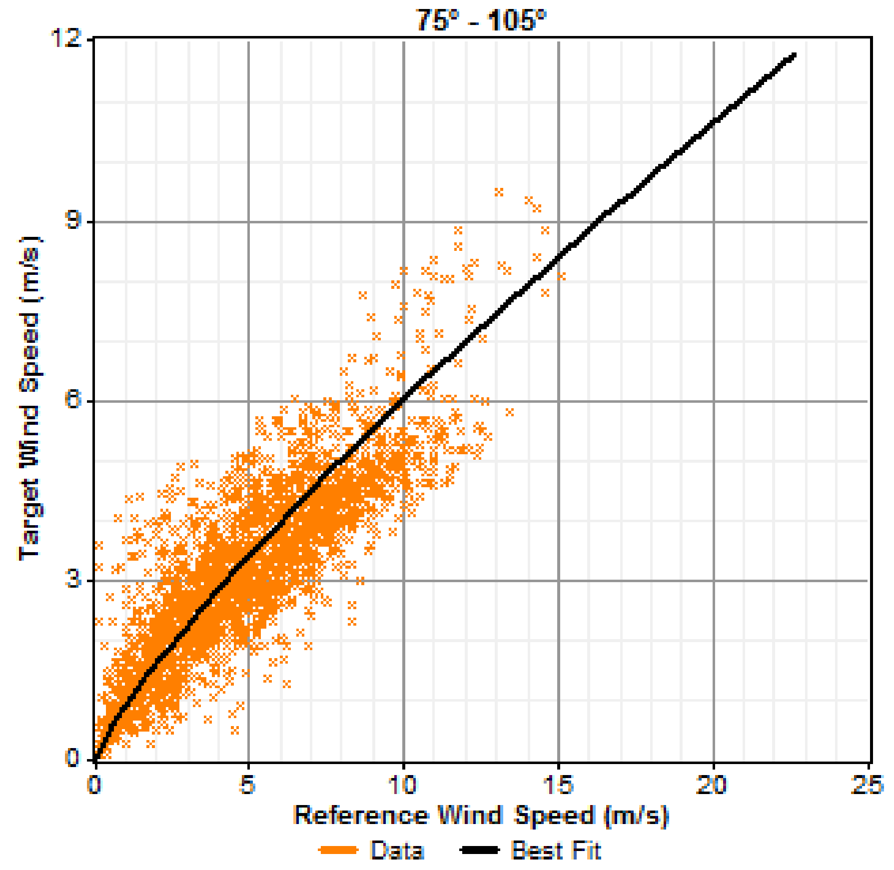
where x denotes observed reference site wind speeds and y denotes observed target site wind speeds.

To calculate the exponent, Windographer calculates the Weibull shape factors of the two data sets and calculates their ratio:

$$\beta = \frac{k_x}{k_y}$$

The scale factor is equal to the Weibull scale factor at the target site divided by the Weibull scale factor at the reference site, raised to the exponent β:

$$\alpha = \frac{A_y}{A_x^{\beta}}$$



The graph below shows an example of a Weibull Fit curve fit with a decidedly non-linear character. Note that it follows from the curve fit equation that the line of best fit will always pass through the origin.

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速度追踪法

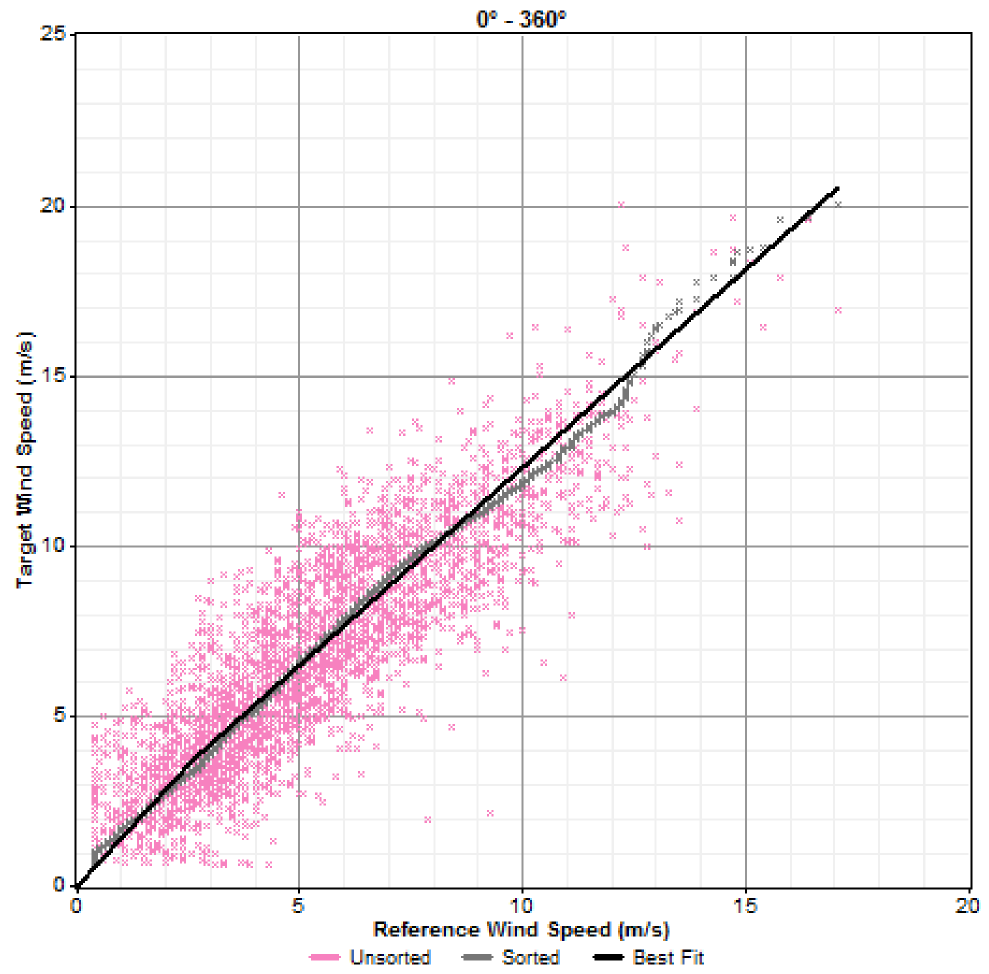
The SpeedSort algorithm is an MCP method described fully in **King and Hurley (2005)**.

SpeedSort is unique among MCP algorithms in that it does not operate on the original scatter plot of target speed versus reference speed. Rather, it involves sorting the data points before performing the curve fit process.

SpeedSort uses a linear model of the form $y = mx + b$. However, the model also incorporates a 'dog leg' from that line down to the origin for speeds below a certain threshold. Windographer calculates the curve fit parameters and the wind speed threshold using the following process:

1. It independently sorts reference and target speeds in ascending order, then plots a scatter plot of the sorted target speeds versus the sorted reference speeds.
2. It chooses the threshold wind speed for the 'dog leg' as the lesser of 4 m/s or half the long-term mean reference wind speed.
3. It uses orthogonal least squares to fit a line to the portion of the sorted scatter plot above the threshold reference wind speed.

The graph below shows an example of a SpeedSort curve fit. The graph shows the original (unsorted) data, the sorted data, and the best-fit line. Note the slight 'dog leg' at around 2.5 m/s (reference). The angle of the 'dog leg' will be greater in cases where the line of best fit has a y-intercept value farther away from zero.



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分风速段回归

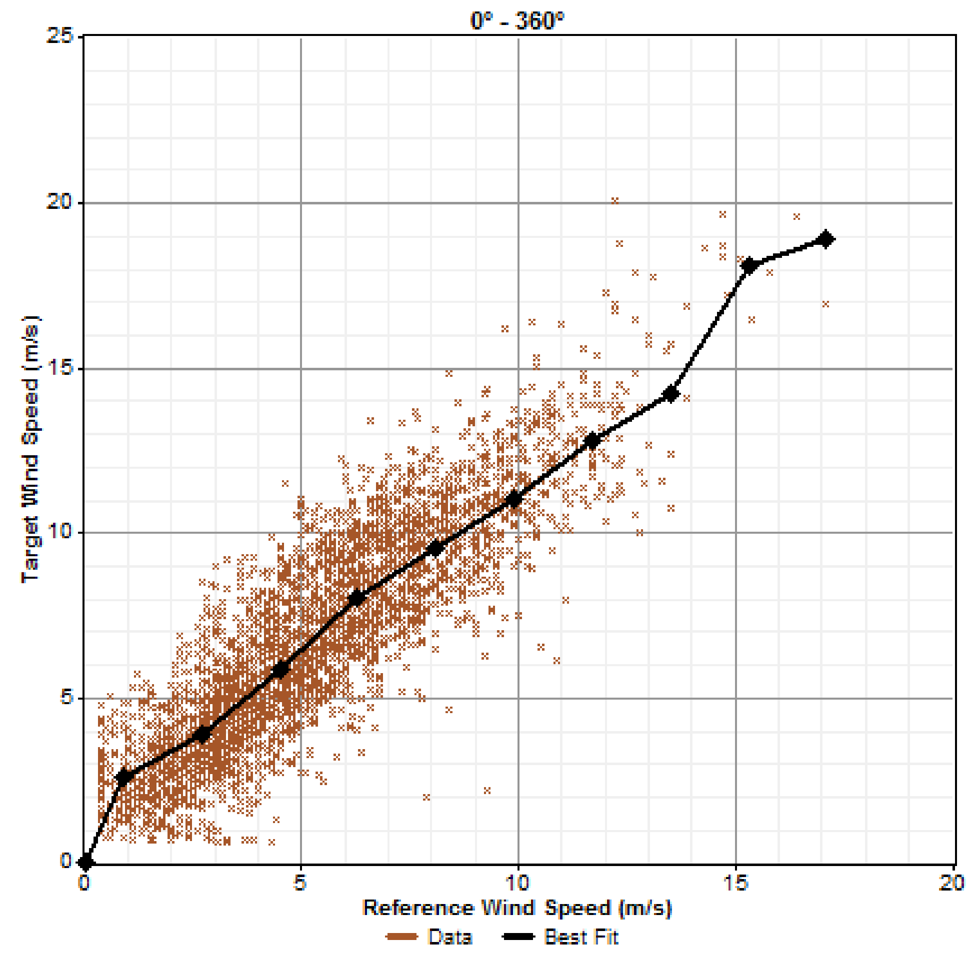
The 'Vertical Slice' algorithm, described fully in **Leblanc et al. (2009)**, is an MCP algorithm that performs a piecewise linear curve fit on the scatter plot of target wind speeds versus reference wind speeds.

To obtain the piecewise linear curve fit, Windographer first splits the target wind speed versus reference wind speed scatter plot into N equally sized bins (vertical slices) along the x-axis. Then it calculates the mean target wind speed value for each of these bins. Windographer then assigns a point to each bin where the x value is the midpoint of the bin along the x-axis and the y value is the mean target wind speed in that bin. The piecewise linear curve then simply consists of these points connected by straight lines.

In an ideal situation, each vertical slice would contain enough data to calculate a reliable mean target wind speed value for the bin. In real data sets, however, this will not always happen, especially if the data set is short, heavily filtered, or has been divided into a large number of direction sectors. Therefore for slices with insufficient data (fewer than 5 data points), Windographer calculates the mean target wind speed by another method: using the value predicted for the midpoint of the bin by the overall linear least squares fit.

Also, the curve fit generated via the above method does not cover reference speed values below the midpoint of the first bin, or above the midpoint last bin. Therefore to handle low wind speeds, Windographer adds the origin as another point in the piecewise linear curve fit. To handle high wind speeds, it extrapolates the curve fit upwards from the last calculated point using the slope of the overall linear least squares fit.

The graph below shows an example of a vertical slice curve fit, along with the points that define each linear segment.



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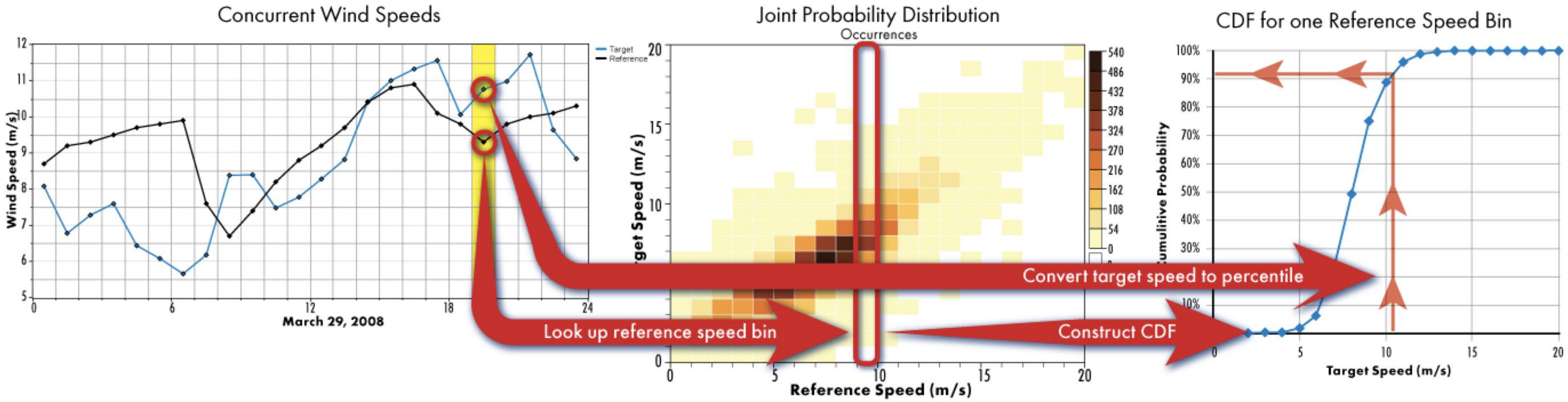
联合概率密度分布



