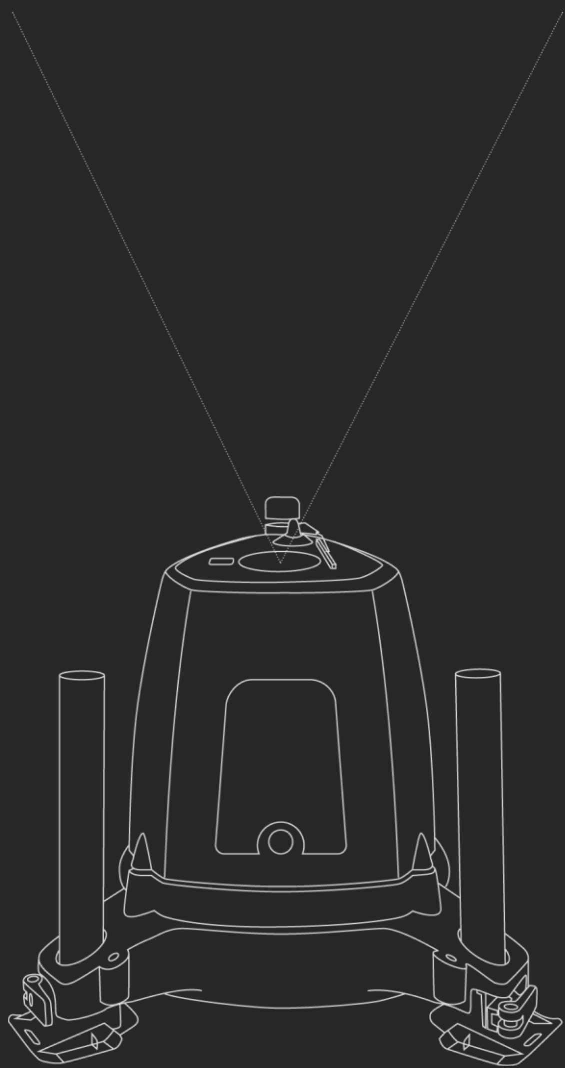
# CLASSIFICATION OF ZEPHIR 300 LIDAR AT THE UK REMOTE SENSOR TEST SITE



John Medley

November 2014

# 1 INTRODUCTION

The Wind Turbine Technical Committee of the International Electrotechnical Commission (IEC) has produced a document [1] that describes a uniform methodology aimed at standardising the measurement and analysis of wind turbine power curves. As remote sensing devices such as lidar have become more widely recognized as valuable tools for making such measurements, Annex L of that standard has been written to ensure the traceability of remote sensor measurements to National Standards. It describes a procedure to assess the uncertainty contribution of those measurements to power curve evaluation through a two part test of the sensor, a classification test and a verification test.

In the classification test, the sensitivity of the measurements of a particular type of remote sensor to environmental parameters such as temperature, wind shear, etc, is assessed. Example units of that type of sensor are deployed close to a tall meteorological mast with well-calibrated cup anemometers for an extended period of time, during which there should be a wide range of environmental conditions. The differences in measured wind speed between the remote sensor and the mast sensors are considered as a function of one environmental parameter at a time. An accuracy class for the remote sensor is derived by combining the results of these sensitivity analyses, suitably extrapolated to cover a similar range of conditions as those used in the classification of cup anemometers (see Annex I of [1].)

The purpose of the verification test is to convey traceability to international standards to a particular device, in the form of an uncertainty. The verification test also allows for an assessment of random contributions to measurement uncertainty through a statistical analysis of a series of observations (a “Type-A” uncertainty assessment [2].) The verification test is not discussed further in this report.

It should be noted that this analysis methodology makes the assumption that data from the reference cup anemometers is always correct. In reality, any imperfect response of the cups to environmental parameters will add a contribution to the apparent accuracy class of the remote sensor. Hence, the assessment of standard uncertainty for the ZephIR 300 units here can be considered an upper limit.

The current report describes the results of classification tests of two recent production-standard ZephIR 300 lidars at the UK Remote Sensor Test Site (UK RSTS) at Pershore, superseding the evaluation of the pre-production ZephIR 300 described in [3]. It implements a technique for dealing with correlations between environmental variables that was introduced in [3].

## 2 TEST SITE

The UK RSTS is owned and operated by ZephIR Lidar. It features a 91.5 m tall meteorological mast (met mast) that has been constructed to conform with the recommendations for mast anemometry given in [1] and it has been approved for use by technical and engineering services provider GL Garrad Hassan (now DNV-GL). The terrain in the vicinity of the mast is flat and covered with sparse, low-growing vegetation. On a wider scale the site is surrounded by flat arable land that is devoid of any dense closed-canopy forest. The terrain surrounding the tall mast at Pershore has been assessed in order to determine whether any sectors need to be screened from the mast data due to the orography of the site or local obstacles. The site meets the IEC requirements in [1] for maximum terrain variation in all sectors.

Wind speed comparisons are carried out from ground-based ZephIR units, operating in their standard mode with the conical scan aligned vertically, at 4 heights: 91.5m, 70.5m, 45.5m and 20.5m. The units are located between 3m and 8m from the base of the mast (see Figure 1). Data for lidar validation is provided by Risø P2546A cup anemometers on the North West side of the test mast and Vector A100LM cups on the South East side of the mast. A METEK USA-1 sonic anemometer replaces the cup anemometer on the North West side at 91.5 m. Comparison of paired cup anemometers is used to provide a robust method for identifying any problems with the mast instrumentation. Direction data is taken from the Vector W200P wind vanes at the 88.0m and 43.5m levels.

