Wind turbine long-term energy forecast

Contents

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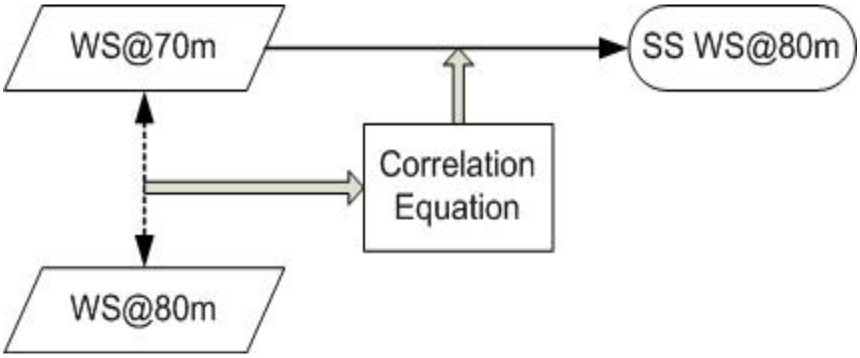
1. Reconstruct SS WS@80m

(column F, worksheet "Mast Measurement")

Process:



Steps:

- Load data from Excel worksheet "Mast Measurement".
- Identify time points where data are valid (WS value ≠ 9999) in both WS@70m (column H) and WS@80m (column G).
- Examine correlation between two valid datasets and determine the linear equation.
- Reconstruct SS WS@80m from WS@70m using linear interpolation.

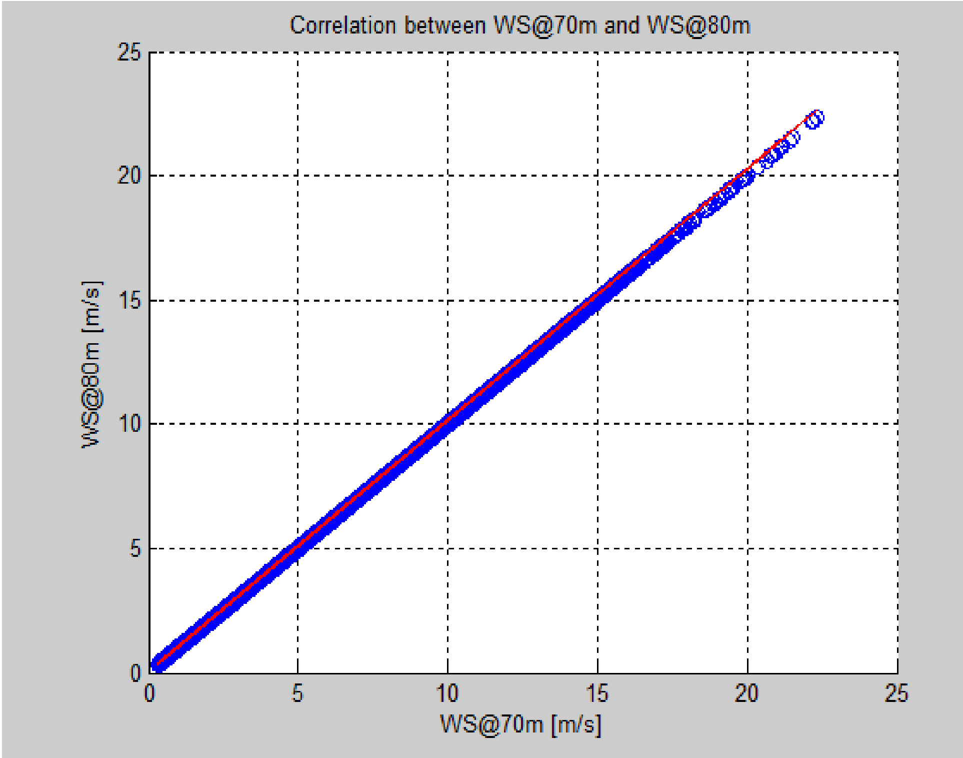
Code snippet:

```
% Load data
filename = 'Wind-turbine-long-term-energy-forecast_Workbook.xlsx';
sheetname = 'Monthly Correlation with Ref';
Mast_Measurements = xlsread(filename,sheetname);

%...

% WS@70m --> col = 8
WS_70m = Mast_Measurements(:,8);
% WS@80m --> col = 7
WS_80m = Mast_Measurements(:,7);

% Index of common valid data in both WS@70m and WS@80m
Index_com_vd = find(WS_70m~=9999 & WS_80m~=9999);

% Linear correlation model with degree n = 1: y = p1*x + p2
[f_WS70m_WS80m,gof_WS70m_WS80m]
                     = fit(WS_70m(Index_com_vd,1),WS_80m(Index_com_vd,1),'poly1')


% Linearly Interpolated SS WS@80m from WS@70m
SS_WS80m = 9999*ones(length(WS_70m),1);
Index_vd_WS70m = find(WS_70m~=9999);       % Index of valid data in WS@70m
Temp = feval(f_WS70m_WS80m,WS_70m(Index_vd_WS70m));

% Round result to 4 decimal places
SS_WS80m(Index_vd_WS70m,1)= round(Temp*10000)/10000;
```

Results:

Linear equation represents the correlation between WS@70m and WS@80m:

$y = 0.0116x + 0.0507$ ($R^2 = 0.9942$)



SS WS@80m (column F) is interpolated from WS@70m based on the linear equation that relates WS@70m (column H) and WS@80m (column G)

	A	B	C	D	E	F	G	H
22								
23		Date	Time	Turbine WS@100 m [m/s]	LTWS@100 m [m/s]	SS WS@80 m [m/s]	WS@80 m [m/s]	WS@70 m [m/s]
24		1/26/2011	13:00			2.901	2.506	2.817
25		1/26/2011	13:10			3.177	2.783	3.090
26		1/26/2011	13:20			3.767	3.398	3.674
27		1/26/2011	13:30			2.147	1.748	2.073
28		1/26/2011	13:40			3.465	3.021	3.375
29		1/26/2011	13:50			2.838	2.474	2.755
30		1/26/2011	14:00			2.106	1.634	2.031
31		1/26/2011	14:10			3.786	3.458	3.692
32		1/26/2011	14:20			3.325	2.924	3.237
33		1/26/2011	14:30			1.862	1.382	1.791
34		1/26/2011	14:40			4.446	4.173	4.344
35		1/26/2011	14:50			2.916	2.518	2.833
36		1/26/2011	15:00			3.423	3.124	3.334
37		1/26/2011	15:10			3.616	3.271	3.524
38		1/26/2011	15:20			4.240	3.890	4.141
39		1/26/2011	15:30			4.492	4.210	4.391
40		1/26/2011	15:40			4.603	4.336	4.500
41		1/26/2011	15:50			4.549	4.167	4.447
42		1/26/2011	16:00			4.266	3.972	4.167
43		1/26/2011	16:10			3.802	3.462	3.708
44		1/26/2011	16:20			4.264	3.945	4.165
45		1/26/2011	16:30			4.193	3.873	4.095
46		1/26/2011	16:40			3.875	3.573	3.781
47		1/26/2011	16:50			4.117	3.775	4.019
48		1/26/2011	17:00			4.755	4.435	4.650
49		1/26/2011	17:10			4.696	4.402	4.592
50		1/26/2011	17:20			4.442	4.197	4.341
51		1/26/2011	17:30			4.431	4.226	4.330
52		1/26/2011	17:40			3.779	3.554	3.685

2. Compute the General Statistics and the Monthly Statistics tables

(Worksheet “Mast Measurements”)

From the measurement data associated to WS@30m, WS@50m, WS@70m and WS@80m, we compute the values: Max – Average value – Period – Period of valid data (in table General Statistics) and Monthly mean – MOMM (in table Monthly Statistics)

Code snippet:

```
% Load data
filename = 'Wind-turbine-long-term-energy-forecast_Workbook.xlsx';
sheetname = 'Mast measurements';

% Read complete Excel worksheet
[num,txt,raw] = xlsread(filename,sheetname);

% Get returns the month in numeric (1-12) and string (Jan-Dec) form
% given a serial date string.
Date = raw(24:end,2);
[MonthNum, MonthString] = month(Date,'mm/dd/yyyy');

% Pre-allocate vector of monthly mean values
SS_WS80m_Monthly_means = zeros(12,1);

for mon = 1:12
    % Index of valid data in each month
    Index = MonthNum(:,1)==mon & SS_WS80m~=9999;

    Monthly_vd = SS_WS80m(Index,1);                  % Valid data in each month
    SS_WS80m_Monthly_means(mon,1) = mean(Monthly_vd); % Monthly mean value
end

% Round result to 4 decimal places
SS_WS80m_Monthly_means = round(SS_WS80m_Monthly_means*10000)/10000;

% MOMM
weight = [31 28.25 31 30 31 30 31 31 30 31 30 31];
Temp = sum(weight'.*SS_WS80m_Monthly_means)/sum(weight);
SS_WS80m_MOMM = round(Temp*10000)/10000;

% Max and average
max_value = max(SS_WS80m(Index_vd_WS70m,1));
avg_value = mean(SS_WS80m(Index_vd_WS70m,1));

Nb_period = length(SS_WS80m);            % Total number of period
Nb_period_vd = sum(SS_WS80m~=9999);      % Number of period of valid data
```