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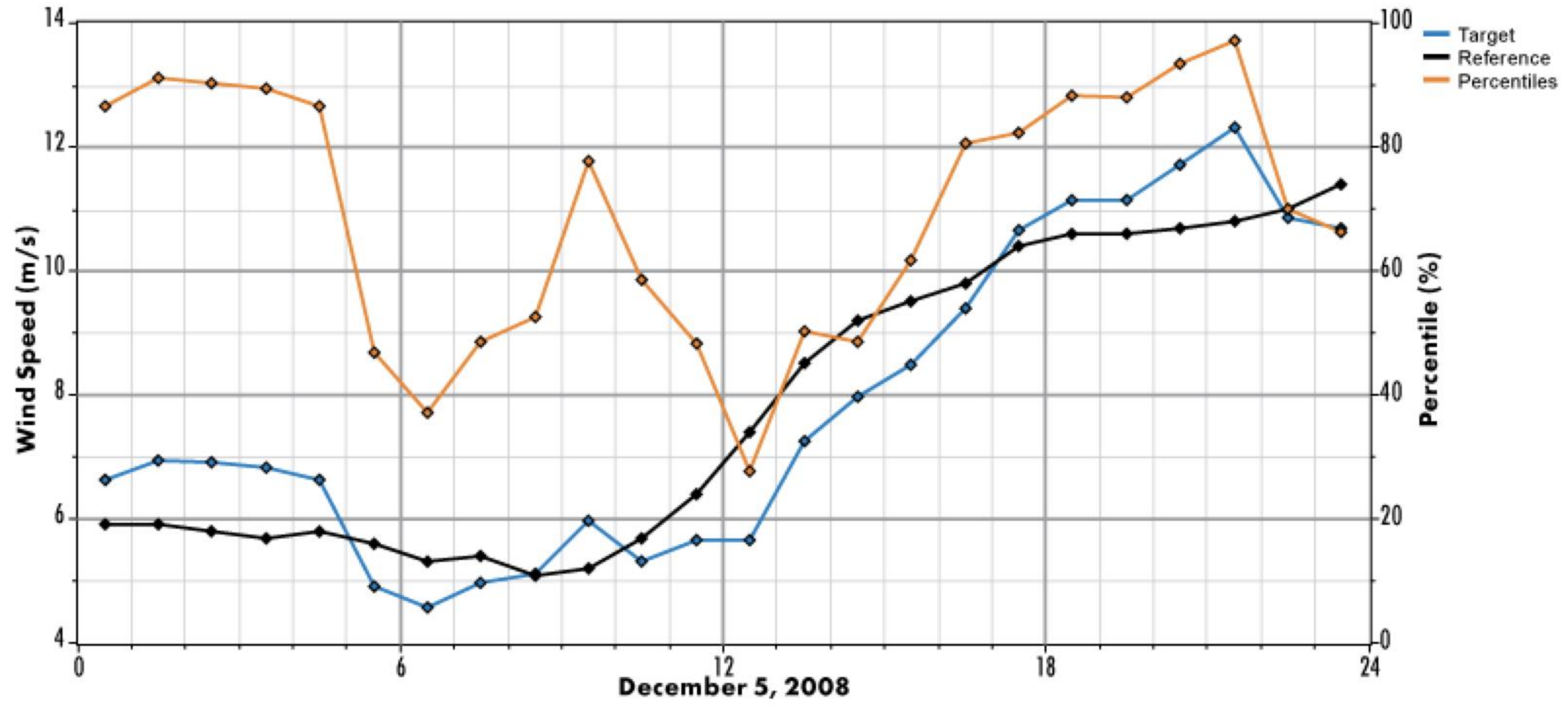
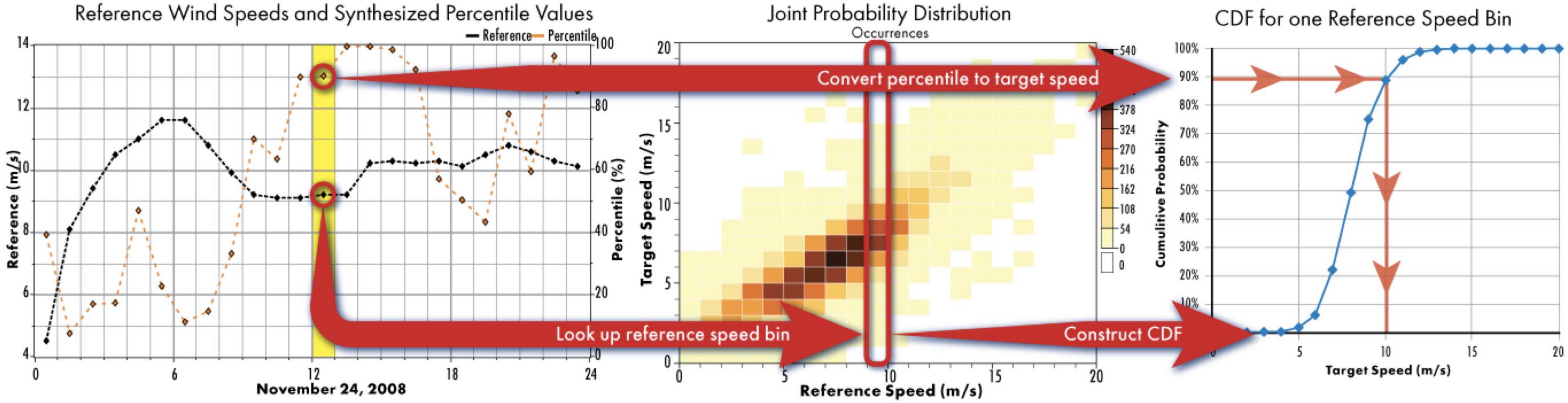
联合概率密度分布





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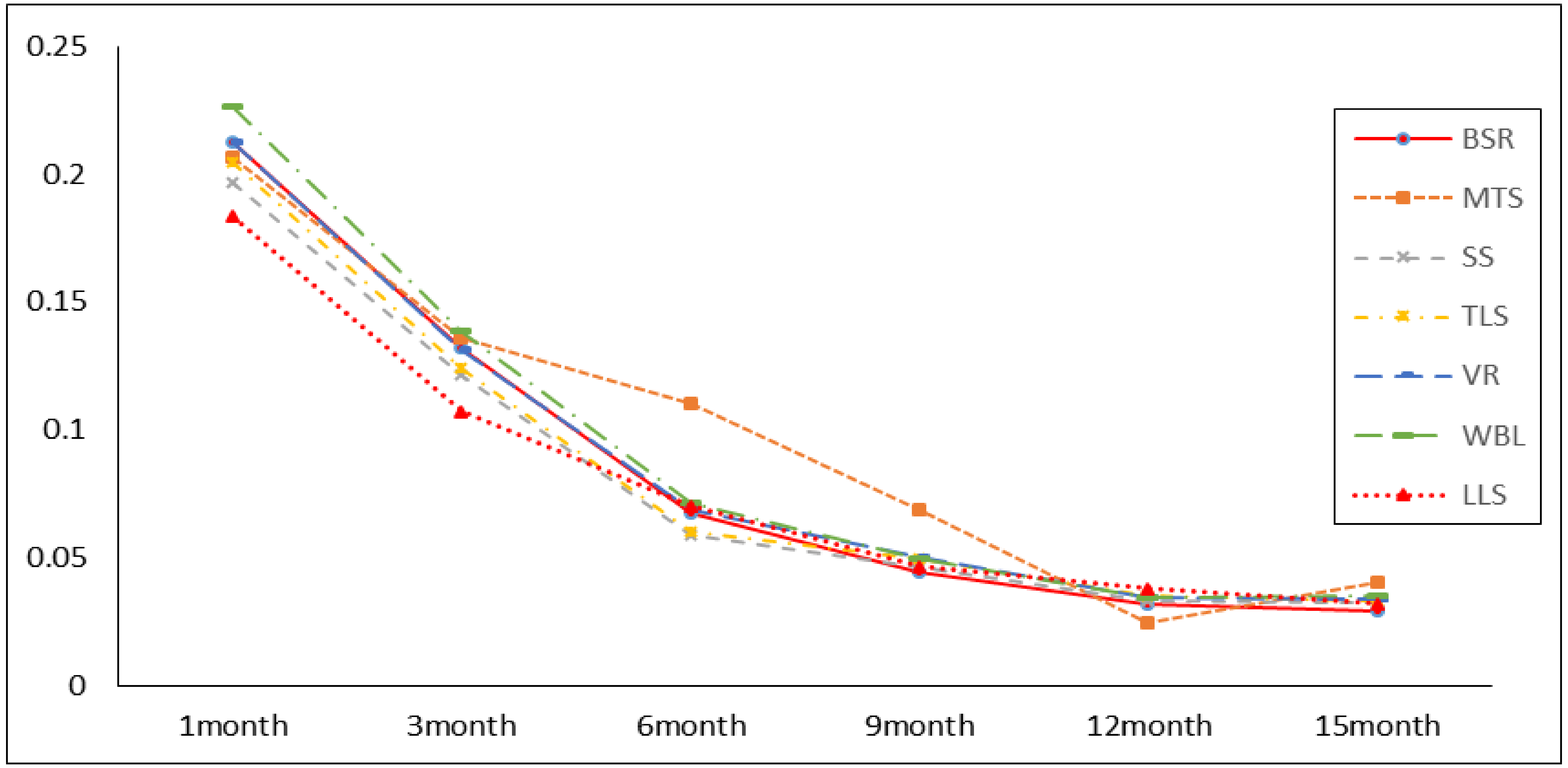
测风时长对风速评估的影响

	1month	3month	6month	9month	12month	15month
BSR	0.2124	0.1319	0.0672	0.0442	0.0319	0.0292
MTS	0.2067	0.1362	0.1105	0.0686	0.0243	0.0404
SS	0.1965	0.1214	0.0590	0.0461	0.0330	0.0323
TLS	0.2047	0.1239	0.0602	0.0496	0.0350	0.0332
VR	0.2128	0.1311	0.0685	0.0502	0.0347	0.0340
WBL	0.2265	0.1386	0.0716	0.0493	0.0342	0.0349
LLS	0.1833	0.1073	0.0701	0.0463	0.0377	0.0317



- 无论何种方法，季节性因素对数据订正的影响不可忽略
- MTS方法与其他方法相比误差较大
- 在达到12个月之后，随时间长度的增加，各方法误差分布下降趋势明显减缓。

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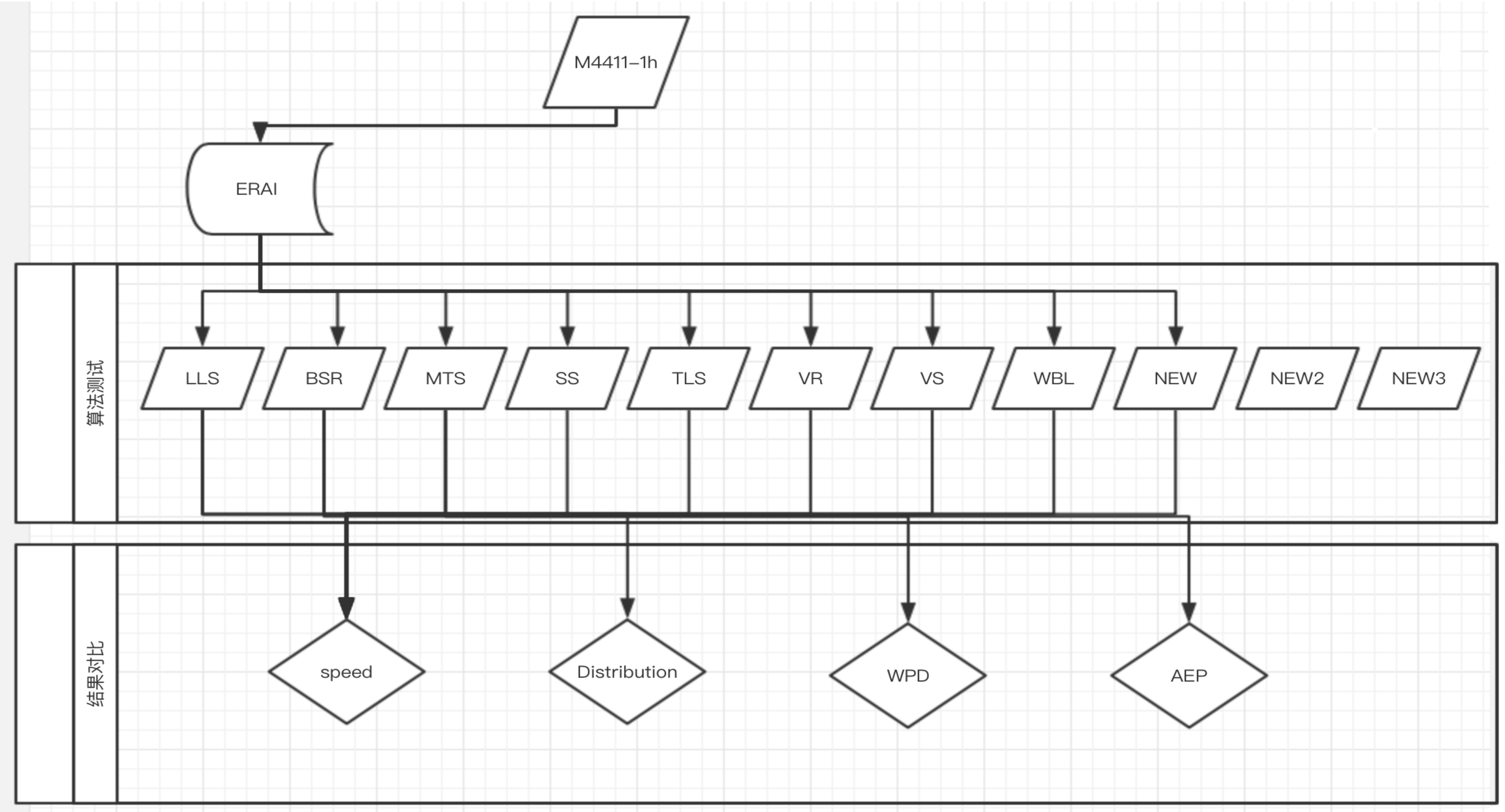
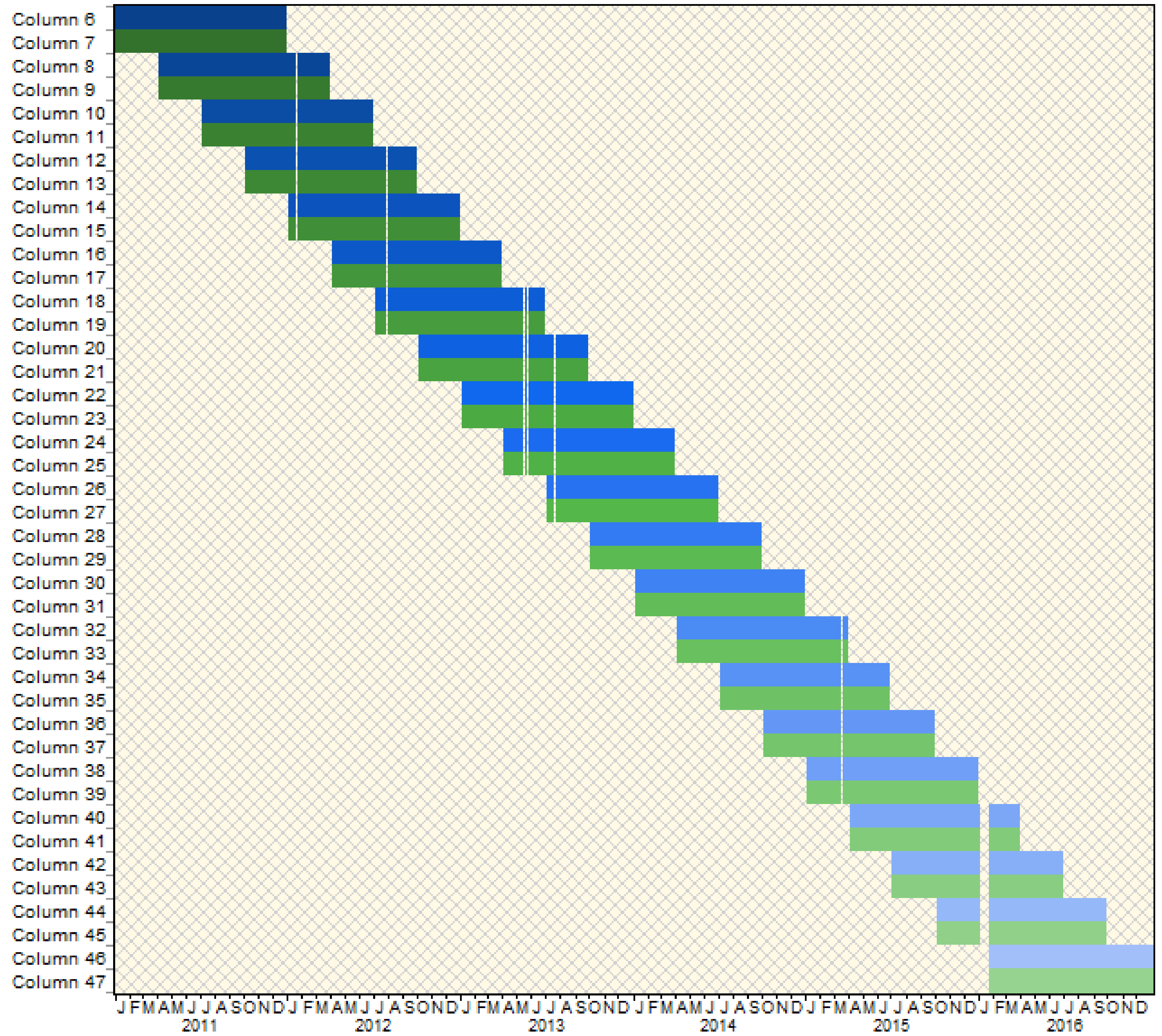
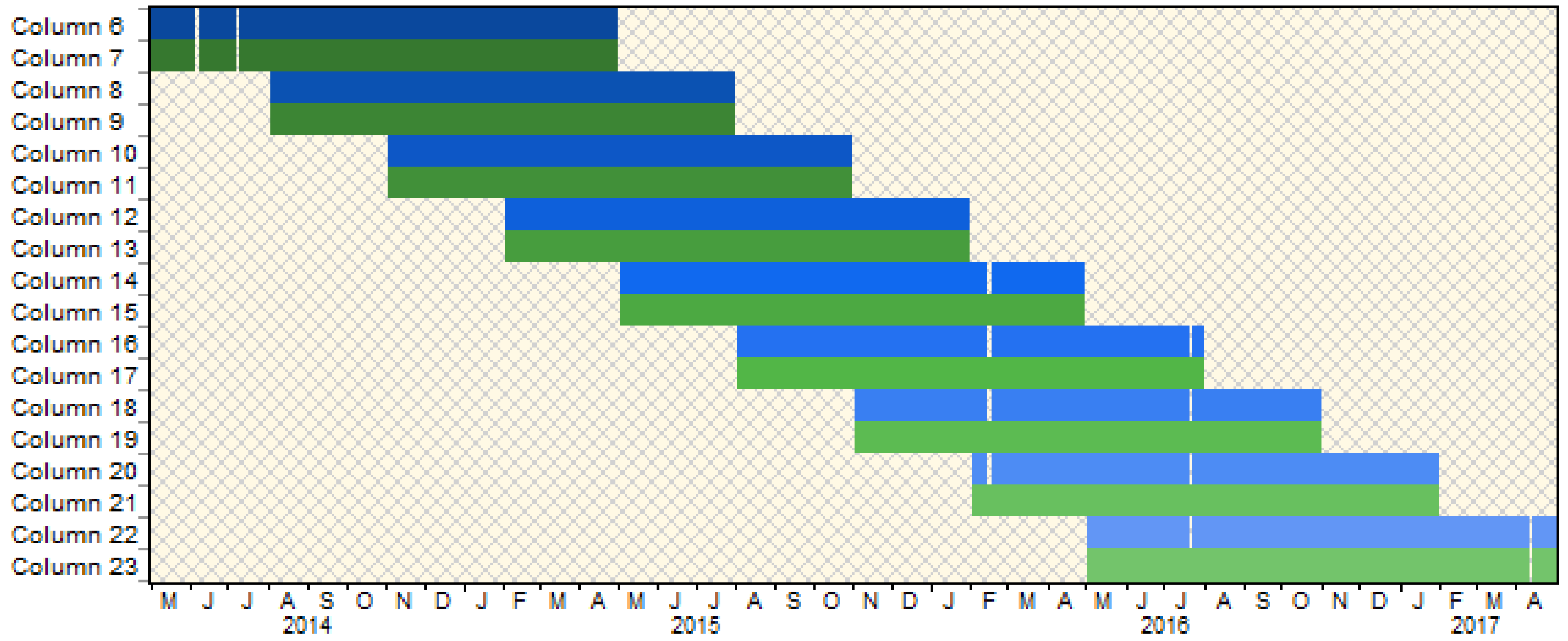
测风塔信息