**Figure 1: Test pad at base of mast at the UK Remote Sensor Test Site**

Further environmental information is available from a meteorological station belonging to the UK Government's Meteorological Office, situated about 850 m to the north of the mast. Cloud height measurements from a ceilometer located at this station were used to assess the contribution of cloud height to the assessment of accuracy class of the lidar.

## 3 ZEPHIR DEPLOYMENT

The ZephIR 300 lidar units analysed in this report were deployed close to the met mast at the UK RSTS over the following period(s):

**Table 3-1: Deployment periods for ZephIR 300 units at UK RSTS**

| Unit Reference | Start | End |
|---|---|---|
| Unit A | 18 September 2013 | 25 October 2013 |
| | 17 March 2014 | 24 July 2014 |
| Unit B | 24 January 2014 | 30 May 2014 |

# 4 SENSITIVITY ANALYSIS

## 4.1 ENVIRONMENTAL PARAMETERS CONSIDERED

The environmental parameters considered in this report are listed in the following table, together with the range of values from which an overall uncertainty component is to be derived due to the sensitivity of the measurement to that environmental parameter.

Table 4-1: Environmental parameters considered

| Parameter | Unit | Sensor | Min | Max | Range | Bin width |
|---|---|---|---|---|---|---|
| Air density | kg / $m^3$ | Derived from temp, pressure and humidity readings from ZephIR's met station | 0.90 | 1.35 | 0.45 | 0.025 |
| Air temperature | °C | Sensor at 43 m | 0 | 40 | 40 | 2 |
| Air temperature gradient | °C / m | Derived from sensors at 91 m and 43 m | -0.05 | 0.03 | 0.08 | 0.005 |
| Inflow angle | ° | Sonic anemometer at 91 m | -3 | 3 | 6 | 0.2 |
| $Log_{10}$ (Cloud height)[1] | $Log_{10}$ (m) | Meteorological Office ceilometer | 1 | 4 | 3 | 0.2 |
| Mast turbulence intensity | - | Mast anemometers at 70 m | 0.03 | 0.24 | 0.21 | 0.01 |
| Rain percentage[2] | % | Rain sensor on lidar (percentage of measurements in 10 minutes for which rain sensor activated) | 0 | 100 | 100 | 1 |
| Rain flag2 | - | Rain sensor on lidar (set to 1 if rain sensor activated at any time during 10 minute period) | 0 | 1 | 1 | 1 |
| Vertical wind speed | m / s | Sonic anemometer at 91 m | -1 | 1 | 2 | 0.1 |
| Wind direction | ° | Mast vane at 43 m | 0 | 360 | 180 | 5 |
| Wind shear exponent | - | Power law shear exponent derived from mast anemometers at 20 m, 45 m, 70 m and 91 m | -0.4 | 0.8 | 1.2 | 0.05 |
| Wind veer | ° / m | Derived from wind vanes at 88 m and 43 m. (Asymmetry of limits due to misalignment of instruments on met mast.) | -0.1 | 0.3 | 0.4 | 0.025 |

[1] The ceilometer reports cloud height at a much finer resolution at lower heights than at higher heights. This naturally fits with representation on a logarithmic scale, hence taking the logarithm to base 10 of the reported heights before performing any analysis.

[2] Two possible parameters representing rain fall were considered: Rain Percent and Rain Flag. For a discussion of this, see section 4.3.3.

## 4.2 BIN SIGNIFICANCE

An analysis was performed on the differences between the horizontal wind speeds measured by the ZephIR 300 lidar and the met mast (as a percentage of the met mast speed) at the four available heights, as a function of each of the above environmental parameters. Following the methodology described in [1], the environmental parameter measurements were binned and only those bins that matched the criteria of having:

(a) a sufficient number of points (equation L.2 in [1]), and;

(b) a small enough standard error in the mean wind speed difference (equation L.3 in [1]),

were considered significant and included in the analysis (except as described in paragraph 4.3.3 below).

## 4.3 DISTRIBUTION OF ENVIRONMENTAL PARAMETER MEASUREMENTS

### 4.3.1 Statistics of distributions

The distribution of the environmental parameters, evaluated over those bins that satisfy the criteria described in section4.2, are summarised as means and standard deviations in Table A-1. The ratio of standard deviation over the maximum range of each parameter is also shown as a percentage in the table. The guidelines for the inclusion of an environmental parameter in the sensitivity analysis suggest that the standard deviation of the observed values should cover at least 10% of the maximum range.

Cells in Table A-1 containing values showing less than 10% coverage are lightly shaded, with values covering less than 1% shaded more darkly.

### 4.3.2 Parameters covering between 5% and 10% of maximum range

Table A-1 shows that air density, air temperature, wind shear exponent, wind veer coefficient and vertical wind speed fail to meet the 10% inclusion criterion for either of the tests, while inflow angle fails for one of the tests. They do however cover more than 5% of the maximum range for at least one of the tests and they have been retained in the classification results to follow.

If a wider range of variation of any of these parameters were to be observed during the application of the lidar then section L.2.4 of [1] recommends that any extra influence on the results should be assessed.

### 4.3.3 Rain metric

Table A-1 shows that the “Proportion Of Packets With Rain (%)” field in the lidar results, labelled “Rain percentage” in the table, covers a tiny proportion of the maximum range of this field (< 1%). This current methodology is therefore not valid for assessing the effects of this parameter on lidar wind speed uncertainty and so an alternative, simpler metric has been included in the analysis: “Rain flag”. This parameter takes the value 1 if the rain sensor is activated at any point with in the 10 minute period and 0 otherwise. A similar parameter is included in the example sensitivity analysis shown in Appendix L of [1].

Note that the Rain Flag = 1 bin does not satisfy the minimum number of points criterion for inclusion in the analysis. As there are only 2 bins for this parameter (0/1 for not raining/raining), each would need over 25% of the available data points. Despite not meeting this criterion, the rain flag parameter has been retained in the classification results to follow.