Results:

	A	B	C	D	E	F	G	H	I	J
1										
2		General Statistics		Turbine WS@100 m [m/s]	LTWS@100 m [m/s]	SS WS@80 m [m/s]	WS@80 m [m/s]	WS@70 m [m/s]	WS@50 m [m/s]	WS@30 m [m/s]
3		Max				22.623	22.734	22.313	22.017	21.068
4		Average				5.717	5.734	5.602	5.291	4.807
5		Period				105891	105891	105891	105891	105891
6		Period of valid data				105070	98694	105070	105221	105109
7										
8		Monthly Statistics		Turbine WS@100 m [m/s]	LTWS@100 m [m/s]	SS WS@80 m [m/s]	WS@80 m [m/s]	WS@70 m [m/s]	WS@50 m [m/s]	WS@30 m [m/s]
9	1	January	31			5.349	5.326	5.237	4.989	4.536
10	2	February	28.25			5.819	5.874	5.702	5.463	4.910
11	3	March	31			6.272	6.284	6.150	5.899	5.441
12	4	April	30			7.164	7.126	7.032	6.723	6.249
13	5	May	31			5.986	5.971	5.867	5.530	5.048
14	6	June	30			6.073	6.034	5.954	5.615	5.188
15	7	July	31			4.933	4.931	4.827	4.547	4.151
16	8	August	31			4.377	4.375	4.277	3.928	3.505
17	9	September	30			5.427	5.456	5.315	4.989	4.414
18	10	October	31			5.175	5.151	5.066	4.723	4.114
19	11	November	30			6.305	6.383	6.182	5.792	5.253
20	12	December	31			5.853	6.375	5.735	5.430	5.004
21		**MOMM**	**Annual**			**5.722**	**5.768**	**5.606**	**5.296**	**4.812**

3. Examine the concurrent period

(Worksheet "Monthly Correlation with Ref")

- Fill column Mast 80SS
- Correlation between Mast 80SS and reference data
- Predict LT Mast 80SS and calculate LT adj factor

3.1. Fill column Mast 80SS

- Fill column Mast 80SS (column M) with monthly data retrieved from column SS WS@80m (column F) in worksheet "Mast Measurements". The concurrent period is from Feb-11 to Dec-12 (23 months). Although values of SS WS@80m are also available in Jan-11 and Jan-13, these 2 months are not taken into account because we only have data from 26th to 31st in Jan-11 and from 1st to 30th in Jan-13.

Code snippet:

```
% Load data
filename = 'Wind-turbine-long-term-energy-forecast_Workbook.xlsx';
sheetname = 'Mast measurements';

% Read complete Excel worksheet
[num,txt,raw] = xlsread(filename,sheetname);

Date = raw(24:end,2);
[MonthNum, MonthString] = month(Date,'mm/dd/yyyy');
Year = year(Date,'mm/dd/yyyy');

% Initialize vectors of monthly mean values and coverage for 2 years 2011 & 2012
Monthly_mean11 = zeros(11,1); Coverage11 = zeros(11,1);
Monthly_mean12 = zeros(12,1); Coverage12 = zeros(12,1);
```

```
% Perform statistics for 11 months in 2011 (Feb-Dec)& 12 months in 2012 (Jan-Dec)

for mon = 1:11
    % Index of valid data in each month
    Index = Year==2011 & MonthNum(:,1)==mon+1 & SS_WS80m~=9999;

    Monthly_vd = SS_WS80m(Index,1);          % Valid data in each month
    Temp = mean(Monthly_vd);                             % Monthly mean value
    Monthly_mean11(mon,1) = round(Temp*10000)/10000;

    % Coverage
    Temp= length(Monthly_vd)/length(find(Year==2011 & MonthNum(:,1)==mon+1))*100;
    Coverage11(mon,1) = round(Temp*100)/100;
end
%}

% Repeat in the same way with year 2012
for mon = 1:12
    Index = Year==2012 & MonthNum(:,1)==mon & SS_WS80m~=9999;

    Monthly_vd = SS_WS80m(Index,1);
    Temp = mean(Monthly_vd);
    Monthly_mean12(mon,1) = round(Temp*10000)/10000;

    Temp = length(Monthly_vd)/length(find(Year==2012 & MonthNum(:,1)==mon))*100;
    Coverage12(mon,1) = round(Temp*100)/100;
end
```

Results:

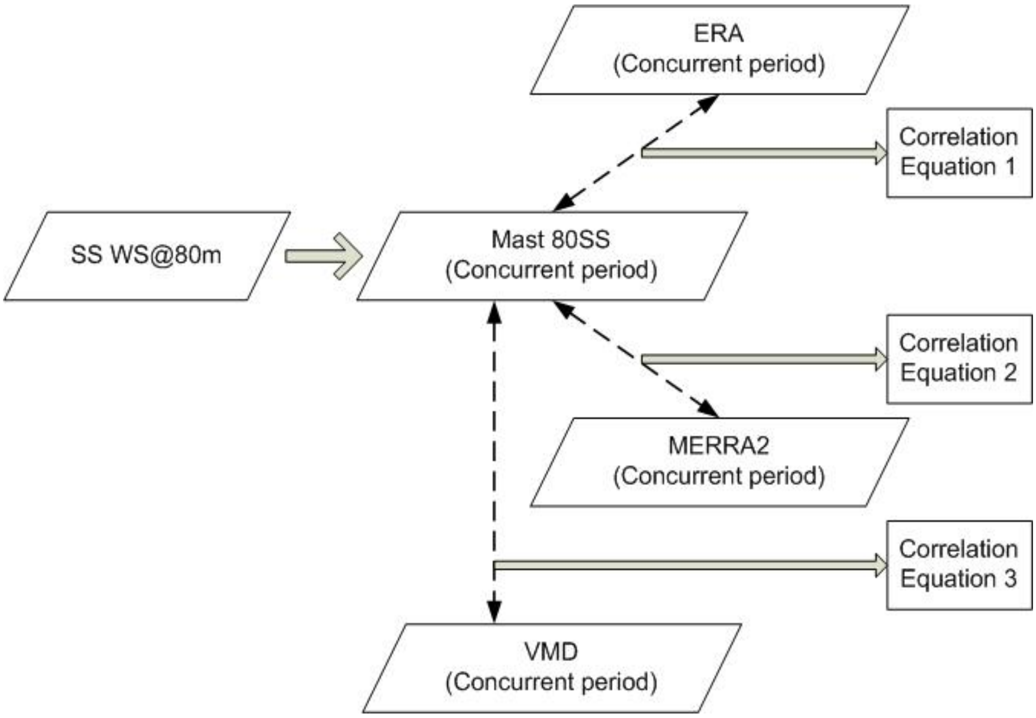
The concurrent period is surrounded by the red rectangle in the figure below. The 2nd column in the right (column M) is the data of Mast 80SS. The 1st column in the right (column N) is the coverage [%], which represent the ratio of the number of valid data points over the total number of data points within this month. We observe that the coverages associated to the current period are all greater than the threshold (90%), thus these 23 values will be used to identify the correlation with reference data.