	Mast1	Mast2	Mast3	Mast4
Duration	6 years	6 years	3 years	3 years
R^2	0.644	0.575	0.621	0.598
Recovery Rate	99.29%	99.93%	99.69%	99.54%
Time steps of comparison	60min	60min	60min	60min
	21	21	9	9







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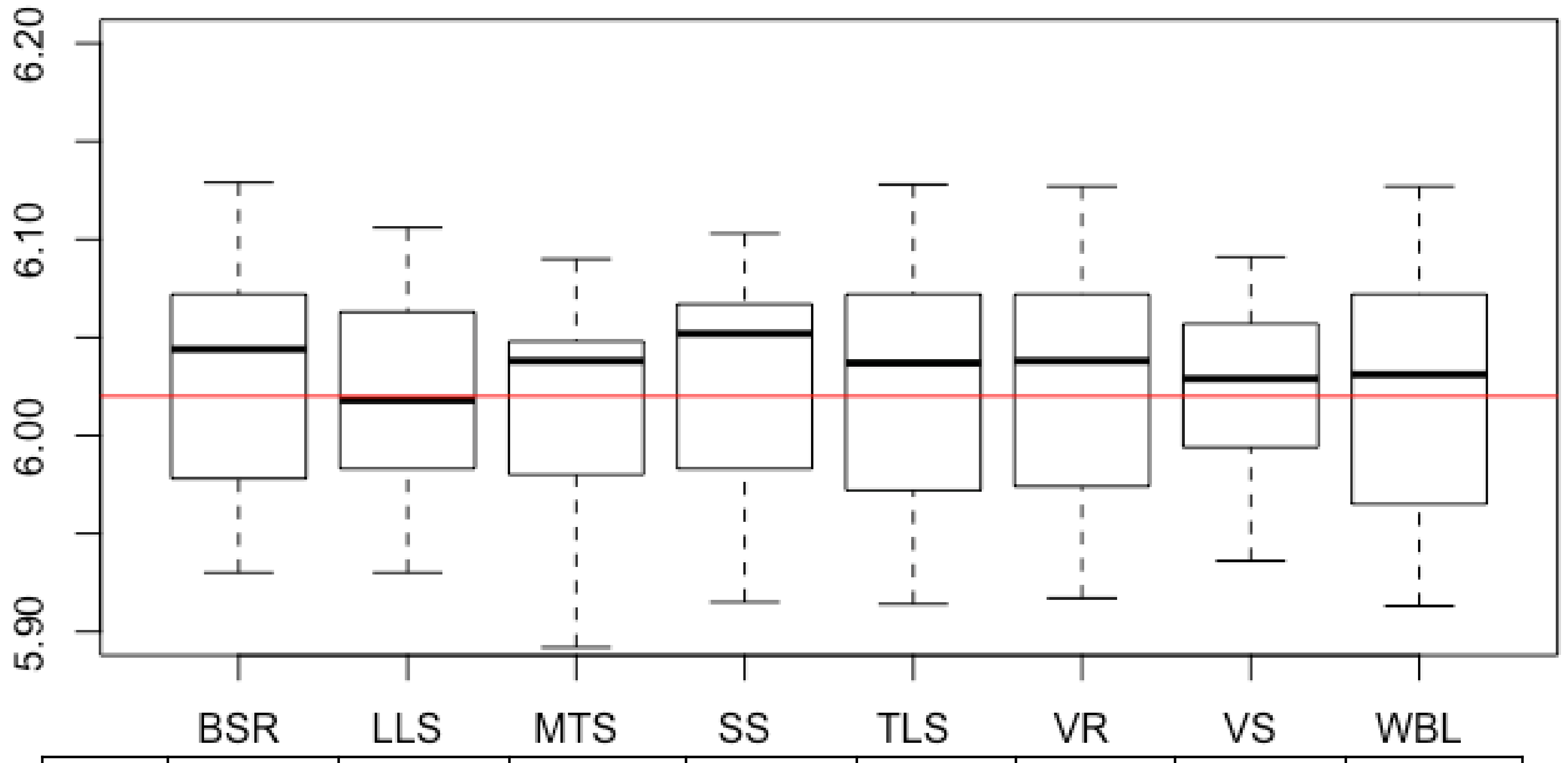
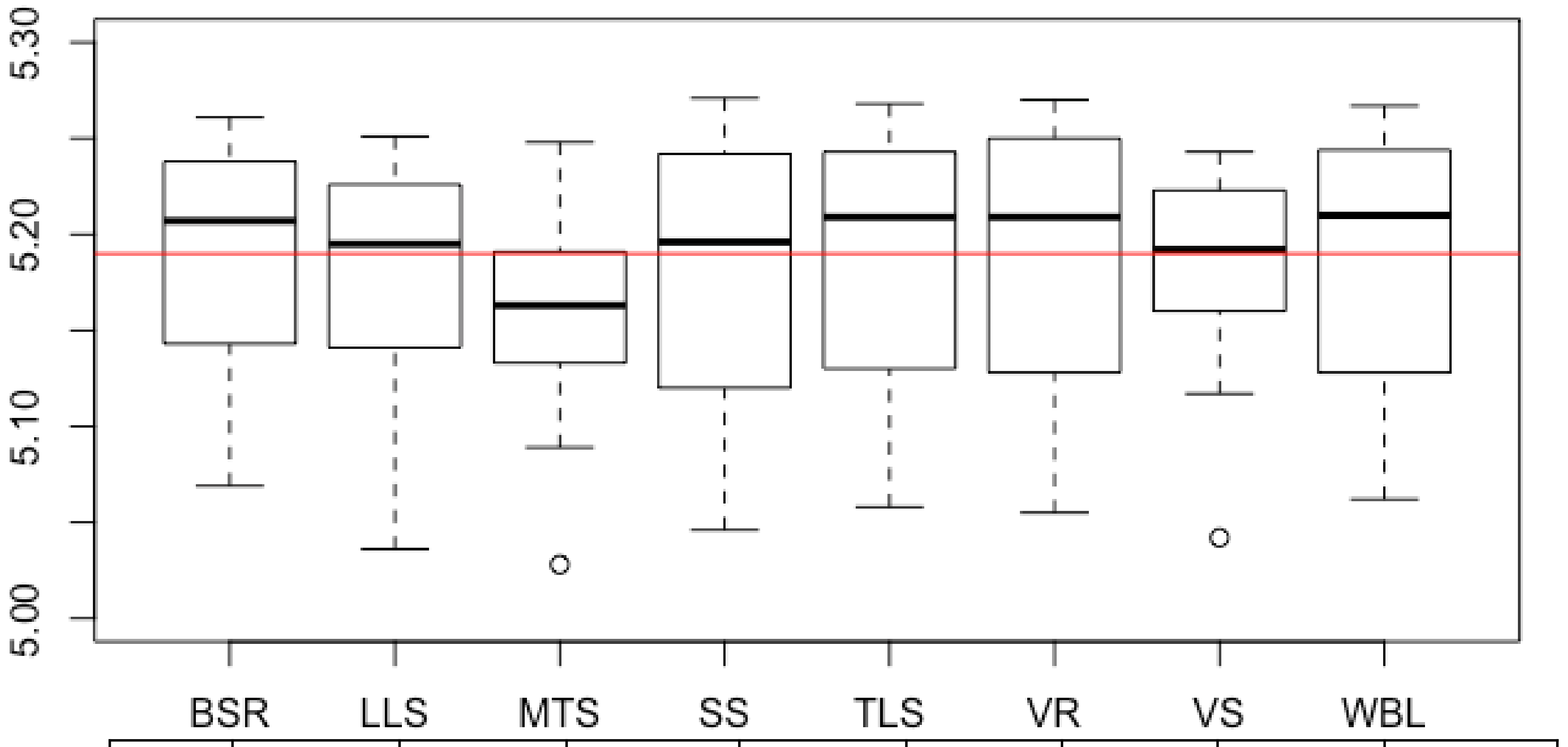
风速