### 4.3.4 Wind direction

Wind direction is a circular variable and as such does not lend itself to establishing trends through linear regression. For example, a different linear dependence could be found by analysing lidar to mast differences with respect to directions in the range [-180°, +180°] instead of in the conventional range [0°, 360°]. That, however, is the approach recommended in [1] and so it has been followed in this analysis.

#### 4.3.5 Vertical wind speed and inflow angle

The sensitivity of the horizontal wind speed measurements made by the ZephIRs to both vertical wind speed and inflow angle has been assessed by reference to measurements made by the sonic anemometer on the mast. These two parameters are expected to be highly correlated but initially their effects have been assessed separately, before any correlation is taken into account.

#### 4.3.6 Within 10-minute data availability

The example classification test in [1] includes a parameter that measures the data availability within a 10 minute period. It is believed that this captures periods of low signal-to-noise levels as experienced by pulsed lidars. As the ZephIR lidar is a continuous-wave (CW) system, it is much less sensitive to low signal levels and consequently does not need to report an equivalent statistic (the “Packets In Average” field in the 10-minute data is more of a measure of system availability than data availability).

The data availability within each 10-minute period is not considered further in this report.

### 4.4 SENSITIVITY ANALYSIS METHOD

A two-parameter linear regression was performed between the bin mean values of the ZephIR-Mast differences and the environmental parameter measurements using only the bins identified as significant following the criteria in section 4.2 (except as discussed in section 4.3.3). The slope (m) and the correlation coefficient (R) from the regression are used to determine the relevance of each environmental parameter as follows:

The sensitivity is defined as the product of the regression slope (m) and the standard deviation of the environmental parameter measurements in the significant bins.

An environmental parameter is considered to be relevant if either:

- the absolute value of the calculated sensitivity exceeds 0.5, or;
- the product of the absolute value of the sensitivity and the correlation coefficient (R) exceeds 0.1.

If a parameter passes the relevance test at one height it must be included in the assessment of accuracy class at all heights.

# 5 SENSITIVITY ANALYSIS RESULTS

## 5.1 NUMERICAL RESULTS

The numerical results of the sensitivity analysis for each of the environmental parameters to be used are summarised in tables in APPENDIX B and APPENDIX C for the two production units tested. All of the parameters investigated are relevant when compared against the criteria described in section 4.4.

## 5.2 GRAPHICAL RESULTS

Example plots showing the correlation of ZephIR-to-Mast differences with the environmental measurements for Unit A are included in APPENDIX D. Data points for individual 10-minute-averaged observations are plotted in green, with binned mean values plotted with red diamonds. The red diamonds are solid if the bin satisfies the criteria for inclusion in the sensitivity analysis and are just shown in outline otherwise. The black line shows the line of best fit derived from the linear regression described in section 4.4.

The regression plots against shear exponent show what looks like a non-linear dependence of deviation on shear. In [3] a cubic model was fitted to the deviation as a function of shear data, but the nonlinearity in the current data sets is much less severe and so this has not been attempted here.

## 5.3 CORRELATION BETWEEN ENVIRONMENTAL PARAMETERS

The methodology of [1] allows for correlations between environmental parameters to be considered to avoid over-estimating uncertainties. A method for removing any such correlations from the results was proposed in [3] and has been applied to the data sets analysed here. This method uses a similar binning approach on values of the environmental parameter being used as the explanatory variable (the ordinate / x-axis). Mean values of the environmental parameter considered as the dependent variable (the abscissa / y-axis) are calculated for each bin and a linear regression performed between these mean values and the bin centre values, if the bins satisfy the significance criteria of section 0.

Tables showing the size of the correlation coefficient between each pair of environmental parameters at 91 m for both units are shown in APPENDIX E. Explanatory variables appear in the columns, with the dependent variables in the rows. Cells in the table are shaded darkly if a correlation coefficient of more than 0.9 has been found, with correlation values of between 0.7 and 0.9 shaded more lightly. Note that the Rain flag parameter has only two possible values, which means that a correlation coefficient of exactly 1 is guaranteed when it is used as an explanatory variable.

Significant correlations can be seen between air density, air temperature, air temperature gradient, wind shear exponent, wind veer coefficient and mast turbulence intensity. The expected high correlation between vertical wind speed and inflow angle is also obvious. Temperature, wind shear exponent and inflow angle were subsequently used as base variables, as described in [3], with air density and air temperature gradient taken as dependent on air temperature; wind veer coefficient and mast turbulence intensity taken as dependent on wind shear exponent; and vertical wind speed taken as dependent on inflow angle. The high correlation between rain flag and air temperature gradient was not found to have a significant effect on the resulting accuracy class and has not been considered further.

A revised sensitivity analysis was conducted for both units after taking into account the parameter dependencies identified above. Numerical results for the revised sensitivity analysis for Unit A are shown in APPENDIX F, with graphical results for the modified parameter analyses shown in APPENDIX G.

Note that the sensitivities to the following parameters have been reduced below the significance levels in section 4.4 after removing their dependence on the associated base variable: air density, air temperature gradient, mast turbulence intensity and vertical wind speed. They have therefore not been included in the final class assessment for this unit. The sensitivity to wind veer coefficient remains significant after removal of the dependence on wind shear exponent and has been retained in the analysis.

# 6 ACCURACY CLASS AND STANDARD UNCERTAINTY RESULTS

## 6.1 COMBINING SENSITIVITIES TO GIVE ACCURACY CLASS AND STANDARD UNCERTAINTY

The accuracy class is derived from the sensitivity analysis by combining, in quadrature, the predicted maximum effects of each of the environmental parameters that are deemed to be significant. To account for a more realistic distribution of conditions between classification test and power curve measurement, this figure is divided by $\sqrt{2}$ to give a final accuracy class result (see section L.2.6 of [1].)