114	Dec-10	12	5.31	100	12	8.78	100	12	8.78	100			
115	Jan-11	1	4.08	100	1	6.53	100	1	7.04	100			
116	Feb-11	2	3.80	100	2	5.87	100	2	6.46	100	2	5.43	94.27
117	Mar-11	3	4.10	100	3	6.55	100	3	7.16	100	3	6.38	90.08
118	Apr-11	4	4.65	100	4	6.86	100	4	7.45	100	4	6.98	100
119	May-11	5	4.45	100	5	6.48	100	5	6.95	100	5	6.46	100
120	Jun-11	6	4.21	100	6	5.94	100	6	6.78	100	6	6.09	100
121	Jul-11	7	2.90	100	7	4.36	100	7	5.03	100	7	4.42	100
122	Aug-11	8	2.57	100	8	4.08	100	8	4.71	100	8	4.21	100
123	Sep-11	9	3.49	100	9	5.64	100	9	6.14	100	9	5.42	100
124	Oct-11	10	3.06	100	10	4.72	100	10	5.20	100	10	4.57	100
125	Nov-11	11	4.06	100	11	6.46	100	11	6.74	100	11	5.97	100
126	Dec-11	12	3.71	100	12	6.11	100	12	6.36	100	12	5.38	100
127	Jan-12	1	3.72	100	1	5.49	100	1	5.98	100	1	5.12	98.84
128	Feb-12	2	4.00	100	2	6.21	100	2	6.84	100	2	6.18	99.64
129	Mar-12	3	4.11	100	3	6.23	100	3	6.74	100	3	6.18	100
130	Apr-12	4	5.08	100	4	7.61	100	4	7.98	100	4	7.35	100
131	May-12	5	3.29	100	5	5.37	100	5	6.18	100	5	5.51	100
132	Jun-12	6	3.97	100	6	6.00	100	6	6.62	100	6	6.06	100
133	Jul-12	7	3.57	100	7	5.30	100	7	6.04	100	7	5.45	100
134	Aug-12	8	2.89	100	8	4.42	100	8	4.96	100	8	4.54	100
135	Sep-12	9	3.40	100	9	5.30	100	9	5.64	100	9	5.44	100
136	Oct-12	10	3.86	100	10	5.97	100	10	6.38	100	10	5.78	100
137	Nov-12	11	4.44	100	11	7.02	100	11	7.18	100	11	6.64	100
138	Dec-12	12	4.12	100	12	6.58	100	12	6.80	100	12	6.33	100
139	Jan-13	1	3.58	100	1	5.36	100	1	6.02	100			
140	Feb-13	2	3.96	100	2	5.83	100	2	6.48	100			

3.2. Correlation between Mast 80SS and reference data

- Determine successively the linear correlation model that relates monthly data in Mast 80SS and three reference datasets ERA, MERRA2, VMD in order to determine the best source of reference data (the reference data that provide best R^2 value).

Process:



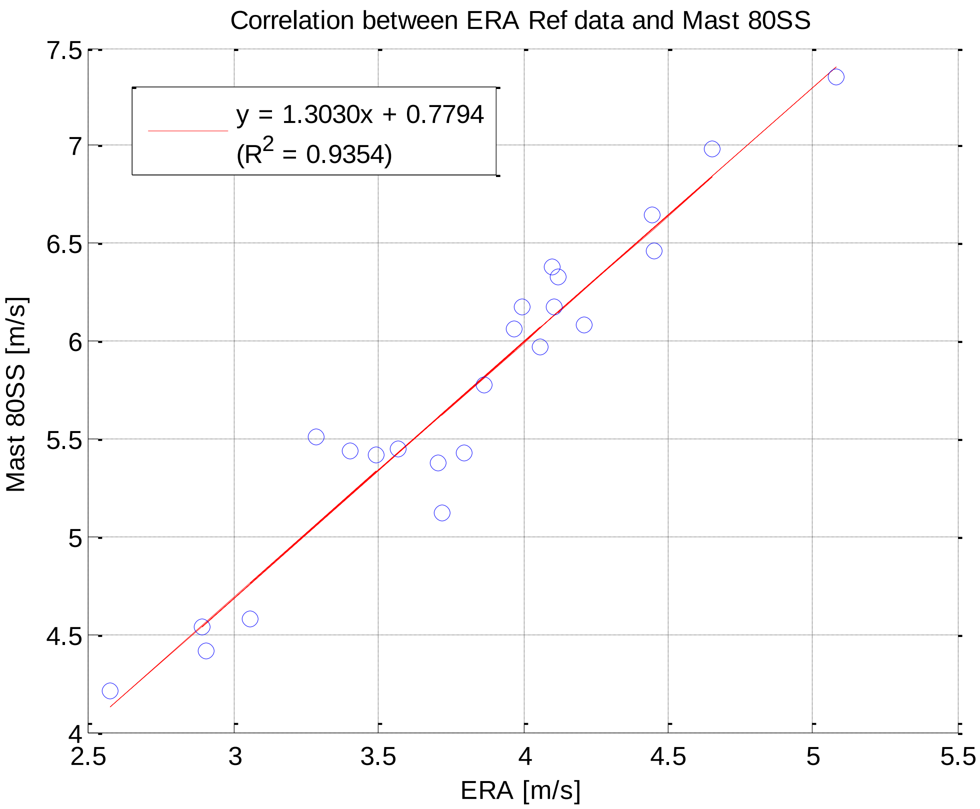
Code snippet:

```
% Load data
filename = 'Wind-turbine-long-term-energy-forecast_Workbook.xlsx';
sheetname = 'Monthly Correlation with Ref';

Monthly_Correlation = xlsread(filename,sheetname);

% Mast_80SS -> col = 13,
Mast_80SS = Monthly_Correlation(116:138,13);

% Relationship between Mast_80SS and ERA Data
% ERA -> col = 4,
ERA = Monthly_Correlation(116:138,4);

% Assume it's a linear interpolation with degree n = 1: y = p1*x + p2
% p(1) is the slope, p(2) is the intercept of the linear predictor
[f_ERA,gof_ERA] = fit(ERA,Mast_80SS,'poly1');

% Relationship between Mast_80SS and MERRA2 Data
% MERRA2 -> col = 7,
MERRA2 = Monthly_Correlation(116:138,7);
[f_MERRA2,gof_MERRA2] = fit(MERRA2,Mast_80SS,'poly1');

% Relationship between Mast_80SS and VMD Data
% VMD -> col = 10,
MERRA2 = Monthly_Correlation(116:138,10);
[f_VMD,gof_VMD] = fit(VMD,Mast_80SS,'poly1');
```

Results:

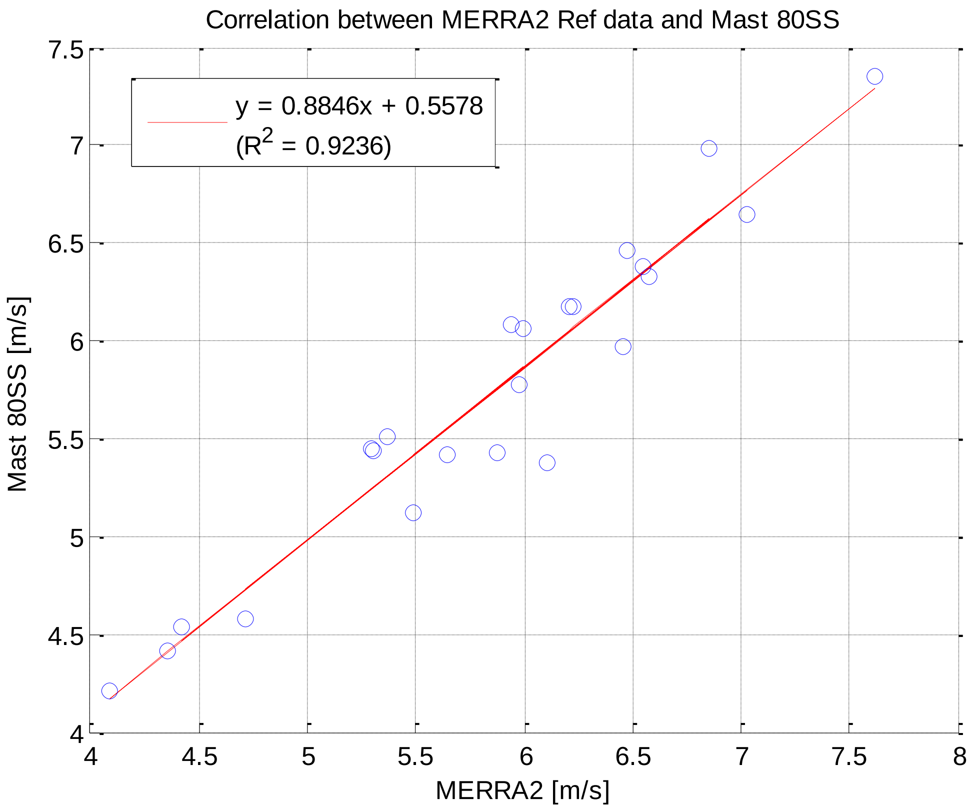
Linear equation represents the correlation between ERA data and Mast 80SS:

$y = 1.3030x + 0.7794$ $(R^2 = 0.9354)$

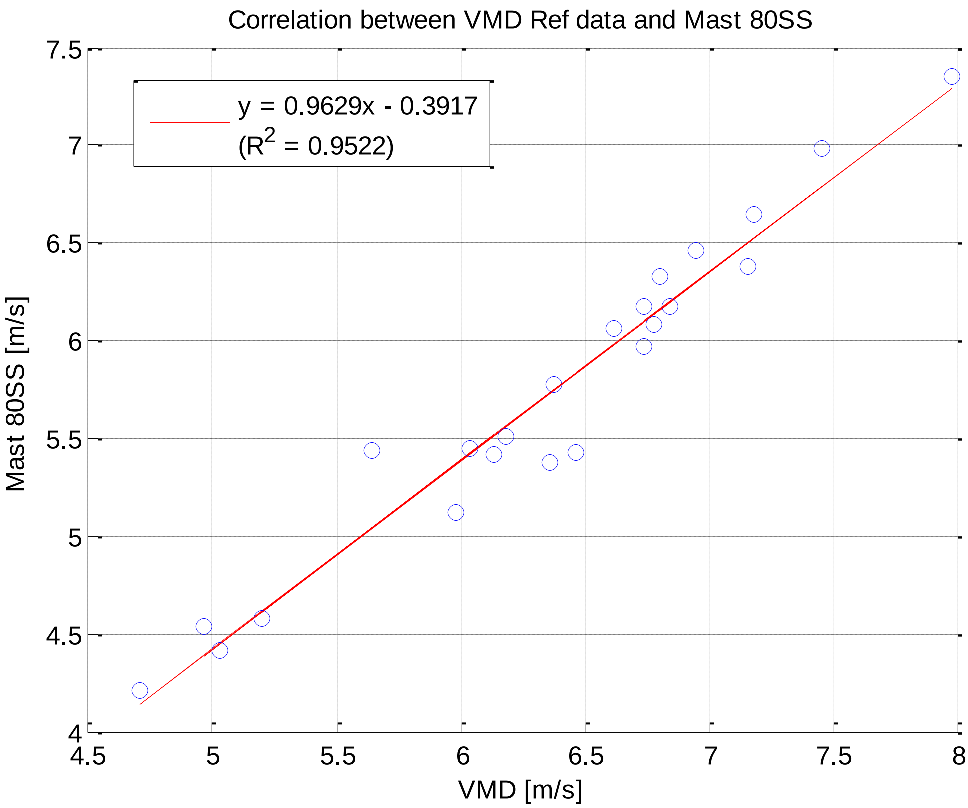


Linear equation represents the correlation between MERRA2 data and Mast 80SS:

$y = 0.8846x + 0.5578$ $(R^2 = 0.9236)$



Linear equation represents the correlation between VMD data and Mast 80SS:
$y = 0.9629x - 0.3917 \quad (R^2 = 0.9522)$



Summary:

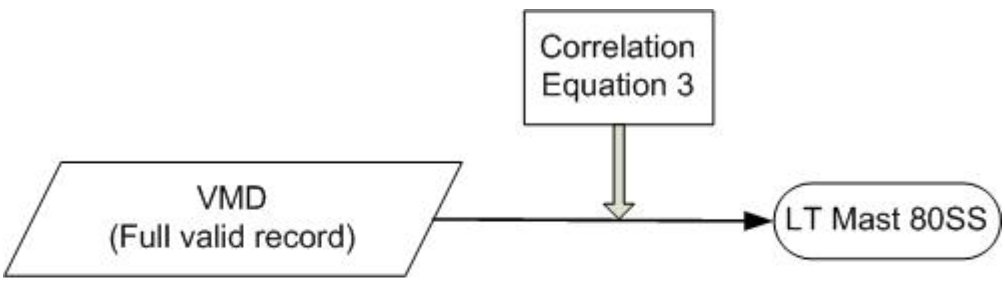
Reference data	ERA	MERRA2	VMD
R^2	0.9354	0.9236	0.9522

From the above table, we find that R^2 corresponding to VMD dataset is the highest among 3 reference datasets. Therefore, VMD will be used as the reference dataset to predict LT Mast 80SS (column P).

3.3. Predict LT Mast 80SS and calculate LT adj factor

- As discussed earlier, the reference data VMD is selected to predict the values of LT Mast 80SS (column P) through the full record length of valid reference data (from Jan-03 to Aug-16 in case of VMD; the reference data in time range Oct-16 to Dec-16 are ignored since the coverage (= 1, 0, 0 %) are below the threshold which equals to 90%)

Process:



Code snippet:

```
% Calculate LT Mast 80SS[m/s] by linearly extrapolating from VMD[m/s] (best R^2)

% VMD -> col = 10,
VMD_LT = Monthly_Correlation(19:132,10);  % valid data range of VMD
Temp = feval(f_VMD,VMD_LT);
Mast_80SS_LT = round(Temp*10000)/10000;
```

Results:

I	J	K	L	M	N	O	P	Q
Month	VMD [m/s]	Coverage [%]	Month	Mast 80SS [m/s]	Coverage [%]	Month	LT Mast 80SS [m/s]	Coverage [%]
1	6.65	100				1	6.01	100
2	6.41	100				2	5.79	100
3	6.39	100				3	5.76	100
4	7.36	100				4	6.70	100
5	6.36	100				5	5.73	100
6	6.18	100				6	5.56	100
7	5.53	100				7	4.93	100
8	5.04	100				8	4.47	100
9	5.37	100				9	4.78	100
10	7.35	100				10	6.68	100
11	6.81	100				11	6.17	100
12	7.16	100				12	6.50	100
1	6.47	100				1	5.84	100
2	8.40	100				2	7.70	100
3	7.09	100				3	6.43	100
4	7.60	100				4	6.92	100
5	6.68	100				5	6.04	100
6	5.36	100				6	4.77	100
7	5.54	100				7	4.95	100
8	5.26	100				8	4.67	100
9	5.19	100				9	4.60	100
10	5.58	100				10	4.98	100
11	6.60	100				11	5.97	100
12	7.04	100				12	6.39	100
1	6.70	100				1	6.06	100
2	7.45	100				2	6.78	100
3	7.75	100				3	7.07	100
4	7.86	100				4	7.18	100
5	7.67	100				5	7.00	100
6	6.46	100				6	5.83	100

- The monthly means and MOMM of ERA, MERRA2 and VMD are computed in the same way as in worksheet “Mast Measurements” (see Section 2).
- The same procedure is performed on the LT Mast 80SS column obtained above to calculate the monthly means and MOMM of LT Mast 80SS. The monthly means and MOMM of Mast 80SS are the monthly statistics values of SS WS@80m (column F, worksheet “Mast Measurements”).

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
	Monthly Statistics		ERA [m/s]			MERRA2 [m/s]			VMD [m/s]			Mast 80SS [m/s]			LT Mast 80SS [m/s]
1	January	31	3.90			6.20			6.68			5.35			6.04
2	February	28.25	3.94			6.25			6.87			5.82			6.22
3	March	31	4.21			6.62			7.21			6.27			6.55
4	April	30	4.61			7.02			7.51			7.16			6.84
5	May	31	4.25			6.47			7.08			5.99			6.42
6	June	30	3.60			5.41			6.18			6.07			5.56
7	July	31	3.20			4.77			5.49			4.93			4.89
8	August	31	2.89			4.66			5.18			4.38			4.59
9	Septembe	30	2.99			4.83			5.33			5.43			4.74
10	October	31	3.65			5.85			6.21			5.18			5.58
11	November	30	4.10			6.62			6.80			6.30			6.15
12	December	31	4.18			6.76			7.02			5.85			6.37
	MOMM	Annual	3.79			5.95			6.46			5.72			5.83
			Threshold	90										LT adj	1.0183 (or +1.83%)