Wind Speed 1



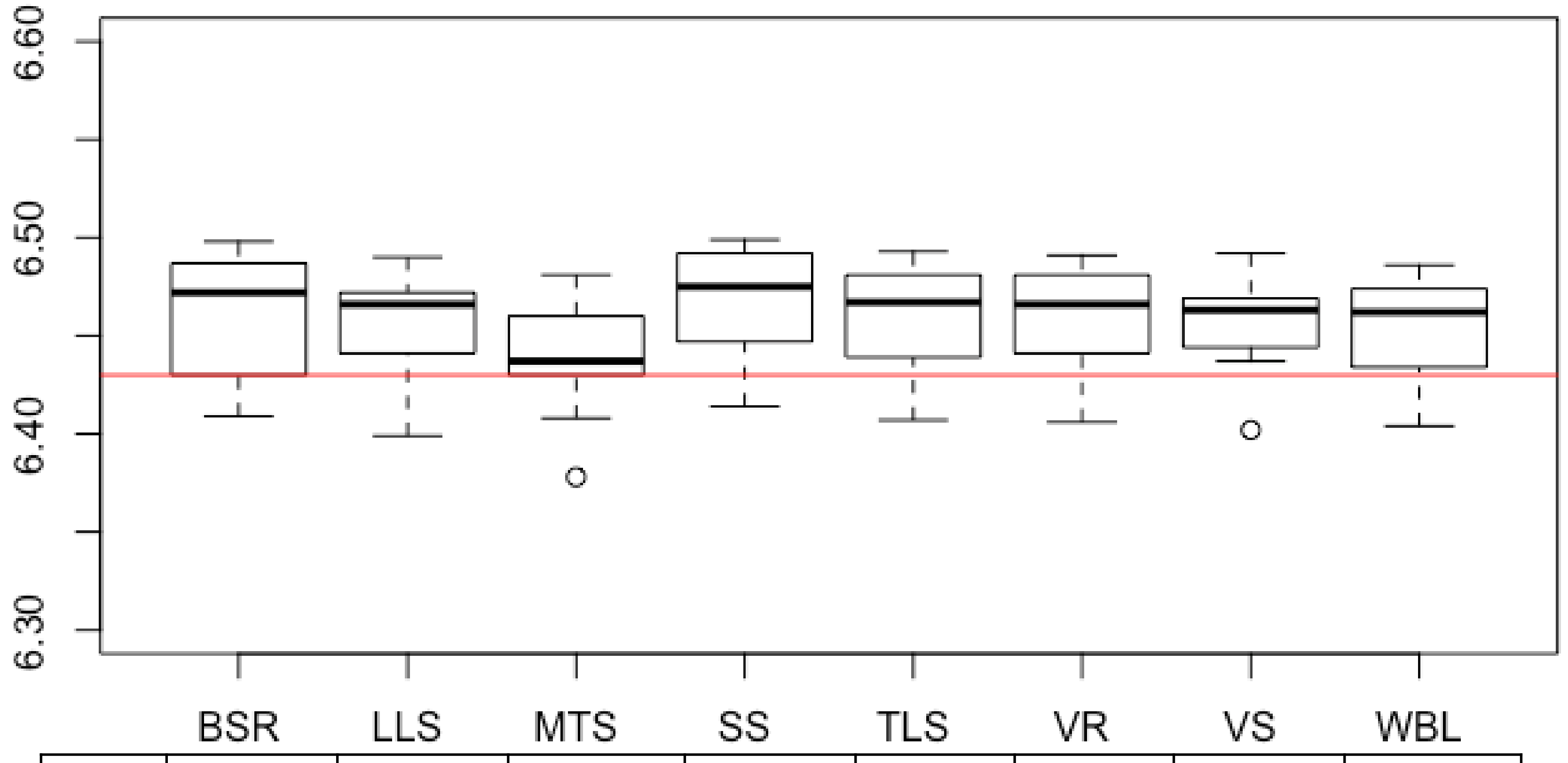
	BSR	LLS	MTS	SS	TLS	VR	VS	WBL
SD	0.0580	0.0500	0.0550	0.0560	0.061	0.06	0.0450	0.0630
MBE	0.27%	-0.06%	0.44%	0.49%	0.23%	0.23%	0.08%	0.19%

Wind Speed 1



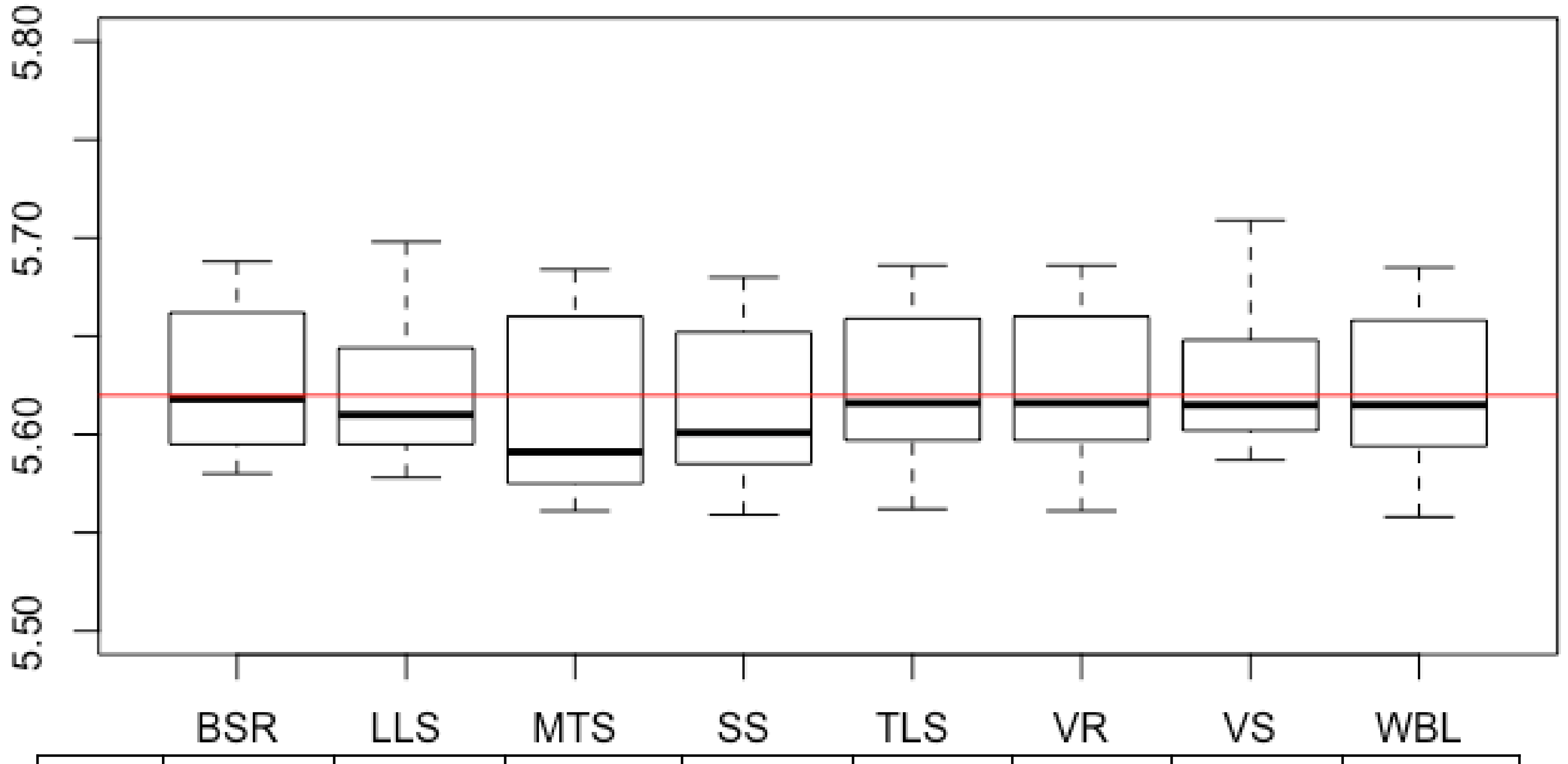
	BSR	LLS	MTS	SS	TLS	VR	VS	WBL
SD	0.0597	0.0538	0.0526	0.0687	0.067	0.07	0.0496	0.0661
MBE	0.33%	0.10%	-0.52%	0.12%	0.37%	0.37%	0.04%	0.39%

Wind Speed 3



	BSR	LLS	MTS	SS	TLS	VR	VS	WBL
SD	0.0336	0.0270	0.0305	0.0313	0.030	0.03	0.0263	0.0292
MBE	0.65%	0.56%	0.11%	0.70%	0.58%	0.56%	0.51%	0.50%

Wind Speed 4



	BSR	LLS	MTS	SS	TLS	VR	VS	WBL
SD	0.0427	0.0382	0.0497	0.0442	0.045	0.05	0.0383	0.0454
MBE	-0.04%	-0.18%	-0.52%	-0.34%	-0.07%	-0.07%	-0.09%	-0.09%

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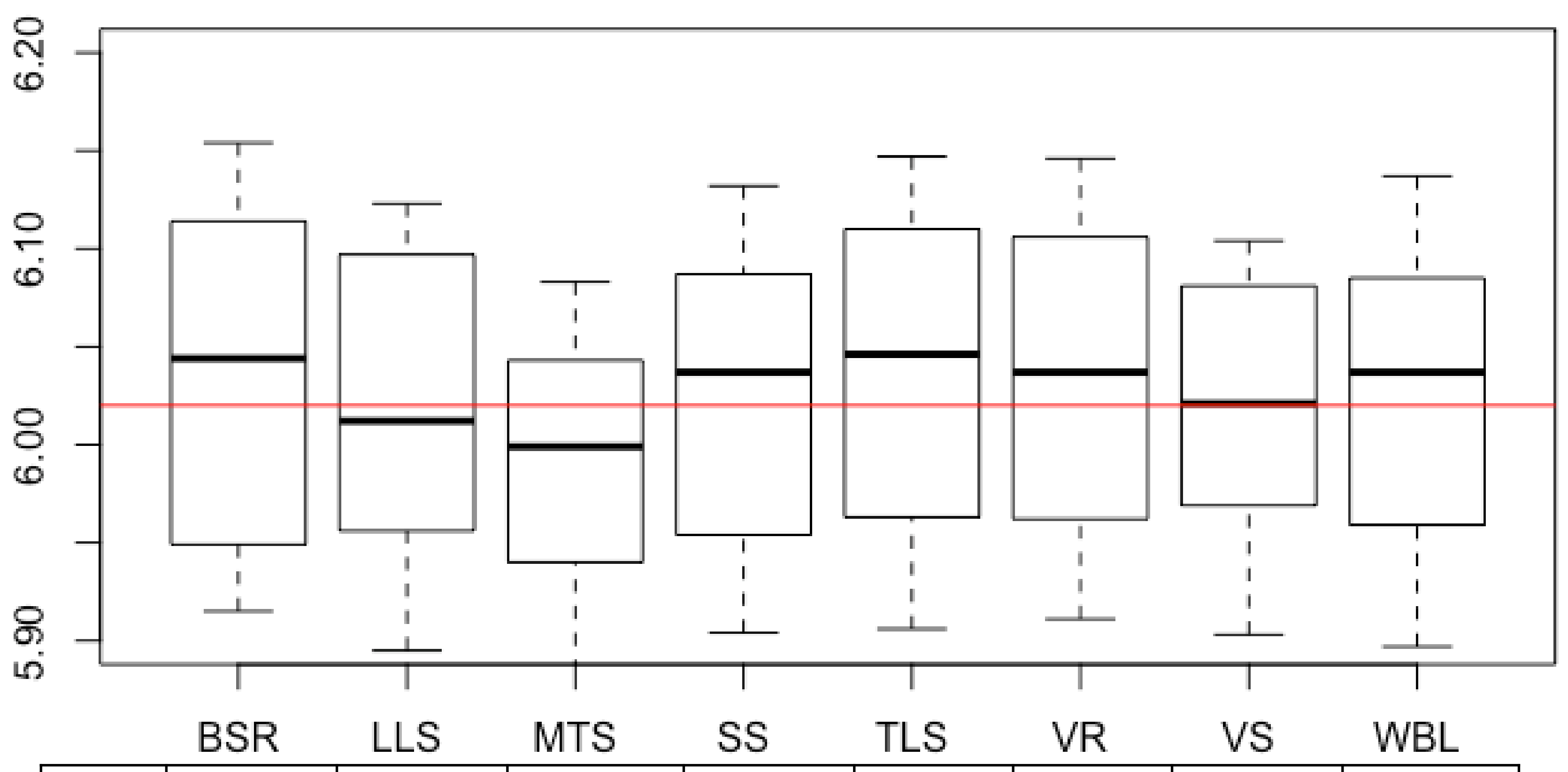
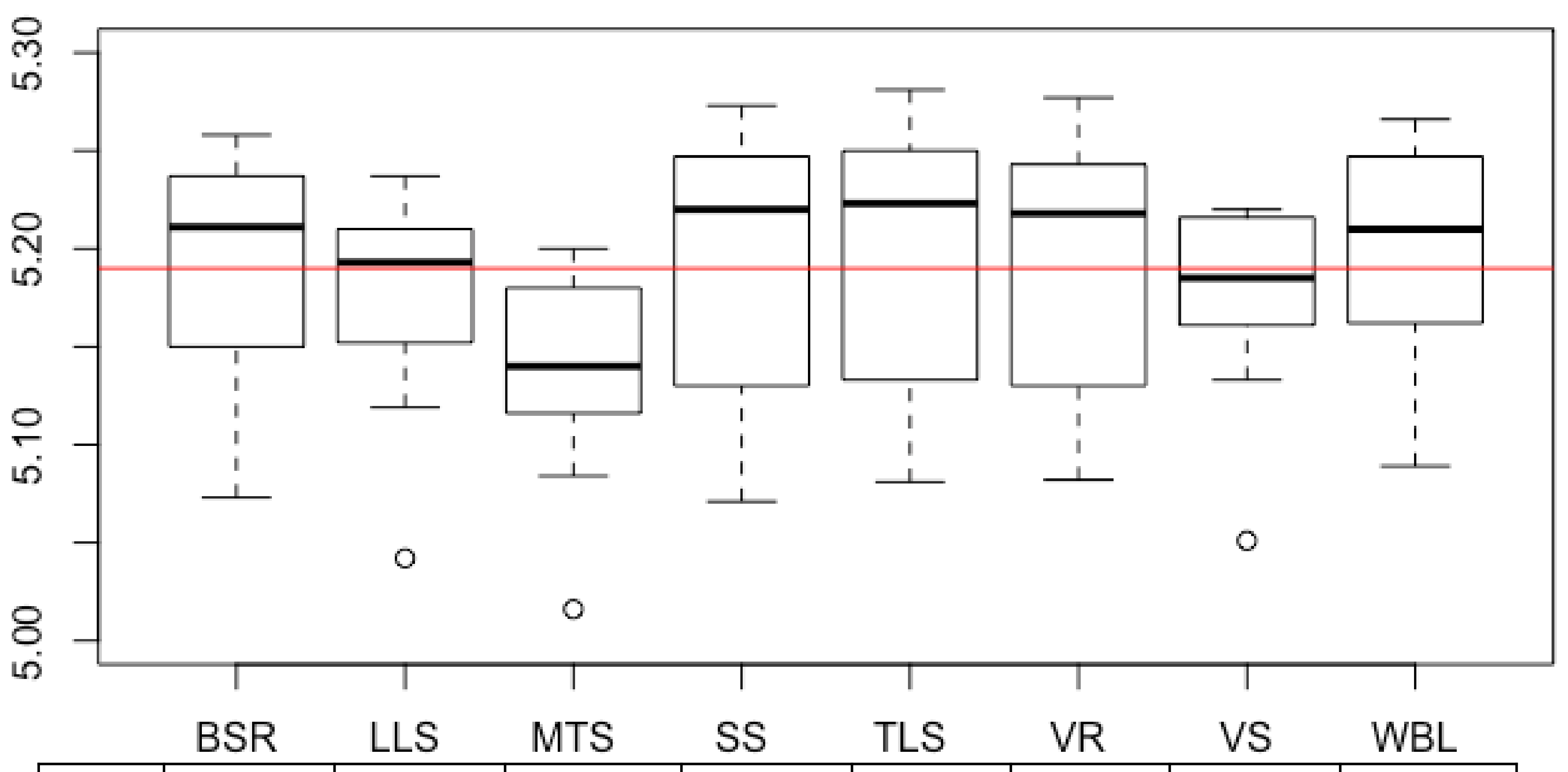
风速-16扇区