The standard uncertainty to be used in a verification test is derived from the accuracy class by dividing the final accuracy class number by $\sqrt{3}$ (see section L.4.3 of [1].)

Accuracy classes and derived standard uncertainties for both production units are shown in Table 6-1, assuming independence, and in Table 6-2, accounting for correlations between environmental parameters. Mean values are also given.

**Table 6-1: Final accuracy classes and standard uncertainties: Assuming independence of environmental parameters**

| Height (m) | Unit A | | Unit B | | Mean | |
|---|---|---|---|---|---|---|
| | Accuracy Class (%) | Standard Uncertainty (%) | Accuracy Class (%) | Standard Uncertainty (%) | Accuracy Class (%) | Standard Uncertainty (%) |
| 20 | 3.7 | 2.2 | 4.0 | 2.3 | 3.9 | 2.2 |
| 45 | 3.6 | 2.1 | 3.1 | 1.8 | 3.4 | 2.0 |
| 70 | 3.7 | 2.2 | 3.0 | 1.7 | 3.4 | 1.9 |
| 91 | 4.9 | 2.8 | 3.2 | 1.8 | 4.0 | 2.3 |

**Table 6-2: Final accuracy classes and standard uncertainties: Accounting for correlation between environmental parameters**

| Height (m) | Unit A | | Unit B | | Mean | |
|---|---|---|---|---|---|---|
| | Accuracy Class (%) | Standard Uncertainty (%) | Accuracy Class (%) | Standard Uncertainty (%) | Accuracy Class (%) | Standard Uncertainty (%) |
| 20 | 3.5 | 2.0 | 4.0 | 2.3 | 3.8 | 2.2 |
| 45 | 3.3 | 1.9 | 2.9 | 1.7 | 3.1 | 1.8 |
| 70 | 3.3 | 1.9 | 2.6 | 1.5 | 3.0 | 1.7 |
| 91 | 3.7 | 2.1 | 2.9 | 1.7 | 3.3 | 1.9 |

# 7 SUMMARY

Two ground-based ZephIR 300 lidars have been classified at the UK Remote Sensor Test Site at Pershore according to the procedure described in Annex L of the IEC draft guidelines.

The mean accuracy classes for these units cover the ranges 3.0% – 3.8% for heights between 20 m and 91 m, after accounting for correlations between the environmental parameters. These values correspond to mean standard uncertainties of 1.7% - 2.2%.

It should be noted that this analysis methodology makes the assumption that data from the reference cup anemometers is always correct. In reality, any imperfect response of the cups to environmental parameters will add a contribution to the apparent accuracy class of the remote sensor. Hence, the assessment of standard uncertainty for the ZephIR 300 units here can be considered an upper limit.

# 8 REFERENCES


[1] IEC-TC88 Maintenance Team MT12-1, *Power performance measurements of electricity producing turbines*, CDV IEC 61400-12-1.

[2] Joint Committee for Guides in Metrology, *Evaluation of measurement data — Guide to the expression of uncertainty in measurement*, JCGM 100: 2008. Available from: http://www.iso.org/sites/JCGM/GUM/JCGM100/C045315e-html/C045315e.html?csnumber=50461.

[3] Will Barker, Julia Gottschall, Michael Harris, John Medley, Edward Burin des Roziers, Chris Slinger and Mark Pitter, *Correlation effects in the field classification of ground based remote wind sensors*, Proceedings of EWEA 2014, Barcelona, March 2014.

# APPENDIX A SENSITIVITY ANALYSIS: ENVIRONMENTAL PARAMETER STATISTICS

**Table A-1: Ranges of environmental parameters derived from significant bins in sensitivity analysis**

| Unit Reference | Unit A | | | Unit B | | |
|---|---|---|---|---|---|---|
| Parameter | Mean | Std Dev | Std Dev / Range (%) | Mean | Std Dev | Std Dev / Range (%) |
| Air density | 1.220 | 0.022 | 8.6 | 1.232 | 0.018 | 7.0 |
| Air temperature | 13.4 | 3.7 | 9.4 | 8.6 | 3.2 | 7.9 |
| Air temperature gradient | -0.028 | 0.009 | 11.9 | -0.023 | 0.009 | 10.8 |
| Inflow angle | -0.55 | 0.62 | 10.3 | -0.50 | 0.54 | 9.1 |
| $Log_{10}$ (Cloud height) | 3.06 | 0.74 | 24.8 | 3.04 | 0.76 | 25.3 |
| Mast turbulence intensity | 0.127 | 0.027 | 13.0 | 0.120 | 0.026 | 12.6 |
| Rain percentage | 0.11 | 0.45 | 0.45 | 0.27 | 0.86 | 0.86 |
| Rain flag | 0.122 | 0.327 | 32.7 | 0.197 | 0.398 | 39.8 |
| Vertical wind speed | -0.061 | 0.095 | 4.7 | -0.064 | 0.094 | 4.7 |
| Wind direction | 209 | 89 | 49.2 | 200 | 61 | 33.7 |
| Wind shear exponent | 0.171 | 0.093 | 7.7 | 0.180 | 0.081 | 6.8 |
| Wind veer coefficient | 0.084 | 0.039 | 9.8 | 0.090 | 0.036 | 9.1 |