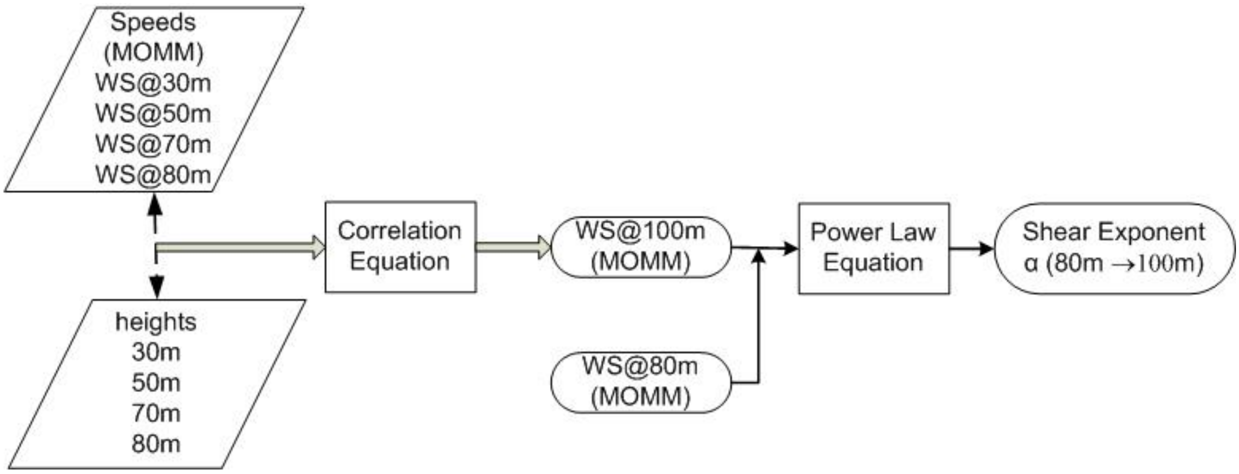
- Calculate the LT adj factor:

$$LT_{adj} = \frac{MOMM(LT\ Mast\ 80SS)}{MOMM(Mast\ 80SS)} = \frac{5.8264}{5.7215} = 1.0183$$

4. Shear exponent profile

Assuming that the shear remains constant above the mast, we assess the value of shear exponent α when going from 80m to 100m, which will be subsquently used to estimate LT WS@100m (column E) in worksheet "Mast Measurements".

Process:



Steps:

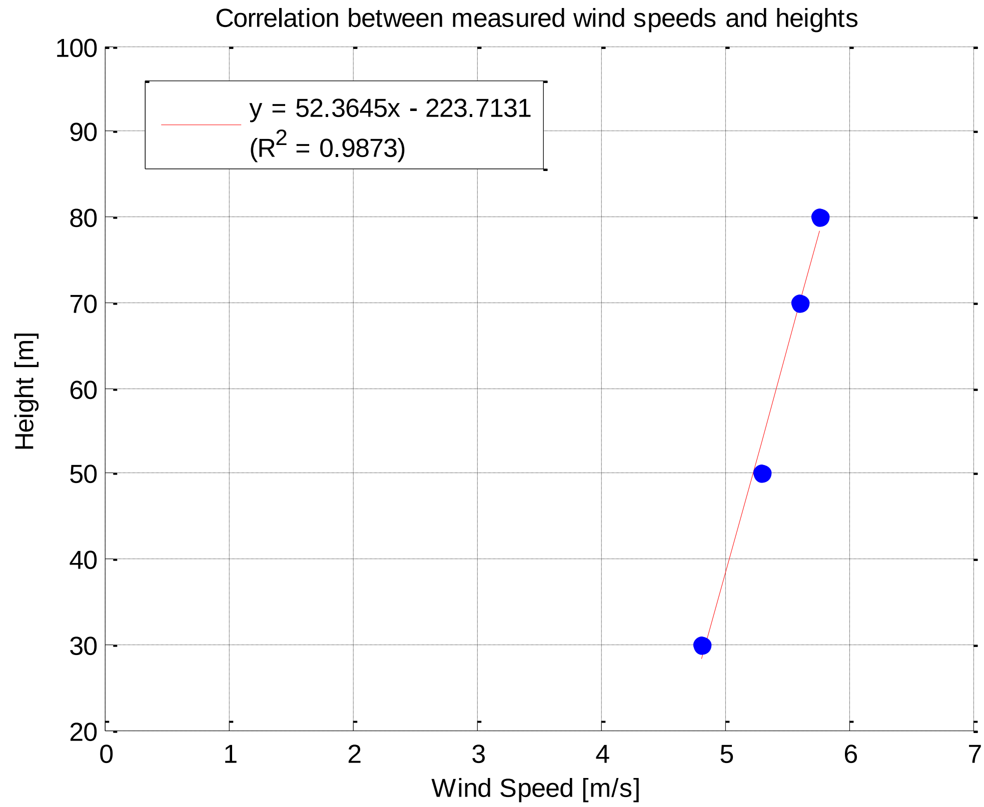
- Use the MOMM values of WS@30m (column J), WS@50m (column I), WS@70m (column H), WS@80m (column G) in worksheet "Mast measurements" and determine the linear correlation model.
- Calculate wind speed at 100m height, using the linear equation.
- Calculate the shear exponent $\alpha_{80m®100m}$ based on the given power law equation.

Code snippet:

```
% 4 data points corresponding to mast at 30 - 50 - 70 - 80m
speed = [4.8118 5.2957 5.6057 5.7680];
height = [30 50 70 80];

% Linear correlation model with degree n = 1: y = p1*x + p2
% Calculate (p1, p2) and r-square (R^2)
f = fit(speed',height','poly1');

% Calculate wind speed at 100m height
mast_height = 100;
Temp = (mast_height - f.p2)/f.p1;
WS_100m = round(Temp*10000)/10000;

% Calculate the shear exponent alpha (80m -> 100m)
alpha = log(6.1819/speed(1,4))/log(mast_height/height(1,4))
```

Results:

Linear equation represents the correlation between mast's measured wind speeds at different heights:
y = 52.3645x - 223.7131 (R^2 = 0.9873)



Calculate wind speed at 100m height, using the linear equation:

$$\mathrm{WS@100m} = \frac{100 + 223.7131}{52.3645} = 6.1819$$

Calculate the shear exponent $\alpha_{80m®100m}$ based on the given power law equation:

$$\alpha_{80m®100m} = \frac{\log\left(\frac{\mathrm{WS@100m}}{\mathrm{WS@80m}}\right)}{\log\left(\frac{100}{80}\right)} = \frac{\log\left(\frac{6.1810}{5.7680}\right)}{\log\left(\frac{100}{80}\right)} = 0.3106$$

Power Law

$$\frac{\overline{U}(z_1)}{\overline{U}(z_2)} = \left(\frac{z_1 - d}{z_2 - d}\right)^{\alpha}$$

where	a is power law wind shear exponent,
	$\overline{U}$ is the mean wind speed,
	z is the height above ground level, and
	d is the effective flow displacement height, if any.

Heights	WS
100	6.182
80	5.768
70	5.606
50	5.296
30	4.812

5. Estimate LTWS@100m

(Column E, worksheet "Mast Measurements")

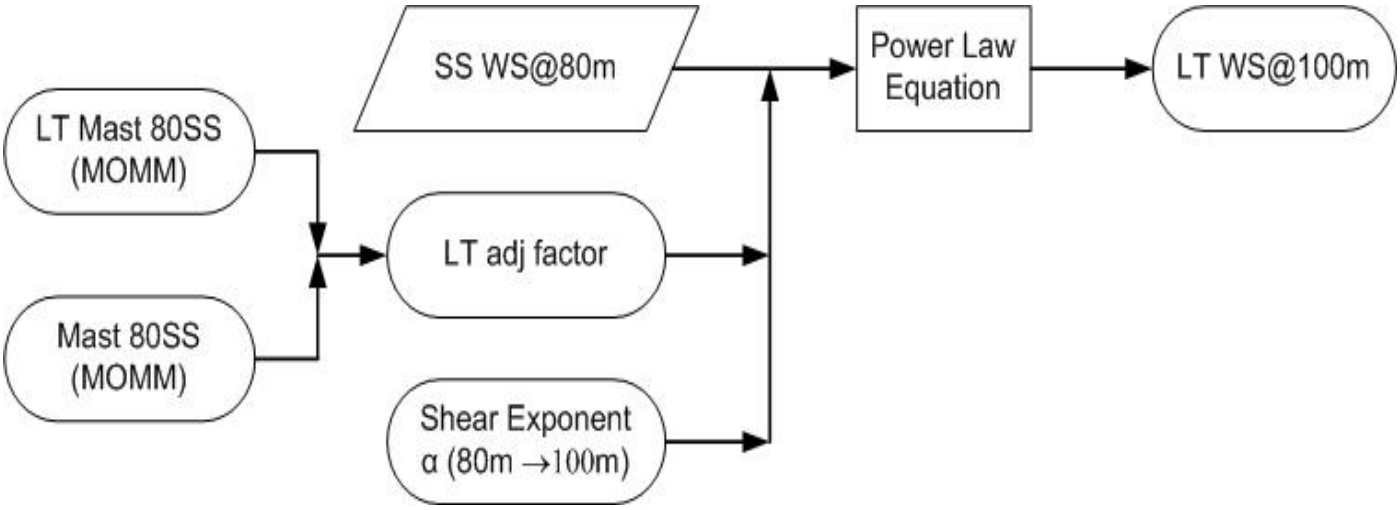
The LTWS@100m is estimated using the equation below:

$$\text{LTWS@100m} = \left(\text{SS WS@80m x } LT_{adj}\right) \text{ x } \left(\frac{100}{80}\right)^{\alpha_{80m@100m}}$$

Where:

- SS WS@80m is reconstructed in worksheet "Mast Measurements", column F (see section 1)
- LT_{adj} factor is calculated in worksheet "Monthly Correlation with Ref" (see sub-section 3.3)
- Shear exponent $\alpha_{80m@100m}$ is calculated in section 4.