Wind Speed 1



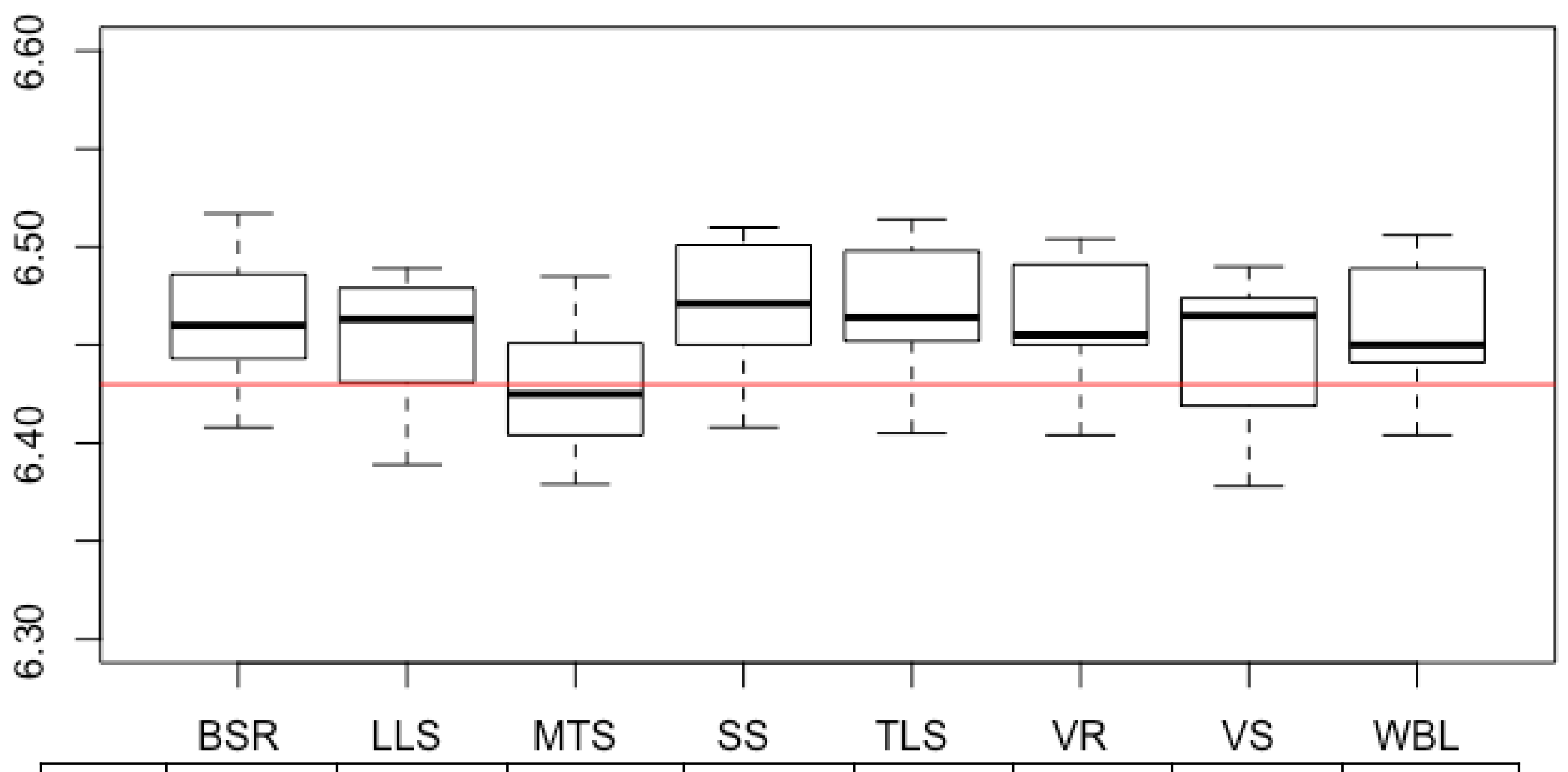
SD	0.0581	0.0496	0.0554	0.0559	0.061	0.06	0.0454	0.0626
MBE	0.40%	-0.03%	0.30%	0.53%	0.28%	0.30%	0.15%	0.18%

Wind Speed 1



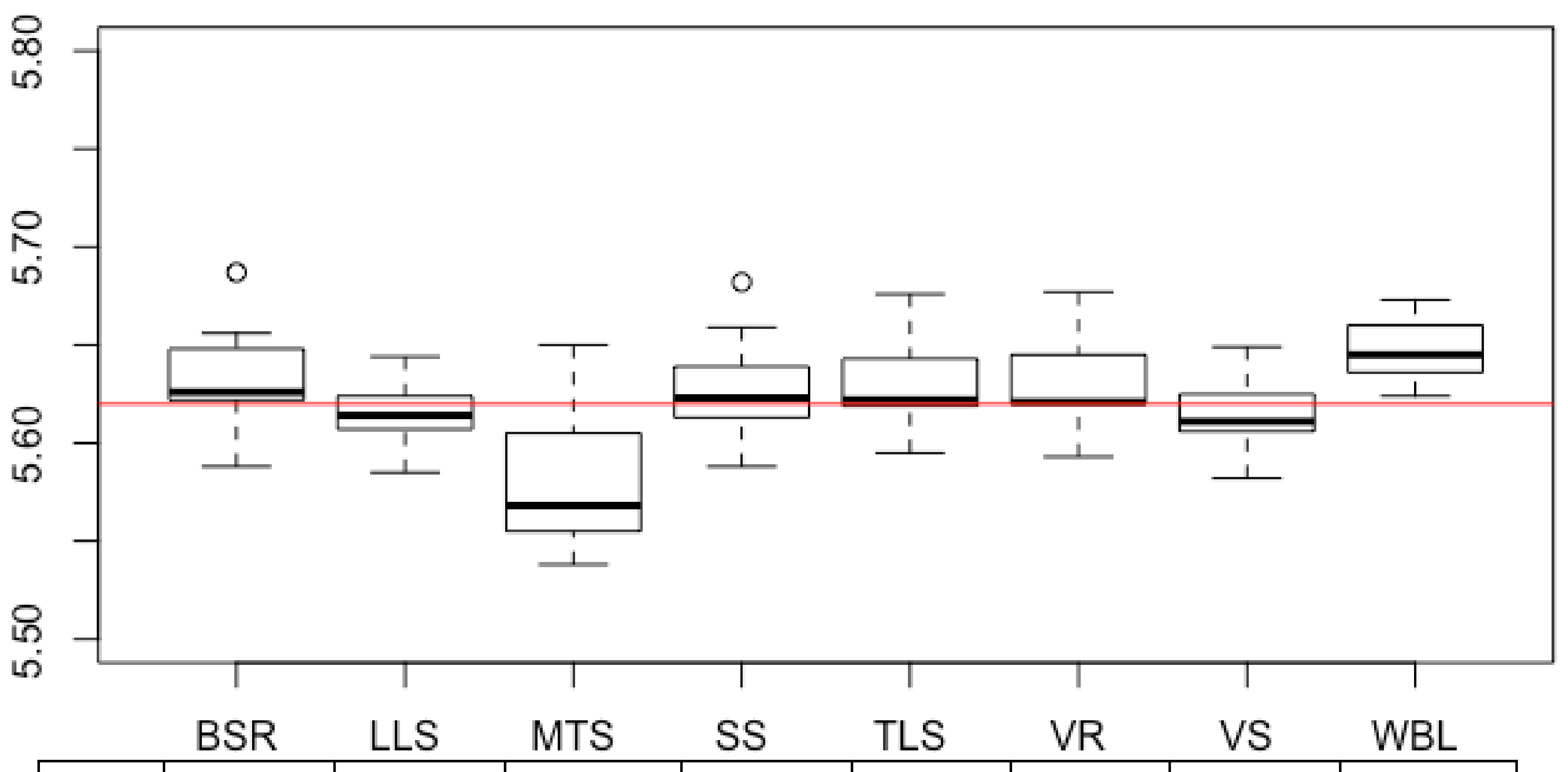
SD	0.0525	0.0480	0.0460	0.0699	0.065	0.06	0.0405	0.0554
MBE	0.40%	0.06%	-0.96%	0.58%	0.64%	0.54%	-0.10%	0.39%

Wind Speed 3



SD	0.0365	0.0344	0.0387	0.0335	0.035	0.03	0.0389	0.0357
MBE	0.47%	0.51%	-0.08%	0.64%	0.53%	0.39%	0.54%	0.31%

Wind Speed 4



SD	0.0305	0.0184	0.0408	0.0300	0.027	0.03	0.0205	0.0180
MBE	0.11%	-0.11%	-0.93%	0.05%	0.04%	0.02%	-0.16%	0.44%

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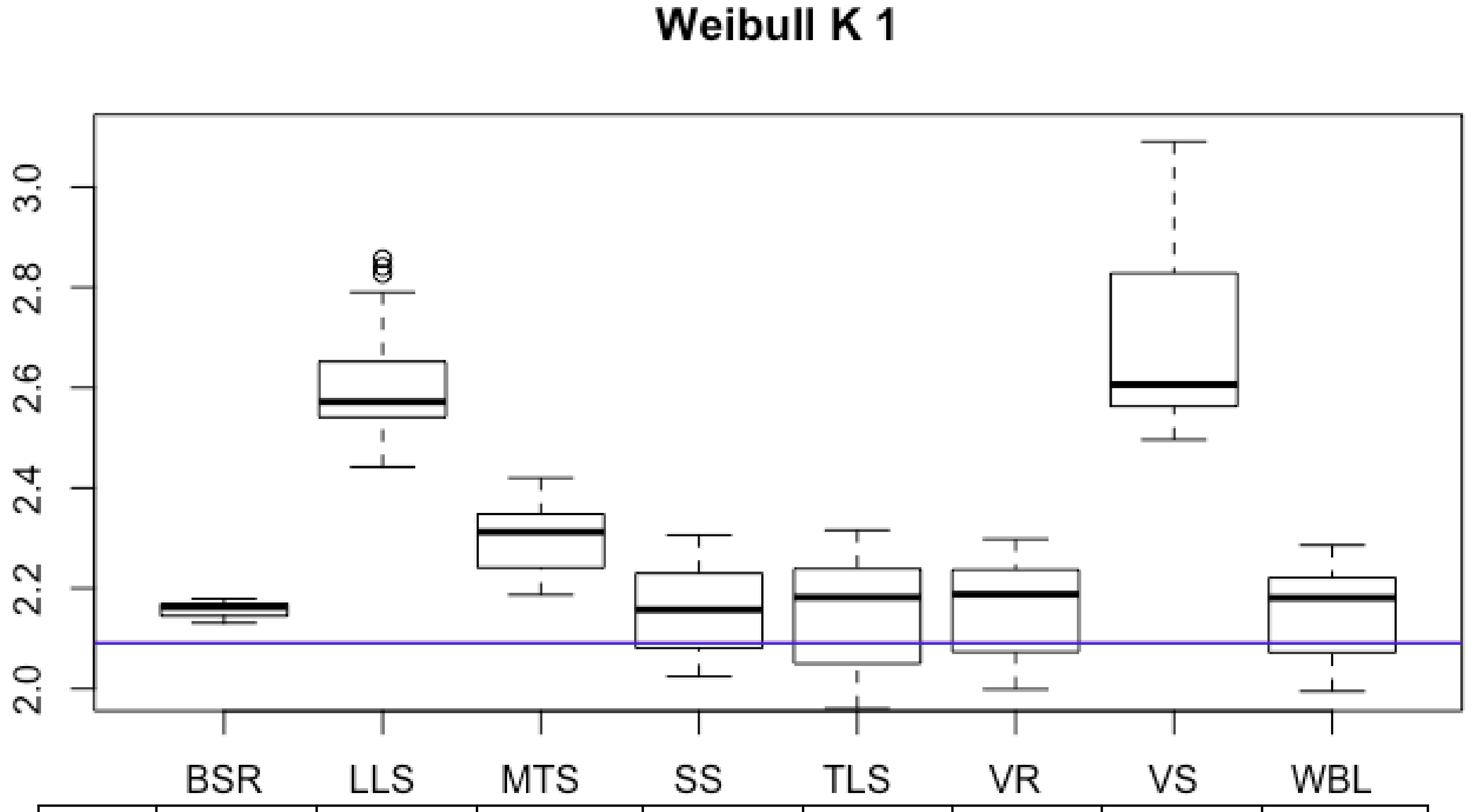
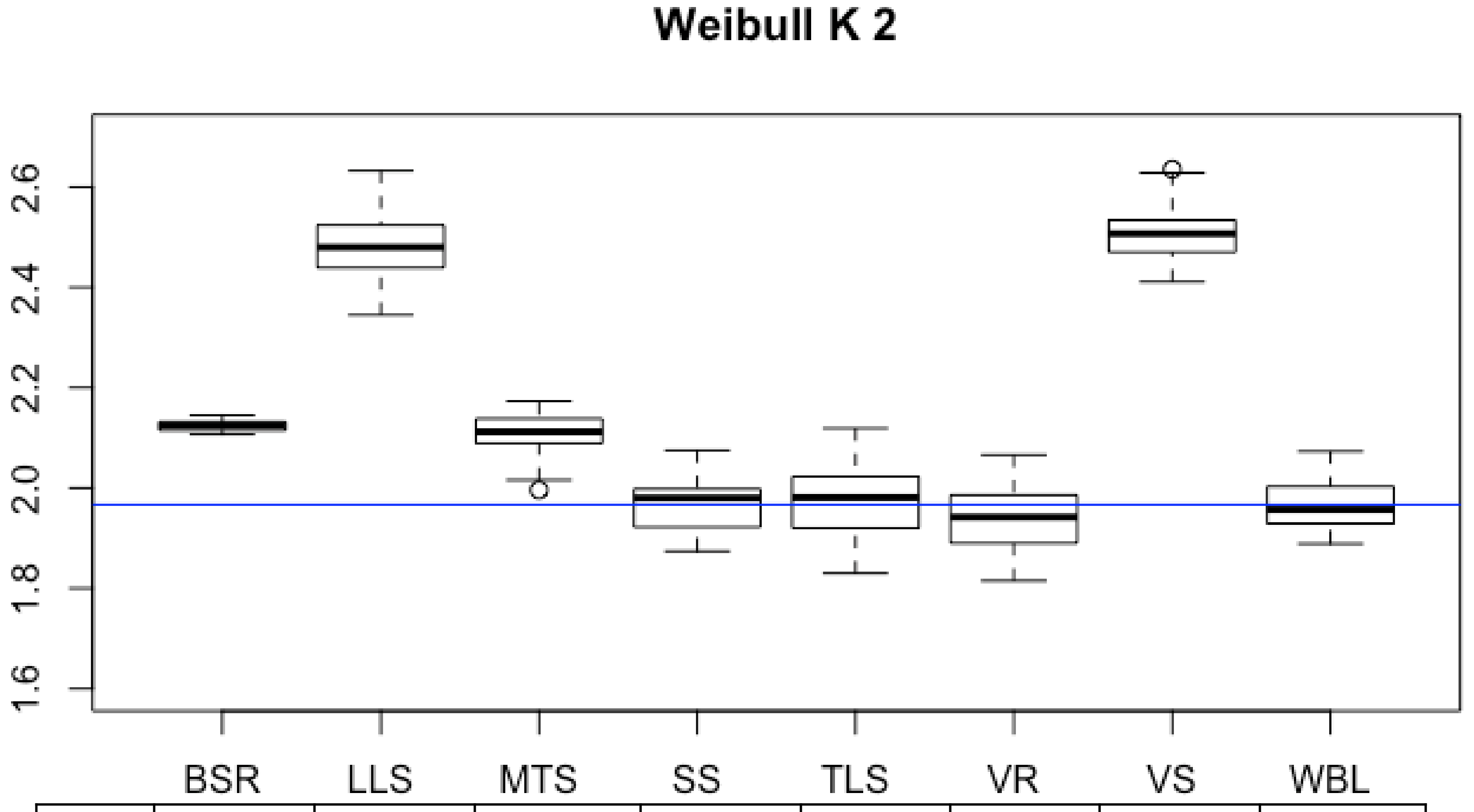
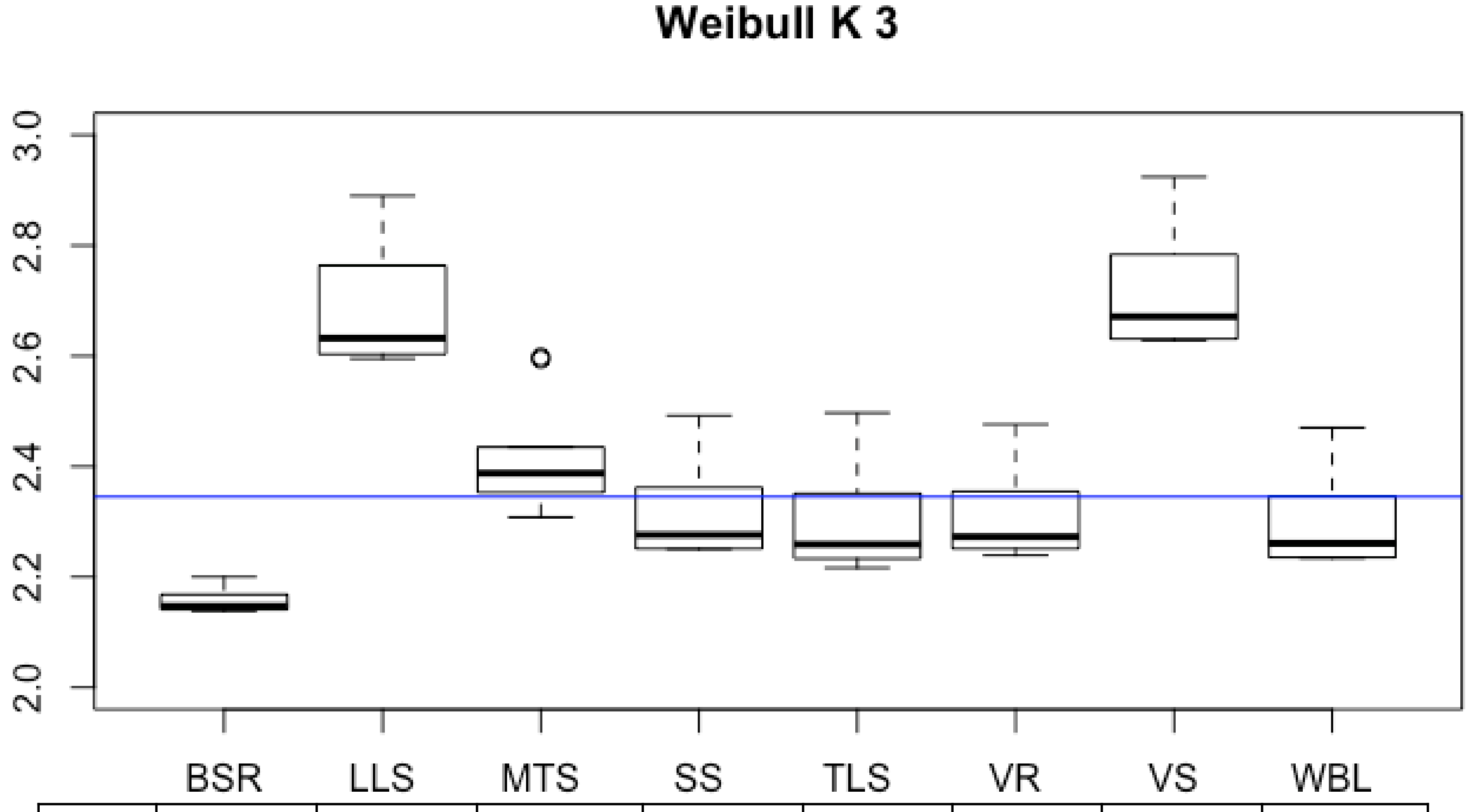
Weibull K