# APPENDIX B UNIT A SENSITIVITY ANALYSIS: NUMERICAL RESULTS

Table B-1: Sensitivity analysis for Unit A measurement at 20 m

| Parameter | Slope (m) | $R^2$ | Sensitivity | Sensitivity × R | m × Range |
|---|---|---|---|---|---|
| Air density | -3.76 | 0.50 | -0.08 | -0.06 | -0.94 |
| Air temperature | 0.01 | 0.18 | 0.05 | 0.02 | 0.58 |
| Air temperature gradient | -1.78 | 0.00 | -0.02 | 0.00 | -0.14 |
| Inflow angle | 0.01 | 0.00 | 0.00 | 0.00 | 0.04 |
| Log10 (Cloud height) | 1.20 | 0.45 | 0.89 | 0.60 | 3.59 |
| Mast turbulence intensity | 0.17 | 0.00 | 0.00 | 0.00 | 0.04 |
| Rain flag | 1.18 | 1.00 | 0.39 | 0.39 | 1.18 |
| Vertical wind speed | -0.30 | 0.31 | -0.03 | -0.02 | -0.59 |
| Wind direction | 0.00 | 0.22 | 0.22 | 0.11 | 0.46 |
| Wind shear exponent | 2.35 | 0.72 | 0.22 | 0.19 | 2.82 |
| Wind veer coefficient | 5.07 | 0.98 | 0.20 | 0.20 | 2.03 |

Table B-2: Sensitivity analysis for Unit A measurement at 45 m

| Parameter | Slope (m) | $R^2$ | Sensitivity | Sensitivity × R | m × Range |
|---|---|---|---|---|---|
| Air density | -7.12 | 0.63 | -0.15 | -0.12 | -1.78 |
| Air temperature | 0.03 | 0.54 | 0.12 | 0.09 | 1.26 |
| Air temperature gradient | -0.03 | 0.00 | 0.00 | 0.00 | 0.00 |
| Inflow angle | -0.09 | 0.37 | -0.05 | -0.03 | -0.51 |
| Log10 (Cloud height) | 1.26 | 0.59 | 0.93 | 0.72 | 3.77 |
| Mast turbulence intensity | -2.70 | 0.28 | -0.09 | -0.05 | -0.57 |
| Rain flag | 0.72 | 1.00 | 0.23 | 0.23 | 0.72 |
| Vertical wind speed | -0.30 | 0.36 | -0.03 | -0.02 | -0.60 |
| Wind direction | 0.00 | 0.17 | 0.21 | 0.09 | 0.42 |
| Wind shear exponent | 1.47 | 0.33 | 0.16 | 0.09 | 1.76 |
| Wind veer coefficient | 4.24 | 0.88 | 0.19 | 0.18 | 1.70 |

**Table B-3: Sensitivity analysis for Unit A measurement at 70 m**

| Parameter | Slope (m) | $R^2$ | Sensitivity | Sensitivity × R | m × Range |
|---|---|---|---|---|---|
| Air density | -8.94 | 0.58 | -0.19 | -0.15 | -2.23 |
| Air temperature | 0.04 | 0.68 | 0.16 | 0.13 | 1.62 |
| Air temperature gradient | -7.22 | 0.05 | -0.07 | -0.02 | -0.58 |
| Inflow angle | 0.10 | 0.43 | 0.07 | 0.04 | 0.62 |
| Log10 (Cloud height) | 1.37 | 0.65 | 1.01 | 0.81 | 4.11 |
| Mast turbulence intensity | -0.55 | 0.02 | -0.02 | 0.00 | -0.12 |
| Rain flag | 0.30 | 1.00 | 0.10 | 0.10 | 0.30 |
| Vertical wind speed | 0.44 | 0.39 | 0.05 | 0.03 | 0.88 |
| Wind direction | 0.00 | 0.47 | 0.46 | 0.32 | 0.89 |
| Wind shear exponent | 0.87 | 0.11 | 0.10 | 0.03 | 1.04 |
| Wind veer coefficient | 2.11 | 0.58 | 0.10 | 0.07 | 0.84 |

**Table B-4: Sensitivity analysis for Unit A measurement at 91 m**

| Parameter | Slope (m) | $R^2$ | Sensitivity | Sensitivity × R | m × Range |
|---|---|---|---|---|---|
| Air density | -15.78 | 0.86 | -0.34 | -0.31 | -3.95 |
| Air temperature | 0.08 | 0.94 | 0.31 | 0.30 | 3.23 |
| Air temperature gradient | -20.96 | 0.63 | -0.22 | -0.17 | -1.68 |
| Inflow angle | 0.35 | 0.83 | 0.22 | 0.20 | 2.10 |
| Log10 (Cloud height) | 0.49 | 0.65 | 0.33 | 0.27 | 1.47 |
| Mast turbulence intensity | 8.05 | 0.89 | 0.27 | 0.25 | 1.69 |
| Rain flag | 0.30 | 1.00 | 0.10 | 0.10 | 0.30 |
| Vertical wind speed | 2.27 | 0.90 | 0.22 | 0.21 | 4.55 |
| Wind direction | 0.00 | 0.14 | 0.23 | 0.08 | 0.44 |
| Wind shear exponent | -2.44 | 0.40 | -0.29 | -0.18 | -2.93 |
| Wind veer coefficient | 0.69 | 0.09 | 0.03 | 0.01 | 0.28 |