Process:



Code snippet:

```
% Compute (SS WS@80m * LT adj) with valid 10 minutes-data
% Then, extrapolate to 100m using power law with shear exponent alpha

LT_adj = 1.0183;
alpha = 0.3106;

% Index of valid data of SS_WS80
Index_vd_SSWS80m = find(SS_WS80m~=9999);
% Pre-allocate vector LT_WS100m
LT_WS100m = 9999*ones(length(SS_WS80m),1);

LT_WS100m(Index_vd_SSWS80m,1)  =
                            (SS_WS80m(Index_vd_SSWS80m,1)*LT_adj)*(100/80)^alpha;

% Round result to 4 decimal places
LT_WS100m = round(LT_WS100m*10000)/10000;
```

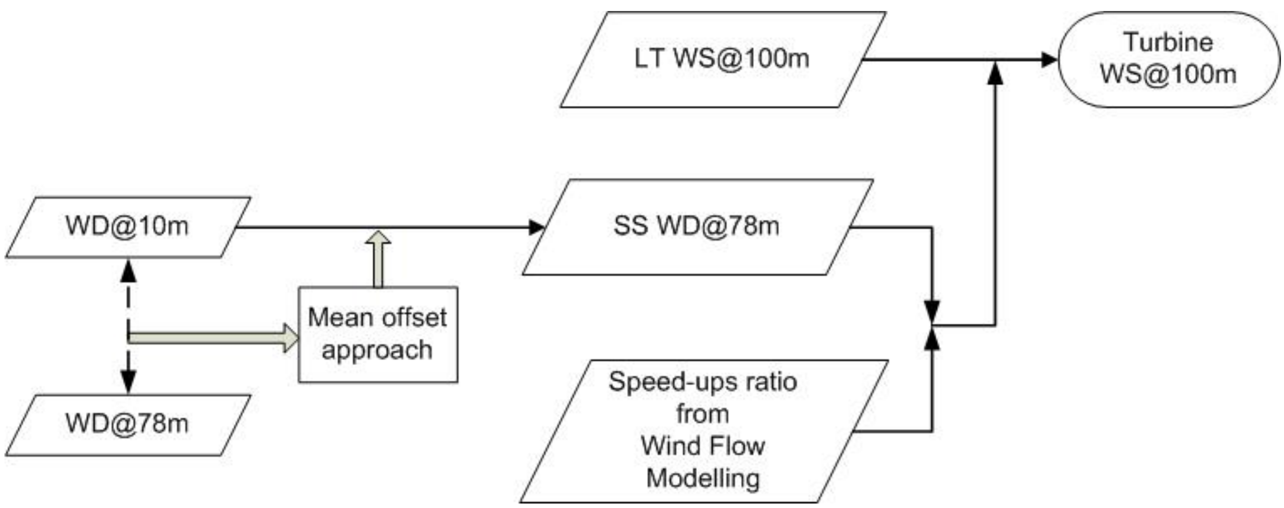
Results:

	B	C	D	E	F
23	Date	Time	Turbine WS@100 m [m/s]	LTWS@100 m [m/s]	SS WS@80 m [m/s]
24	1/26/2011	13:00		3.166	2.901
25	1/26/2011	13:10		3.467	3.177
26	1/26/2011	13:20		4.112	3.767
27	1/26/2011	13:30		2.344	2.147
28	1/26/2011	13:40		3.782	3.465
29	1/26/2011	13:50		3.097	2.838
30	1/26/2011	14:00		2.298	2.106
31	1/26/2011	14:10		4.132	3.786
32	1/26/2011	14:20		3.629	3.325
33	1/26/2011	14:30		2.032	1.862
34	1/26/2011	14:40		4.852	4.446
35	1/26/2011	14:50		3.183	2.916
36	1/26/2011	15:00		3.736	3.423
37	1/26/2011	15:10		3.946	3.616
38	1/26/2011	15:20		4.627	4.240
39	1/26/2011	15:30		4.903	4.492
40	1/26/2011	15:40		5.024	4.603
41	1/26/2011	15:50		4.965	4.549
42	1/26/2011	16:00		4.656	4.266
43	1/26/2011	16:10		4.149	3.802
44	1/26/2011	16:20		4.654	4.264
45	1/26/2011	16:30		4.576	4.193
46	1/26/2011	16:40		4.229	3.875
47	1/26/2011	16:50		4.493	4.117
48	1/26/2011	17:00		5.190	4.755
49	1/26/2011	17:10		5.125	4.696
50	1/26/2011	17:20		4.848	4.442
51	1/26/2011	17:30		4.836	4.431
52	1/26/2011	17:40		4.124	3.779
53	1/26/2011	17:50		3.999	3.665

6. Calculate Turbine WS@100m

(Column D, worksheet "Mast Measurements")

Process:



6.1. Estimate SS WD@78m

(Column K, worksheet "Mast Measurements")

We apply the "mean offset" approach, as stated below:

> "It is usually not necessary to use MCP to predict the target directional distribution, so long as there is at least a year of directional data from the target site. Where the on-site observations are inadequate, the simplest solution is to find the mean offset between the concurrent reference and target directions for each reference direction sector and apply that offset to the full reference data record."

(Brower, Michael. *Wind resource assessment: a practical guide to developing a wind project*. John Wiley & Sons, 2012.)

Steps:

- Determine time points where data are valid (WD value ≠ 9999) in both WD@10m (colum M) and WD@78m (column L)
- Divide the wind direction in 36 sectors, each has 10º width. Classify WD@10m at the time points determined above into 36 sectors.
- For each sector, calculate the mean value of the veers (the mean offset) between WD@78m and WD@10m at the same time points.
- For each valid data point of WD@10m, assign the corresponding offset value considering the sector that this data point belongs to.
- Calculate SS WD@78m by adding the valid data points of WD@10m with its corresponding offset values.

Code snippet:

```
%% Load data
filename = 'Wind-turbine-long-term-energy-forecast_Workbook.xlsx';
sheetname = 'Mast measurements';
Mast_Measurements = xlsread(filename,sheetname);


% Index of valid data in WD@10m (WD@10[m/s] -> col = 13)
Index_vd_WD10m = find(Mast_Measurements(:,13)~=9999);

% Index of valid data in WD@78m (WD@78[m/s] -> col = 12)
Index_vd_WD78m = find(Mast_Measurements(:,12)~=9999);

% Index of valid data in both WD@10m and WD@78m
Index_vd_common = intersect(Index_vd_WD10m,Index_vd_WD78m);
WD10m_vd_common = Mast_Measurements(Index_vd_common,13);
WD78m_vd_common = Mast_Measurements(Index_vd_common,12);


%% Relationship between WD@10m and WD@78m (referring to mean offset approach)

direction_edges = 0:10:360; % Define 36 sectors of 10 degree width

% Return sector index for each valid data point in WD10m
[Nb_Datapoints,Index_Sector] = histc(WD10m_vd_common,direction_edges);

% In each sector, compute the mean value of the veers between WD78m & WD10m
```

```
Mean_veer = zeros(36,1);
for i = 1:1:36
    Mean_veer(i,1)= mean(WD78m_vd_common(Index_Sector == i) -
                                    WD10m_vd_common(Index_Sector == i));
end

% Calculate the offset values: these values are retrieved from the Mean_veer
% vector above depending on the values of WD@10m (Reference data)
WD10m = Mast_Measurements(:,13);
offset_values = 9999*ones(length(Index_vd_WD10m),1);
for j = Index_vd_WD10m
    [n,bin] = histc(WD10m(j),direction_edges);
    offset_values(j,1) = Mean_veer(bin,1);
end

% Add the offset values to Reference data (valid data points of WD@10m) to
% obtain SS_WD@78m
SS_WD78m = 9999*ones(length(WD10m),1);
SS_WD78m(Index_vd_WD10m,1) = WD10m(Index_vd_WD10m) +
                                    offset_values(Index_vd_WD10m);
% Round result to 4 decimal places
SS_WD78m = round(SS_WD78m*1000)/1000;
```

Results:

We divide the wind direction into 36 sectors as presented in the table below. The 3rd column is the calculated mean offset values corresponding to each wind direction sector.