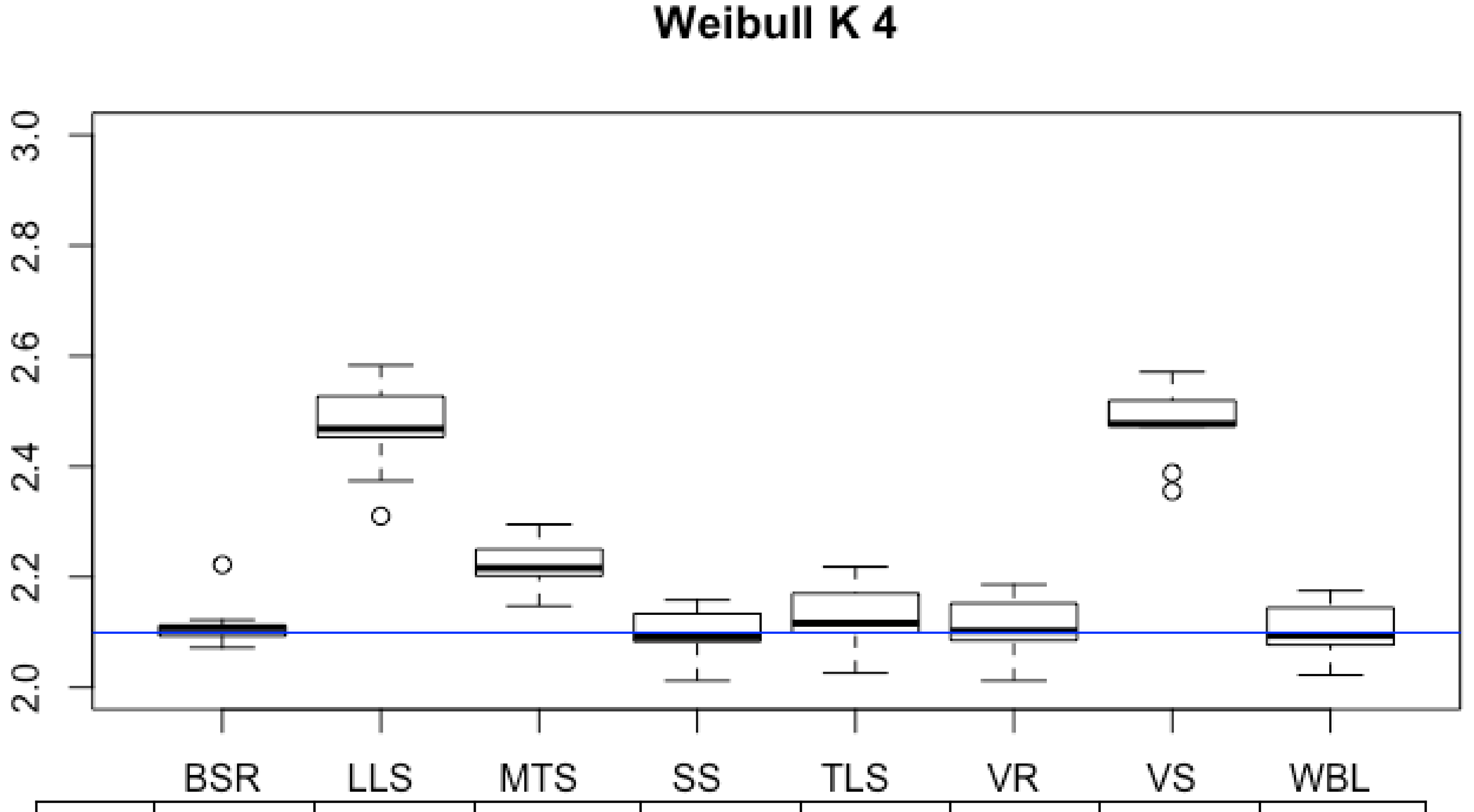
SD	0.0144	0.1238	0.0666	0.0884	0.107	0.09	0.1839	0.0883
MBE	3.44%	23.00%	10.57%	3.16%	4.35%	4.64%	24.63%	4.30%



SD	0.0110	0.0736	0.0458	0.0573	0.080	0.07	0.0620	0.0532
MBE	8.03%	26.08%	7.37%	0.66%	0.71%	-1.27%	27.45%	-0.51%



SD	0.0223	0.1174	0.1057	0.0901	0.101	0.09	0.1159	0.0876
MBE	-8.44%	12.24%	1.83%	-2.94%	-3.67%	-3.07%	13.90%	-3.58%



SD	0.0448	0.0849	0.0428	0.0525	0.066	0.06	0.0690	0.0519
MBE	0.43%	17.58%	5.57%	-0.38%	0.81%	0.14%	18.01%	-0.24%

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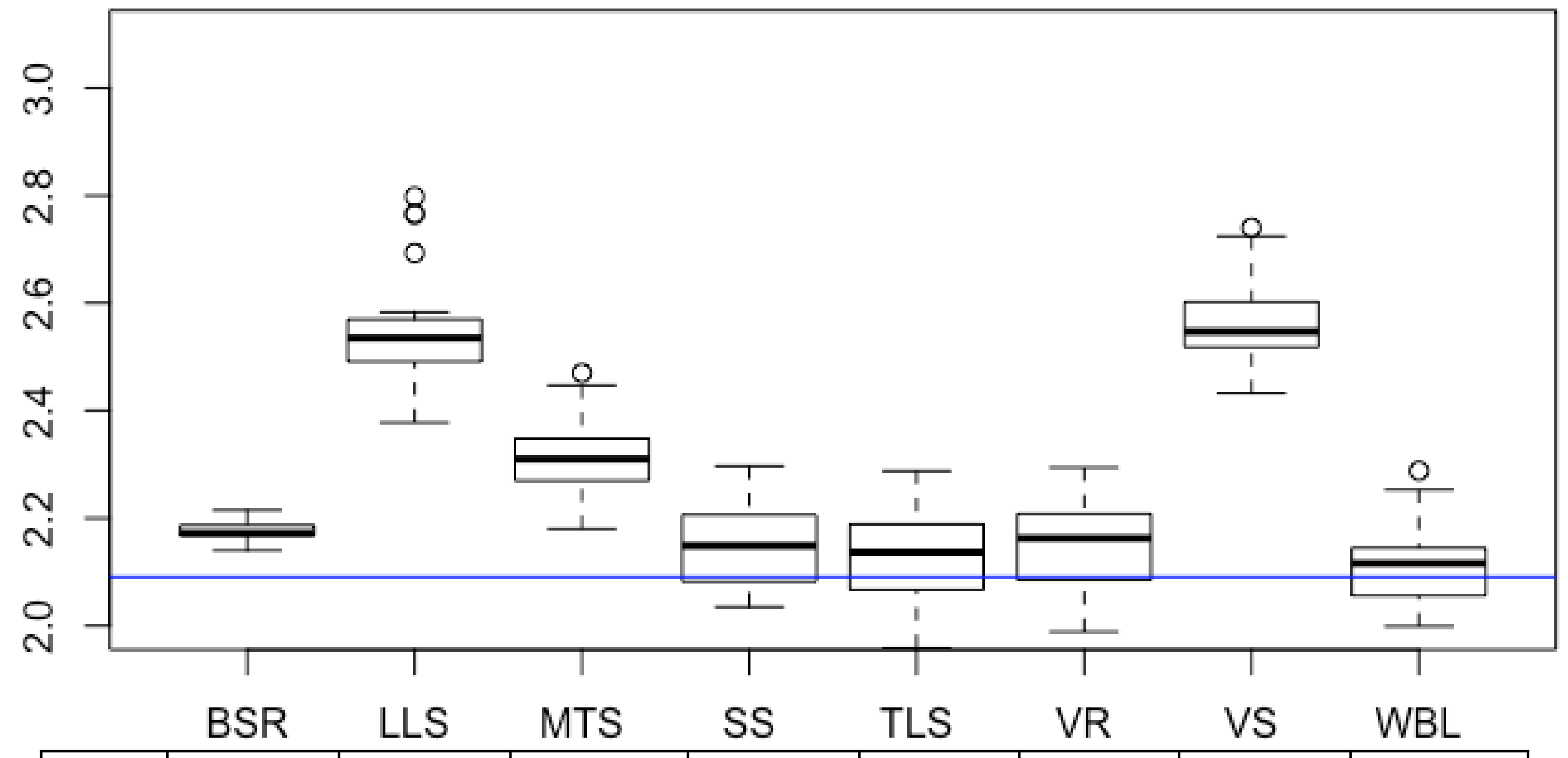
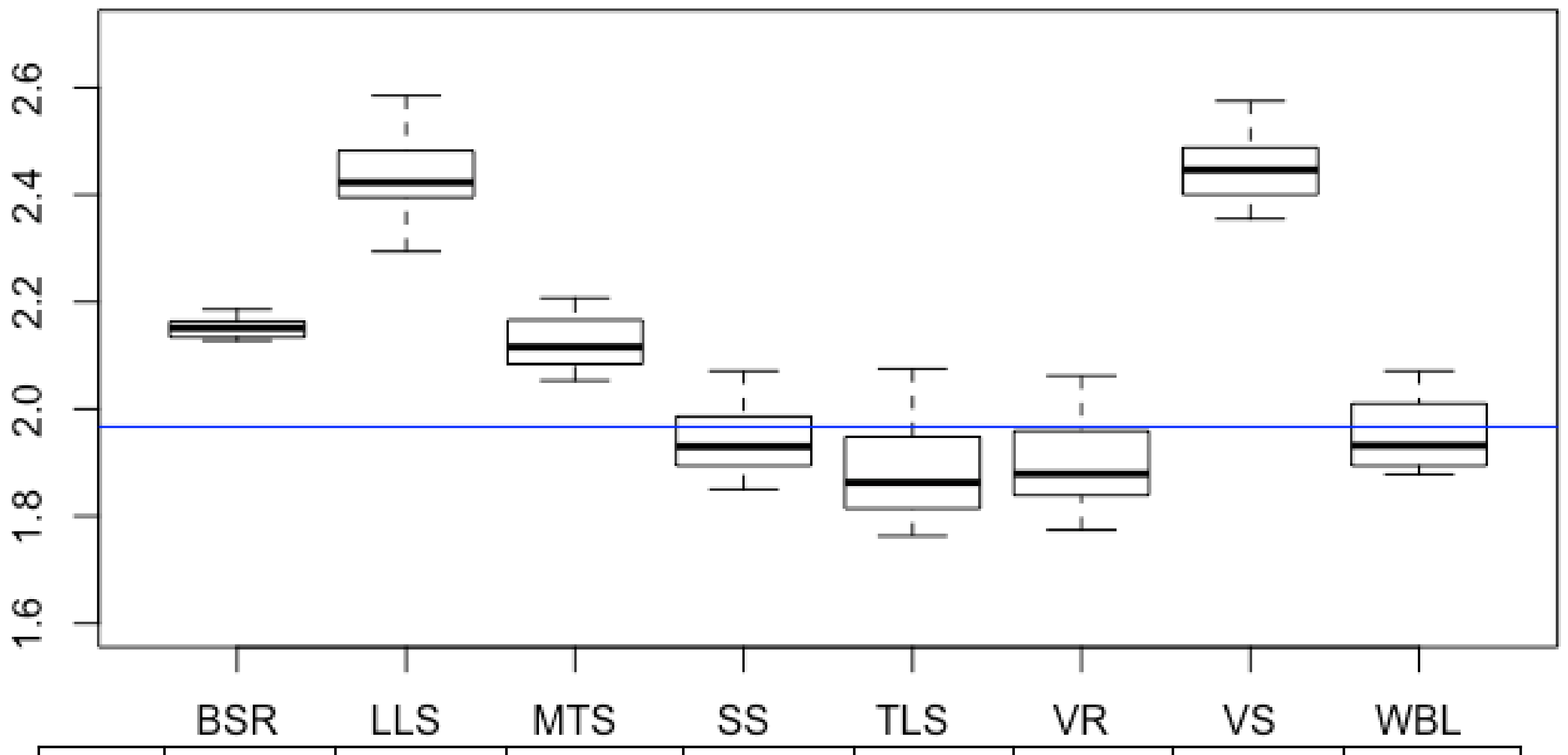
Weibull K-16扇区