# APPENDIX C UNIT B SENSITIVITY ANALYSIS: NUMERICAL RESULTS

**Table C-1: Sensitivity analysis for Unit B measurement at 20 m**

| Parameter | Slope (m) | $R^2$ | Sensitivity | Sensitivity × R | m × Range |
|---|---|---|---|---|---|
| Air density | -5.75 | 0.45 | -0.10 | -0.07 | -1.44 |
| Air temperature | -0.03 | 0.56 | -0.10 | -0.08 | -1.27 |
| Air temperature gradient | 13.97 | 0.33 | 0.12 | 0.07 | 1.12 |
| Inflow angle | -0.06 | 0.09 | -0.03 | -0.01 | -0.35 |
| Log10 (Cloud height) | 0.86 | 0.44 | 0.66 | 0.44 | 2.59 |
| Mast turbulence intensity | -2.43 | 0.42 | -0.06 | -0.04 | -0.51 |
| Rain flag | 0.92 | 1.00 | 0.36 | 0.36 | 0.92 |
| Vertical wind speed | -0.80 | 0.90 | -0.08 | -0.08 | -1.60 |
| Wind direction | 0.00 | 0.17 | 0.17 | 0.07 | 0.49 |
| Wind shear exponent | 3.28 | 0.90 | 0.27 | 0.25 | 3.93 |
| Wind veer coefficient | 4.79 | 0.65 | 0.17 | 0.14 | 1.92 |

**Table C-2: Sensitivity analysis for Unit B measurement at 45 m**

| Parameter | Slope (m) | $R^2$ | Sensitivity | Sensitivity × R | m × Range |
|---|---|---|---|---|---|
| Air density | -4.24 | 0.25 | -0.08 | -0.04 | -1.06 |
| Air temperature | 0.02 | 0.49 | 0.08 | 0.05 | 0.96 |
| Air temperature gradient | -8.60 | 0.14 | -0.08 | -0.03 | -0.69 |
| Inflow angle | -0.08 | 0.32 | -0.04 | -0.02 | -0.47 |
| Log10 (Cloud height) | 0.99 | 0.52 | 0.75 | 0.54 | 2.97 |
| Mast turbulence intensity | -1.74 | 0.17 | -0.05 | -0.02 | -0.36 |
| Rain flag | 0.33 | 1.00 | 0.13 | 0.13 | 0.33 |
| Vertical wind speed | -0.53 | 0.40 | -0.05 | -0.03 | -1.07 |
| Wind direction | 0.00 | 0.38 | 0.31 | 0.19 | 0.84 |
| Wind shear exponent | 1.72 | 0.48 | 0.16 | 0.11 | 2.06 |
| Wind veer coefficient | 4.32 | 0.83 | 0.18 | 0.16 | 1.73 |

**Table C-3: Sensitivity analysis for Unit B measurement at 70 m**

| Parameter | Slope (m) | $R^2$ | Sensitivity | Sensitivity × R | m × Range |
|---|---|---|---|---|---|
| Air density | -9.65 | 0.78 | -0.18 | -0.16 | -2.41 |
| Air temperature | 0.04 | 0.73 | 0.11 | 0.10 | 1.45 |
| Air temperature gradient | -10.04 | 0.24 | -0.09 | -0.05 | -0.80 |
| Inflow angle | 0.14 | 0.50 | 0.08 | 0.06 | 0.86 |
| Log10 (Cloud height) | 0.81 | 0.53 | 0.61 | 0.45 | 2.43 |
| Mast turbulence intensity | 2.60 | 0.41 | 0.08 | 0.05 | 0.55 |
| Rain flag | 0.20 | 1.00 | 0.08 | 0.08 | 0.20 |
| Vertical wind speed | 0.45 | 0.36 | 0.04 | 0.03 | 0.89 |
| Wind direction | 0.01 | 0.46 | 0.37 | 0.25 | 0.97 |
| Wind shear exponent | 0.38 | 0.06 | 0.04 | 0.01 | 0.45 |
| Wind veer coefficient | 2.40 | 0.39 | 0.10 | 0.06 | 0.96 |

**Table C-4: Sensitivity analysis for Unit B measurement at 91 m**

| Parameter | Slope (m) | $R^2$ | Sensitivity | Sensitivity × R | m × Range |
|---|---|---|---|---|---|
| Air density | -8.15 | 0.62 | -0.16 | -0.12 | -2.04 |
| Air temperature | 0.02 | 0.62 | 0.06 | 0.05 | 0.78 |
| Air temperature gradient | -13.62 | 0.62 | -0.13 | -0.10 | -1.09 |
| Inflow angle | 0.34 | 0.74 | 0.19 | 0.16 | 2.03 |
| Log10 (Cloud height) | -0.04 | 0.01 | -0.03 | 0.00 | -0.12 |
| Mast turbulence intensity | 7.22 | 0.85 | 0.23 | 0.21 | 1.52 |
| Rain flag | 0.22 | 1.00 | 0.09 | 0.09 | 0.22 |
| Vertical wind speed | 1.97 | 0.99 | 0.18 | 0.18 | 3.93 |
| Wind direction | 0.00 | 0.15 | 0.18 | 0.07 | 0.49 |
| Wind shear exponent | -2.22 | 0.69 | -0.21 | -0.18 | -2.66 |
| Wind veer coefficient | 1.30 | 0.21 | 0.06 | 0.03 | 0.52 |

# APPENDIX D UNIT A SENSITIVITY ANALYSIS: CORRELATION PLOTS

Plots showing the correlation of ZephIR-to-Mast differences (as a percentage) against each of the environmental parameters under consideration are shown for each of the four measurement heights in Figure D-1 to Figure D-4.