Wind direction sector	Number of data points	Mean offset
0º – 10º	1847	38.4
10º – 20º	1370	33.2
20º – 30º	1739	27.7
30º – 40º	1647	23.6
40º – 50º	1352	25.5
50º – 60º	1212	26.6
60º – 70º	1146	31.5
70º – 80º	1092	24.9
80º – 90º	1276	26.8
90º – 100º	1585	26.0
100º – 110º	2064	18.8
110º – 120º	2822	17.2
120º – 130º	3990	13.2
130º – 140º	6033	11.2
140º – 150º	7017	10.9
150º – 160º	6670	12.5
160º – 170º	6752	12.1
170º – 180º	4954	11.7
180º – 190º	3248	10.8
190º – 200º	1875	9.7
200º – 210º	1299	11.6
210º – 220º	973	8.3
220º – 230º	951	5.0
230º – 240º	836	5.0
240º – 250º	934	2.1
250º – 260º	1342	3.6

260º – 270º	2484	5.0
270º – 280º	4855	5.5
280º – 290º	3753	6.7
290º – 300º	3251	7.3
300º – 310º	3247	6.0
310º – 320º	3935	4.7
320º – 330º	3740	0.7
330º – 340º	4664	-7.4
340º – 350º	4404	-56.2
350º – 360º	3057	-236.3
	Total: 103416	

K	L	M
SS WD@78 m [deg]	WD@78 m [deg]	WD@10 m [deg]
323.6	329.2	318.9
324.5	327.6	319.8
324.8	339.4	332.2
292.4	332.0	348.7
326.8	342.7	334.3
115.2	353.8	351.6
323.8	336.8	319.1
319.9	324.0	315.2
292.4	353.1	348.7
119.4	351.8	355.8
323.2	324.0	322.5
330.8	338.7	338.2
325.9	338.9	333.3
312.1	319.4	306.2
288.1	346.0	344.3
329.3	335.9	328.5
328.9	340.6	336.4
285.0	347.5	341.3
288.8	342.5	345.1
330.6	344.1	338.0
327.8	342.0	335.2
325.9	340.6	333.3
331.7	344.6	339.2
284.6	348.4	340.8
332.0	350.8	339.4
327.1	350.6	334.5
324.5	348.7	332.0
326.6	345.5	334.0
322.7	345.5	330.1

6.2. Calculate Turbine WS@100m from Wind Flow Modeling

Steps:

- Consult worksheet “Wind Flow Modeling” (see Figure below) and compare the direction bins with the direction values in SS WD@78m, in order to find the corresponding Speed-ups ratios.

- Compute the wind speed at the turbine location:

Turbine WS@100m = LTWS@100m * Speed-ups ratio

Directional speed ups from mast to turbine location at 100 m height

Direction	Speed-ups
0	0.9
10	0.92
20	0.94
30	0.96
40	0.98
50	1
60	1.02
70	1.04
80	1.06
90	1.08
100	1.1
110	1.12
120	1.14
130	1.16
140	1.18
150	1.2
160	1.22
170	1.24
180	1.22
190	1.2
200	1.18
210	1.16
220	1.14
230	1.12
240	1.1
250	1.08
260	1.06
270	1.04
280	1.02

Code snippet:

```
% Load data
filename = 'Wind-turbine-long-term-energy-forecast_Workbook.xlsx';
sheetname = 'Wind Flow modelling';

% Get the Speed-ups vector (36 values)
Speed_ups = xlsread(filename,sheetname);

%
Index_vd_LTWS100m = find(LT_WS100m~=9999);
Index_vd_SSWD78m = find(SS_WD78m~=9999);

% Index of valid data in both LTWS@100m and WD@78m
Index_vd_Turbine = intersect(Index_vd_LTWS100m,Index_vd_SSWD78m);
add_values = zeros(length(Index_vd_Turbine),1);

directional_speedups_edges = 0:10:360;

for i = Index_vd_Turbine
  [n,bin] = histc(SS_WD78m(i),directional_speedups_edges);
  ratio_values(i,1) = Speed_ups(bin,2);
end

% Compute Turbine_WS100m
Turbine_WS100m = 9999*ones(length(LT_WS100m),1);
Turbine_WS100m(Index_vd_Turbine) =
                     LT_WS100m(Index_vd_Turbine).*ratio_values(Index_vd_Turbine);

% Round result to 4 decimal places
Turbine_WS100m = round(Turbine_WS100m*10000)/10000;
```

Results:

	B	C	D	E
22				
23	Date	Time	Turbine WS@100 m [m/s]	LTWS@100 m [m/s]
24	1/26/2011	13:00	2.976	3.166
25	1/26/2011	13:10	3.259	3.467
26	1/26/2011	13:20	3.865	4.112
27	1/26/2011	13:30	2.344	2.344
28	1/26/2011	13:40	3.555	3.782
29	1/26/2011	13:50	3.469	3.097
30	1/26/2011	14:00	2.160	2.298
31	1/26/2011	14:10	3.966	4.132
32	1/26/2011	14:20	3.629	3.629
33	1/26/2011	14:30	2.276	2.032
34	1/26/2011	14:40	4.561	4.852
35	1/26/2011	14:50	2.928	3.183
36	1/26/2011	15:00	3.512	3.736
37	1/26/2011	15:10	3.788	3.946
38	1/26/2011	15:20	4.720	4.627
39	1/26/2011	15:30	4.609	4.903
40	1/26/2011	15:40	4.723	5.024
41	1/26/2011	15:50	5.064	4.965
42	1/26/2011	16:00	4.749	4.656
43	1/26/2011	16:10	3.817	4.149
44	1/26/2011	16:20	4.375	4.654
45	1/26/2011	16:30	4.302	4.576
46	1/26/2011	16:40	3.891	4.229
47	1/26/2011	16:50	4.583	4.493
48	1/26/2011	17:00	4.774	5.190
49	1/26/2011	17:10	4.818	5.125
50	1/26/2011	17:20	4.557	4.848
51	1/26/2011	17:30	4.546	4.836
52	1/26/2011	17:40	3.876	4.124

The monthly means and MOMM of LTWS@100m and Turbine WS@100m are computed in the same way as in Section 2.

	A	B	C	D	E	F
1						
2		General Statistics		Turbine WS@100 m [m/s]	LTWS@100 m [m/s]	SS WS@80 m [m/s]
3		Max		24.731	24.690	22.623
4		Average		6.822	6.240	5.717
5		Period		105891	105891	105891
6		Period of valid data		105011	105070	105070
7						
8		Monthly Statistics		Turbine WS@100 m [m/s]	LTWS@100 m [m/s]	SS WS@80 m [m/s]
9	1	January	31	6.174	5.837	5.349
10	2	February	28.25	6.826	6.351	5.819
11	3	March	31	7.364	6.846	6.272
12	4	April	30	8.660	7.819	7.164
13	5	May	31	7.343	6.533	5.986
14	6	June	30	7.694	6.628	6.073
15	7	July	31	6.144	5.384	4.933
16	8	August	31	5.193	4.777	4.377
17	9	September	30	6.314	5.923	5.427
18	10	October	31	6.250	5.648	5.175
19	11	November	30	7.377	6.881	6.305
20	12	December	31	6.684	6.387	5.853
21		**MOMM**	**Annual**	**6.828**	**6.244**	**5.722**
22						

7. Frequency Distribution

Steps:

- Classify into 12 sectors the values of SS WD@78m at time points where Turbine WS@100m has valid values.
- For each of the 12 direction sectors, get all data points in Turbine WS@100m whose corresponding wind direction pertains to the sector.
- Classify successively the 12 sets of Turbine WS@100m data points got above into 50 speed sectors.
- Count the number of data points in each cell of table (WS/WD), then divide these values by the total number of valid data points to obtain the probabilities that the wind blowing in a specified wind speed and wind direction range.