Weibull K 1



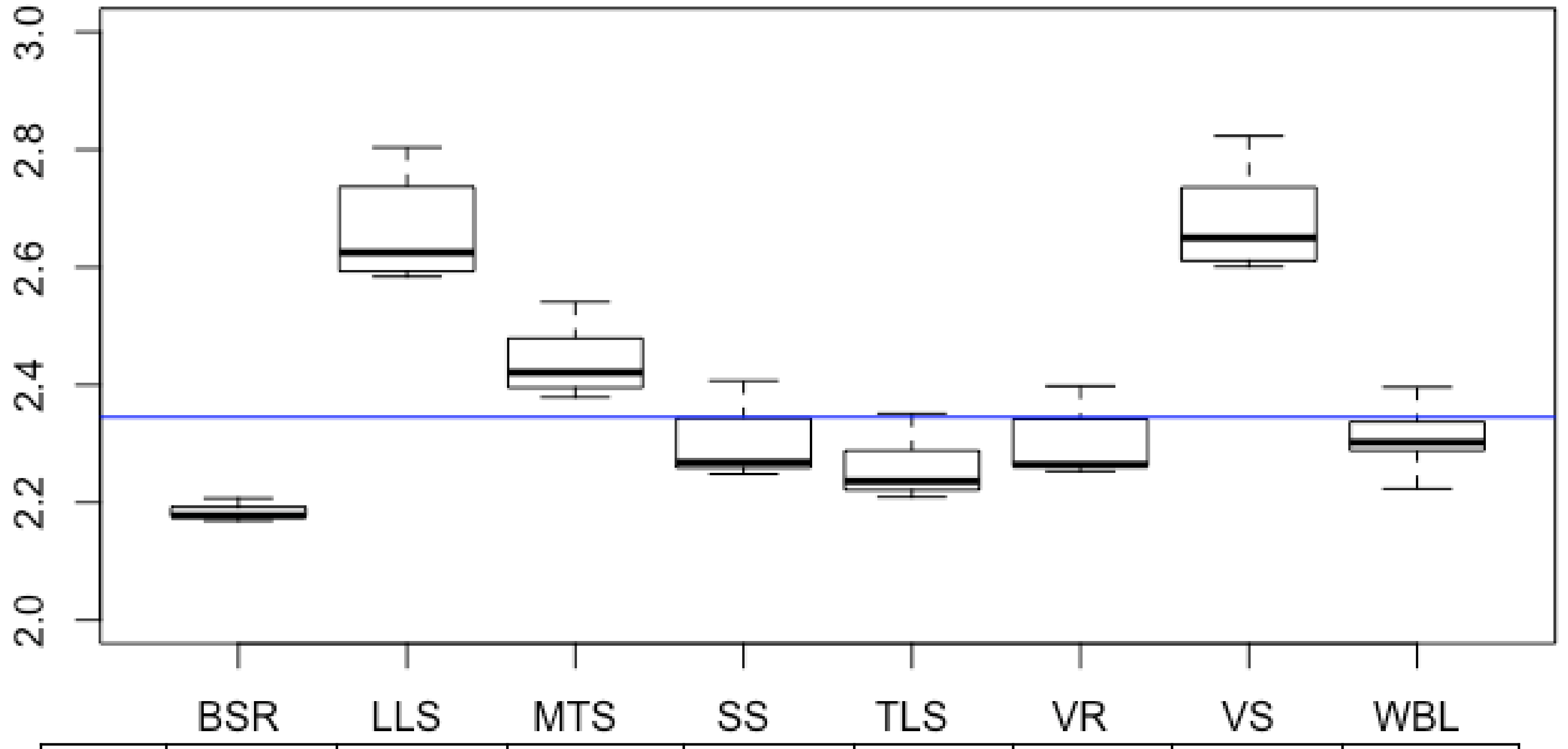
SD	0.0191	0.1158	0.0713	0.0790	0.094	0.08	0.0860	0.0781
MBE	3.87%	21.23%	10.47%	2.77%	2.20%	3.44%	21.81%	1.20%

Weibull K 2



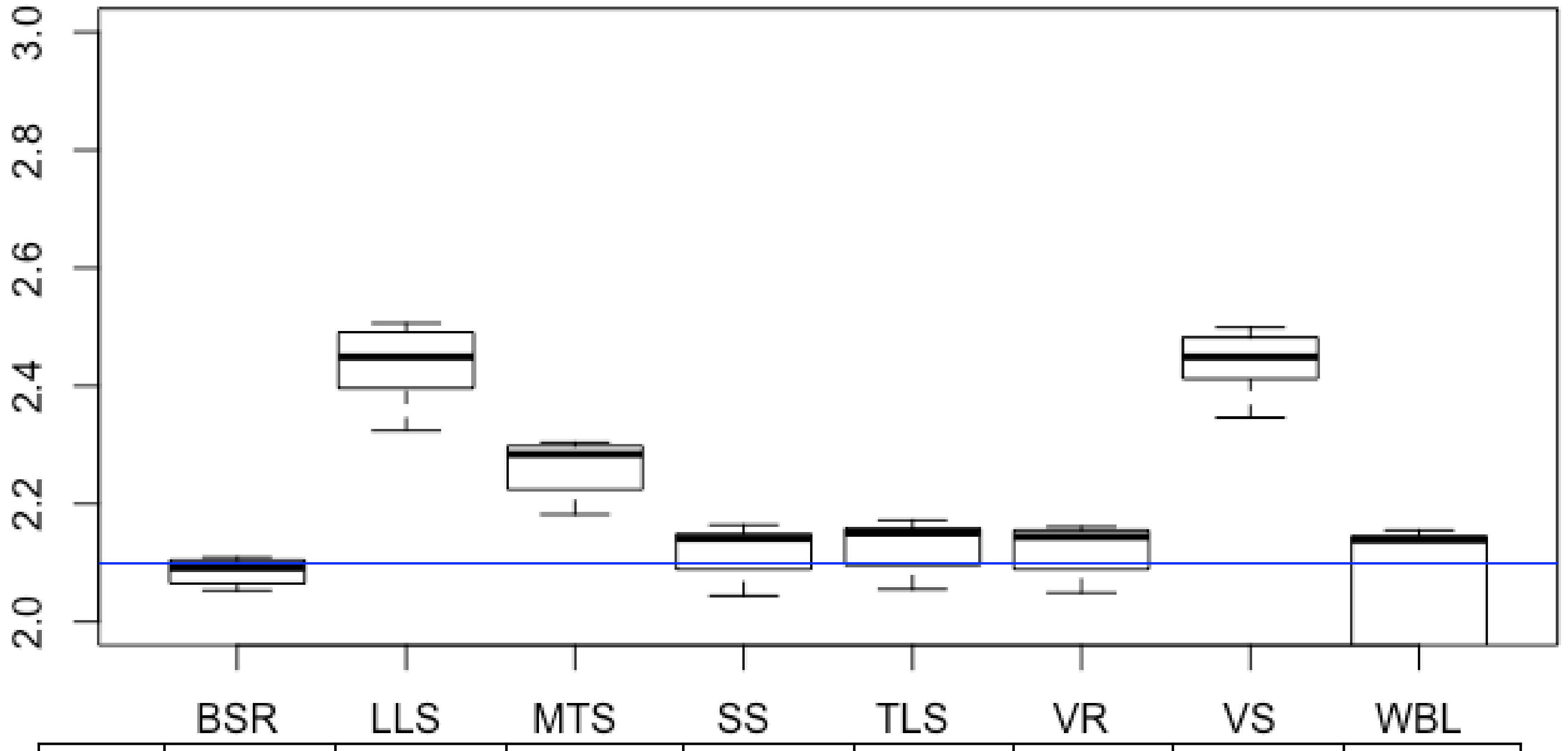
SD	0.0191	0.1158	0.0713	0.0790	0.094	0.08	0.0860	0.0781
MBE	3.87%	21.23%	10.47%	2.77%	2.20%	3.44%	21.81%	1.20%

Weibull K 3



SD	0.0132	0.0881	0.0591	0.0587	0.047	0.05	0.0832	0.0518
MBE	-7.16%	11.94%	3.24%	-3.28%	-4.65%	-3.45%	13.01%	-1.83%

Weibull K 4



SD	0.0207	0.0621	0.0463	0.0399	0.039	0.04	0.0498	0.1364
MBE	-0.38%	16.67%	8.81%	2.00%	2.43%	2.14%	16.67%	1.86%

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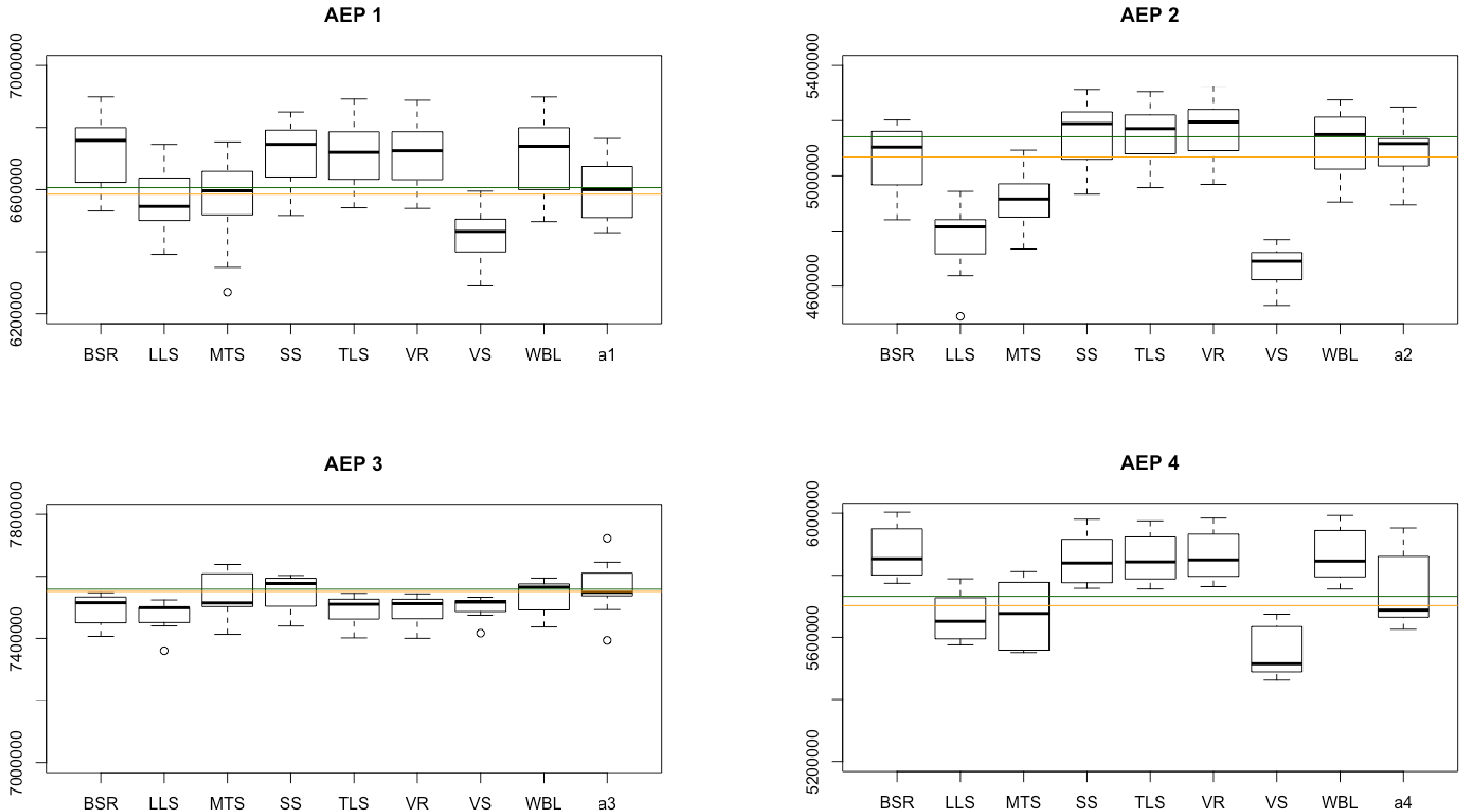
AEP-1sector-GW121