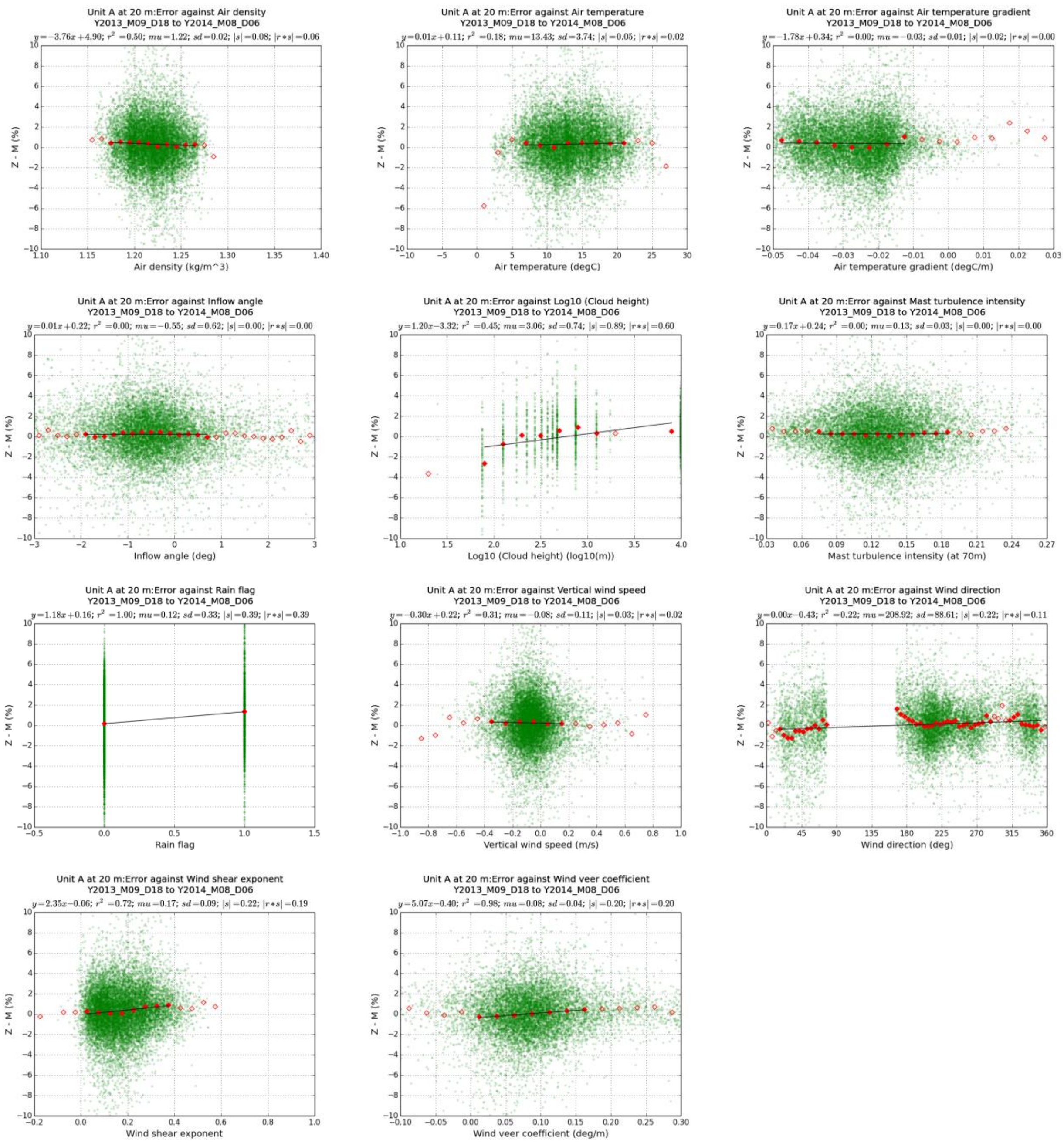



**Figure D-1: Correlating differences between ZephIR and Mast measurements at 20 m with environmental parameters**

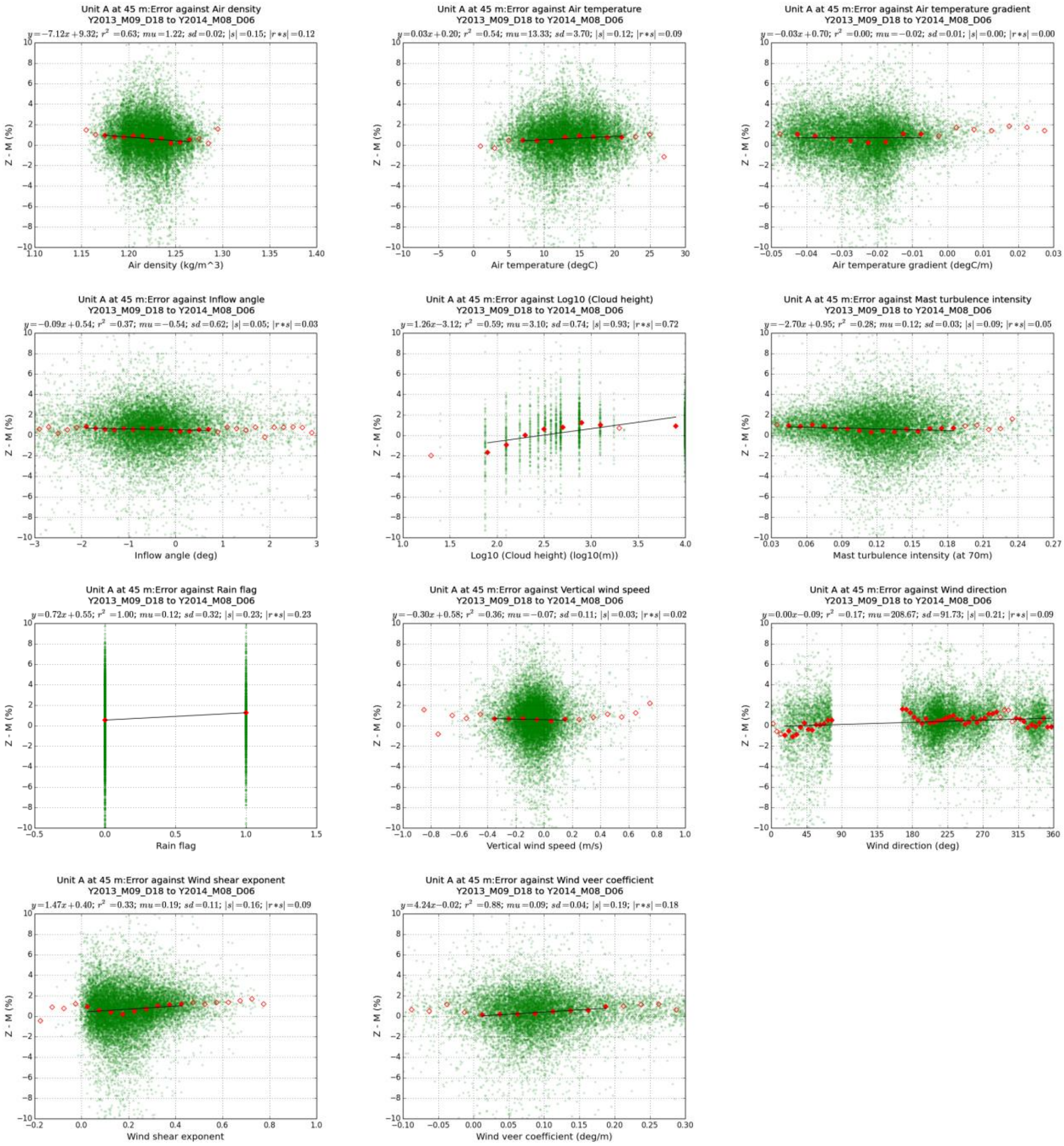