Code snippet:

```
direction_edges = 15:30:345;
speed_edges = [0 0.5:1:49.5];

% Classify SS_WD78m into 12 direction sectors
[NbCount_Direction,Index_St_Direction] =
                              histc(SS_WD78m(Index_vd_Turbine),direction_edges);
NbCount_Direction(end) = [];

% Assign corresponding directional bin to each data point in Turbine WS@100m
Index = NaN(length(Turbine_WS100m),1);
Index(Index_vd_Turbine,1) = Index_St_Direction;

% Pre-allocate the matrix of probabilities, note that there isn't any element in
the first bin (0 <= deg < 15 or 345 <= deg < 360)
Prob_Matrix = zeros(length(speed_edges)-1,length(NbCount_Direction)-1);

% Compute successively the columns of the matrix of probabilities
for j = 1:length(NbCount_Direction)
    [NbCount_Speed,Index_St_Speed] =
                          histc(Turbine_WS100m(find(Index == j),1),speed_edges);
    NbCount_Speed(end) = [];
    Prob = (NbCount_Speed/length(Index_vd_Turbine))*100;
    Prob_Matrix(:,j) = Prob;
end
```

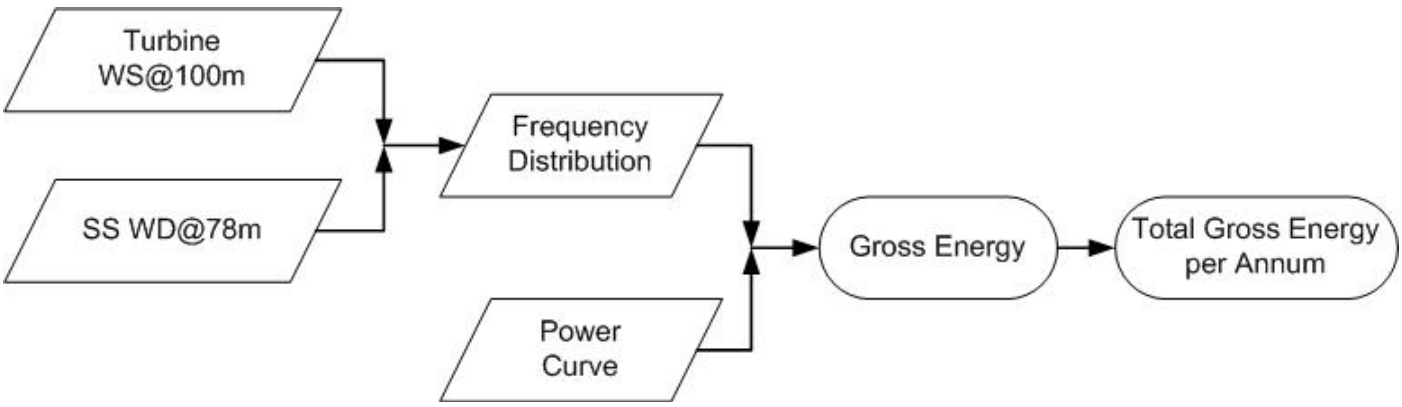
Results:

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1			Binning wind speed and direction				in (%)							
2														
3		WS/WD	0	30	60	90	120	150	180	210	240	270	300	330
4		0	0.000	0.014	0.130	0.092	0.111	0.089	0.089	0.131	0.101	0.049	0.056	0.062
5		1	0.000	0.069	0.361	0.257	0.362	0.289	0.316	0.252	0.229	0.116	0.169	0.171
6		2	0.000	0.097	0.543	0.349	0.595	0.504	0.487	0.499	0.371	0.321	0.416	0.383
7		3	0.000	0.156	0.754	0.492	0.946	0.897	0.896	0.672	0.454	0.525	0.806	0.798
8		4	0.000	0.217	0.848	0.515	1.265	1.346	1.222	0.828	0.462	0.722	1.247	1.236
9		5	0.000	0.226	0.887	0.589	1.411	1.760	1.601	0.860	0.445	0.847	1.498	1.634
10		6	0.000	0.216	0.888	0.409	1.325	2.245	1.891	0.637	0.305	1.019	1.638	1.828
11		7	0.000	0.143	0.649	0.266	1.063	2.354	2.104	0.429	0.258	1.102	1.639	1.709
12		8	0.000	0.147	0.424	0.168	0.855	2.265	2.016	0.360	0.157	1.005	1.479	1.471
13		9	0.000	0.093	0.268	0.112	0.643	1.780	1.935	0.265	0.108	0.981	1.249	1.069
14		10	0.000	0.039	0.142	0.054	0.534	1.493	1.695	0.189	0.076	0.694	1.051	0.706
15		11	0.000	0.028	0.095	0.031	0.418	1.151	1.214	0.113	0.042	0.383	0.855	0.437
16		12	0.000	0.021	0.047	0.014	0.282	0.717	0.896	0.052	0.027	0.255	0.605	0.292
17		13	0.000	0.019	0.030	0.005	0.185	0.469	0.534	0.025	0.012	0.147	0.411	0.172
18		14	0.000	0.011	0.013	0.007	0.158	0.279	0.335	0.022	0.011	0.081	0.260	0.078
19		15	0.000	0.002	0.014	0.006	0.109	0.191	0.169	0.005	0.003	0.049	0.152	0.043
20		16	0.000	0.004	0.010	0.003	0.091	0.148	0.110	0.004	0.005	0.044	0.081	0.022
21		17	0.000	0.000	0.002	0.001	0.061	0.087	0.069	0.000	0.003	0.040	0.027	0.012
22		18	0.000	0.001	0.004	0.001	0.025	0.067	0.027	0.001	0.004	0.026	0.014	0.006
23		19	0.000	0.000	0.001	0.000	0.015	0.037	0.018	0.000	0.003	0.012	0.002	0.004
24		20	0.000	0.000	0.000	0.000	0.010	0.021	0.022	0.000	0.000	0.013	0.000	0.008
25		21	0.000	0.000	0.000	0.000	0.001	0.005	0.011	0.000	0.000	0.007	0.000	0.002
26		22	0.000	0.000	0.000	0.000	0.000	0.003	0.005	0.000	0.000	0.010	0.000	0.004
27		23	0.000	0.000	0.000	0.000	0.000	0.001	0.005	0.000	0.000	0.013	0.000	0.003
28		24	0.000	0.000	0.000	0.000	0.000	0.001	0.005	0.000	0.000	0.003	0.001	0.000
29		25	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.000
30		26	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
31		27	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
32		28	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
33		29	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

8. Calculate Power Output

(Column D and H, worksheet "Total Power Output")

Process:



Steps:

- From the table in sheet "Frequency Distribution", select 25 rows corresponding to 25 wind speed ranges (1 to 25) specified in sheet "Total Power Output". Each row contains 12 values of probability associated to 12 direction sectors.
- Calculate the sum of probability values at each of 12 rows above then perform the multiplication following the equation below to obtain the expected gross energy output for each WS range within one year.

$$Gross\ Energy_i = 8766 \text{ x } f_i . P(ws_i)$$

Where:

- $P(ws_i)$: power output for wind speed bin (i), presented in the power curve
- f_i : sum of frequencies of all wind direction bins in wind speed bin (i), got from worksheet "frequency distribution"
- 8766 : average number of hours in a year (taking into account that every four year there is a lap year, which has 24 extra hours)

- The total gross energy per annum is obtained by summing all values in column Gross Energy:

$$\text{Total gross energy per annum } = \sum_i Gross\ Energy_i$$

Code snippet:

```
% Load data
filename = 'Wind-turbine-long-term-energy-forecast_Workbook.xlsx';
sheetname = 'Total Power Output';

% Get the Speed-ups vector (36 values)
PowerCurve_values = xlsread(filename,sheetname);

% Because 2,5 m/s is the cut-in speed; 25.5 m/s is the cut-out speed
% Range of meaningful frequency distribution: Prob_Matrix(4:26,:)
Gross_Energy = zeros(length(PowerCurve_values)-2,1);

for i = 3:length(PowerCurve_values)
    Gross_Energy(i,1)= 8766*(sum(Prob_Matrix(i+1,:))/100)*PowerCurve_values(i,2);
end

% Total gross energy per annum
Total_GE = sum(Gross_Energy);
```

Results:

Wind Turbine Power Output for different WS

WS	Power Curve	Gross Energy
1	0	0.0
2	0	0.0
3	44	28528.1
4	155	134603.7
5	338	348345.1
6	588	639128.7
7	934	959078.1
8	1394	1264326.3
9	1802	1343149.3
10	2031	1188148.4
11	2140	894454.1
12	2181	613371.2
13	2194	386260.1
14	2199	242123.4
15	2200	143062.8
16	2200	100272.5
17	2200	58033.2
18	2200	33607.8
19	2200	17814.0
20	2200	14141.0
21	2200	4958.5
22	2200	4040.3
23	2200	4223.9
24	2200	1836.5
25	2200	367.3

Total gross energy per Annum
8423874.2