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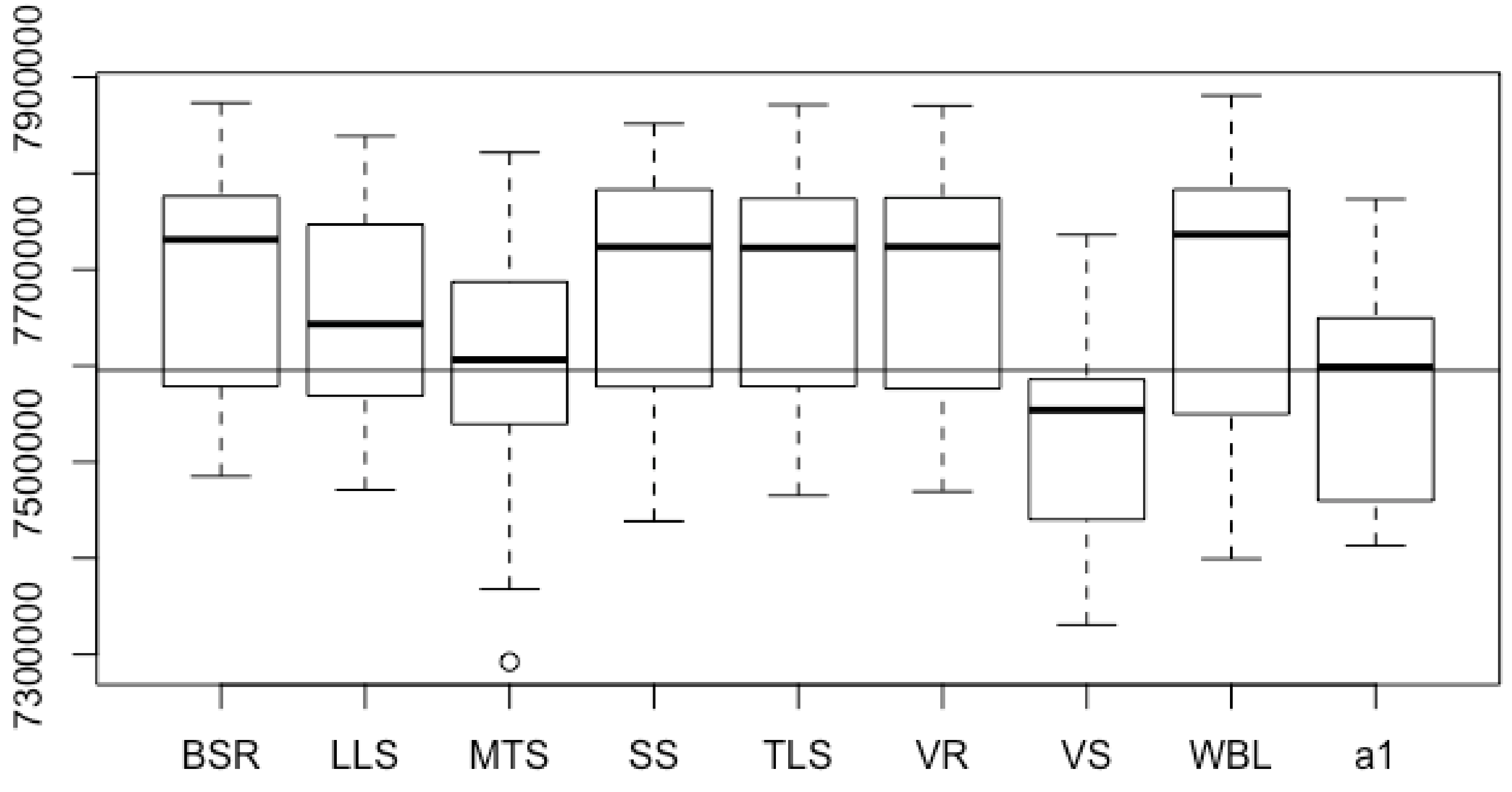

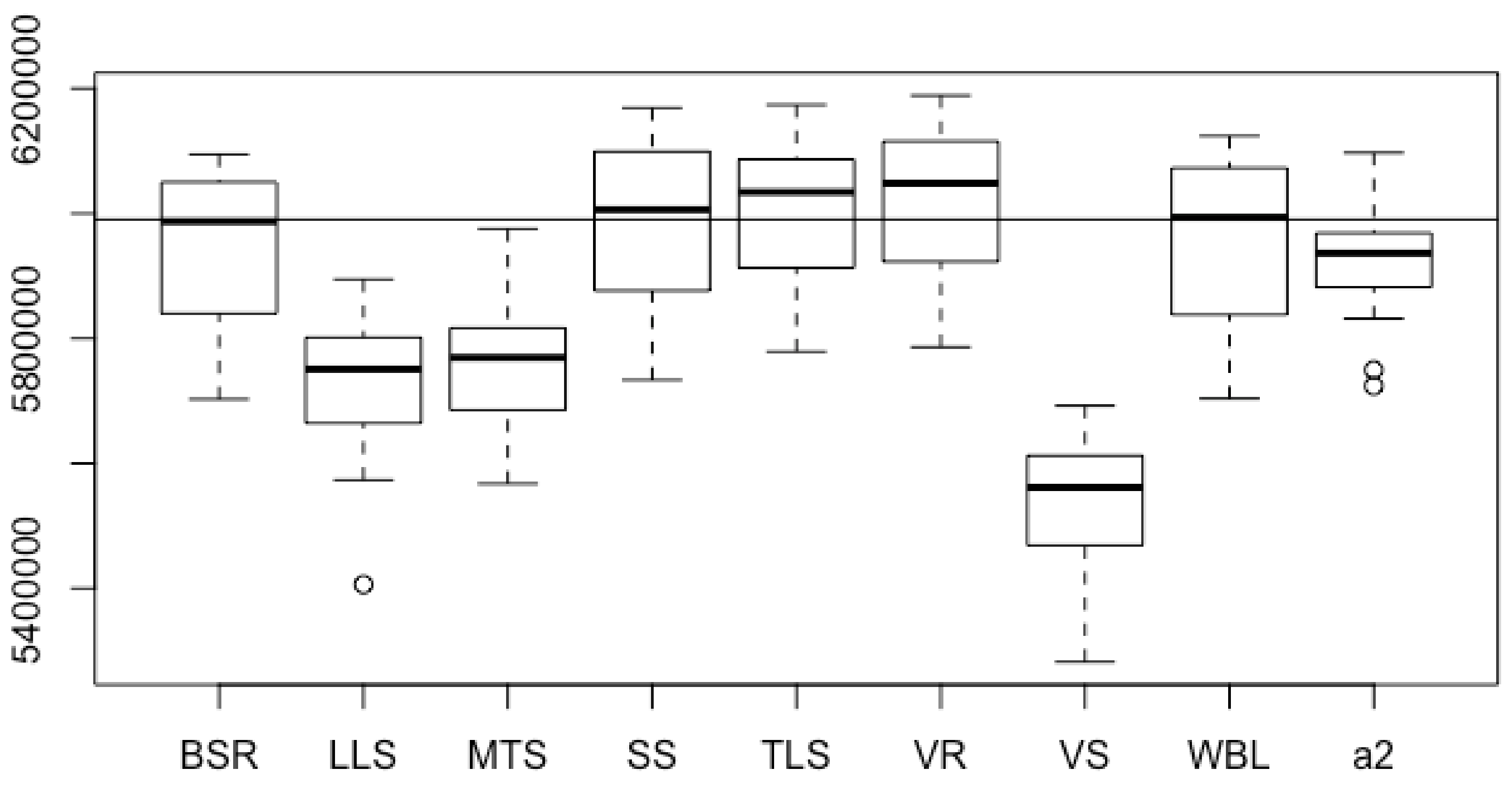

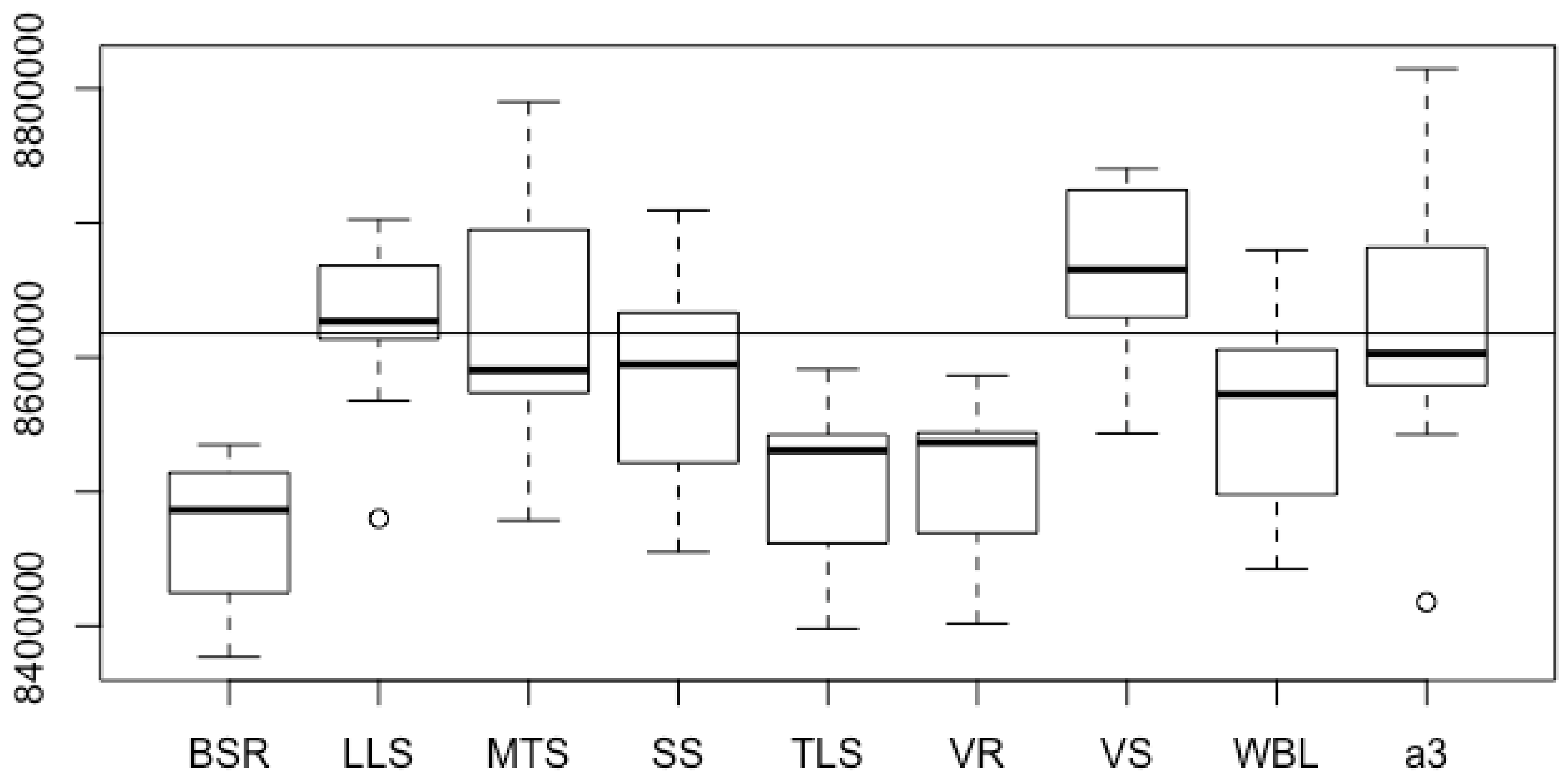

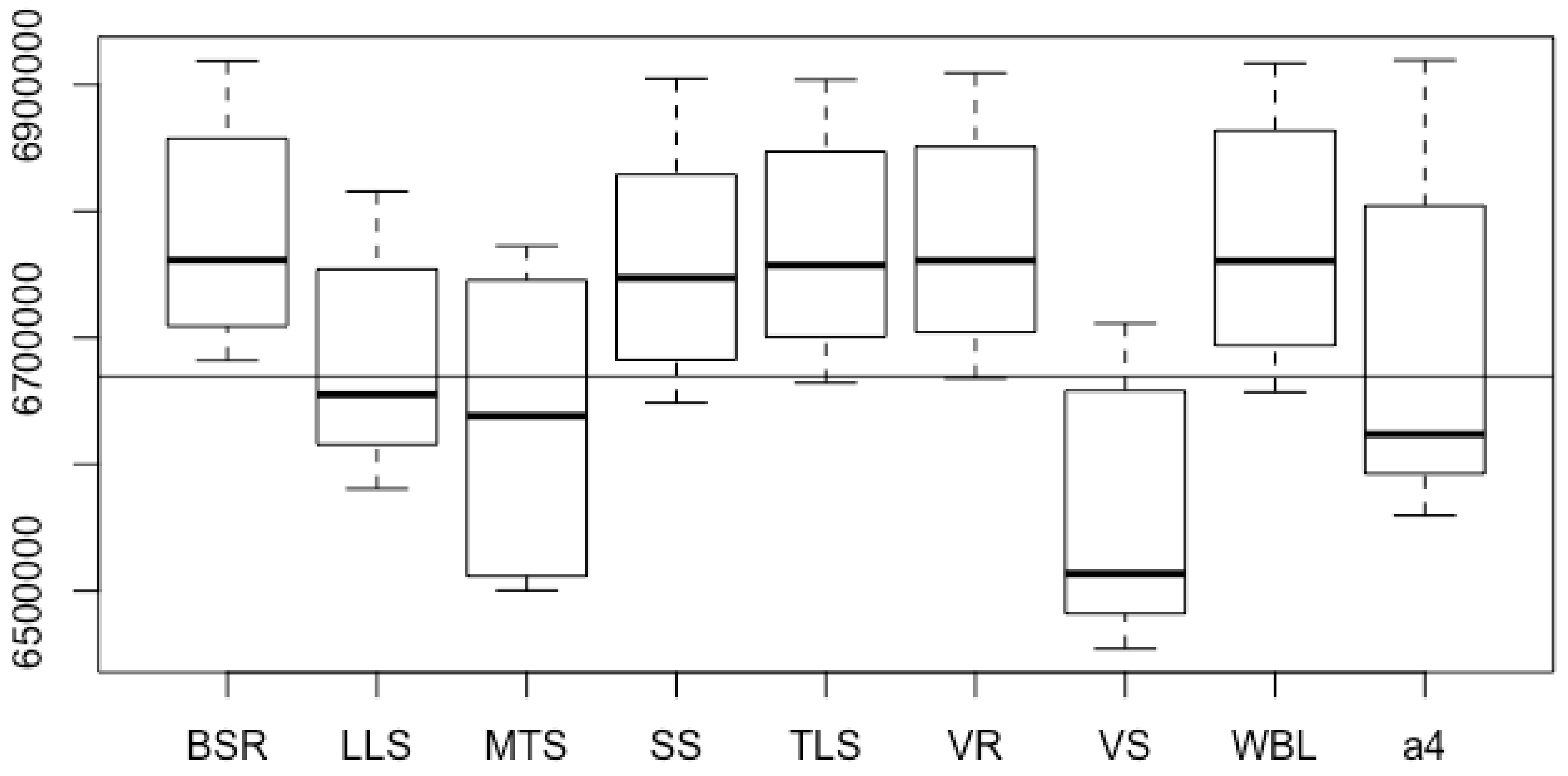

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总结

- 在用中尺度数据做插补时，由于时间分辨率造成样本量减少的问题，在非主风能扇区存在放大误差的情况。
- 在长期订正时，不应只局限与风速，线性回归由于算法本身的特性，会造成风频分布发生较大变化，从而影响发电量准确性。
- 常规8种算法在4基测风塔表现效果不一，新算法稳定性较好，仍需排查第三个测风塔两个极值点出现异常的原因。

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