**Figure D-2: Correlating differences between ZephIR and Mast measurements at 45 m with environmental parameters**

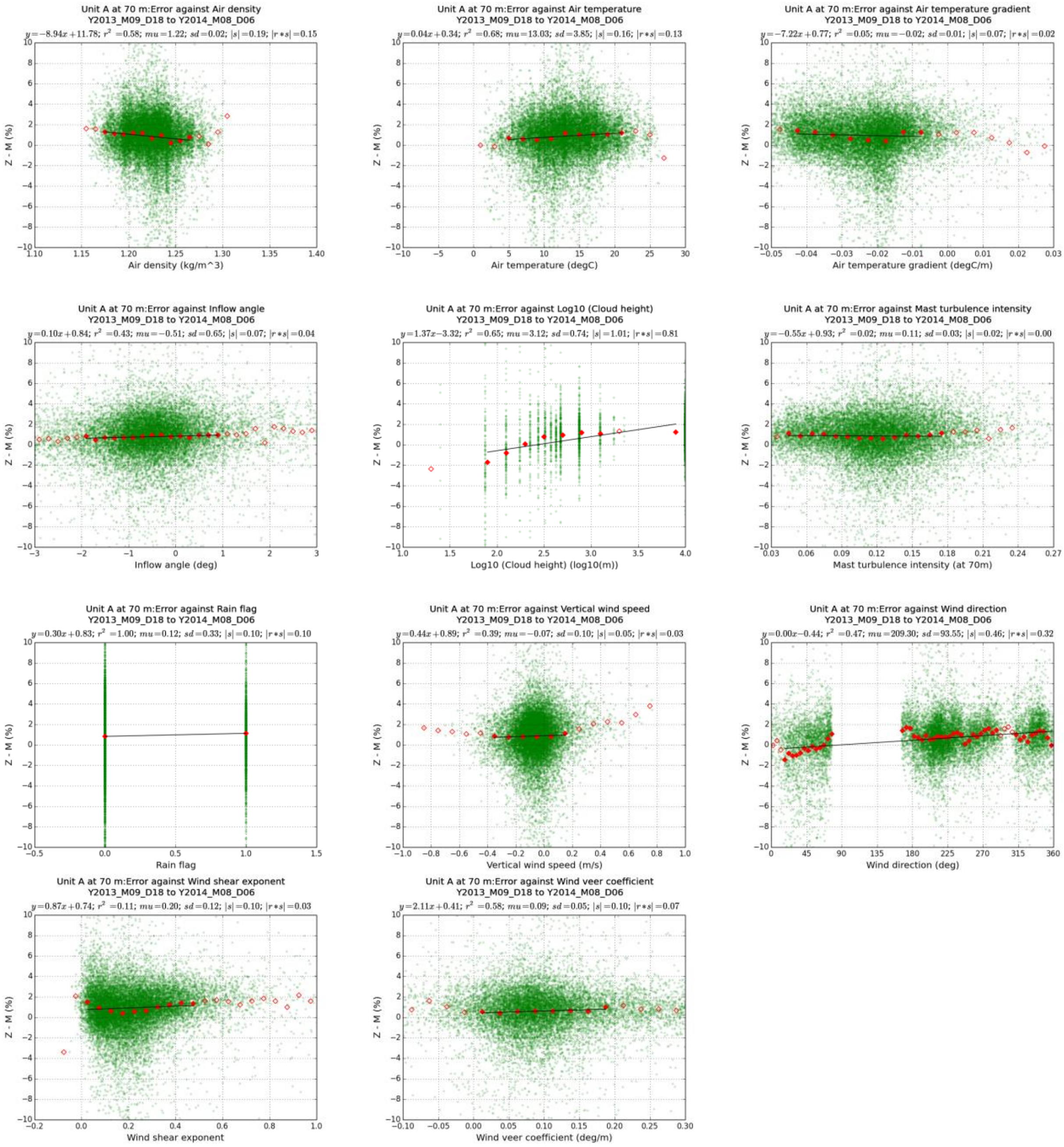



**Figure D-3: Correlating differences between ZephIR and Mast measurements at 70 m with environmental parameters**

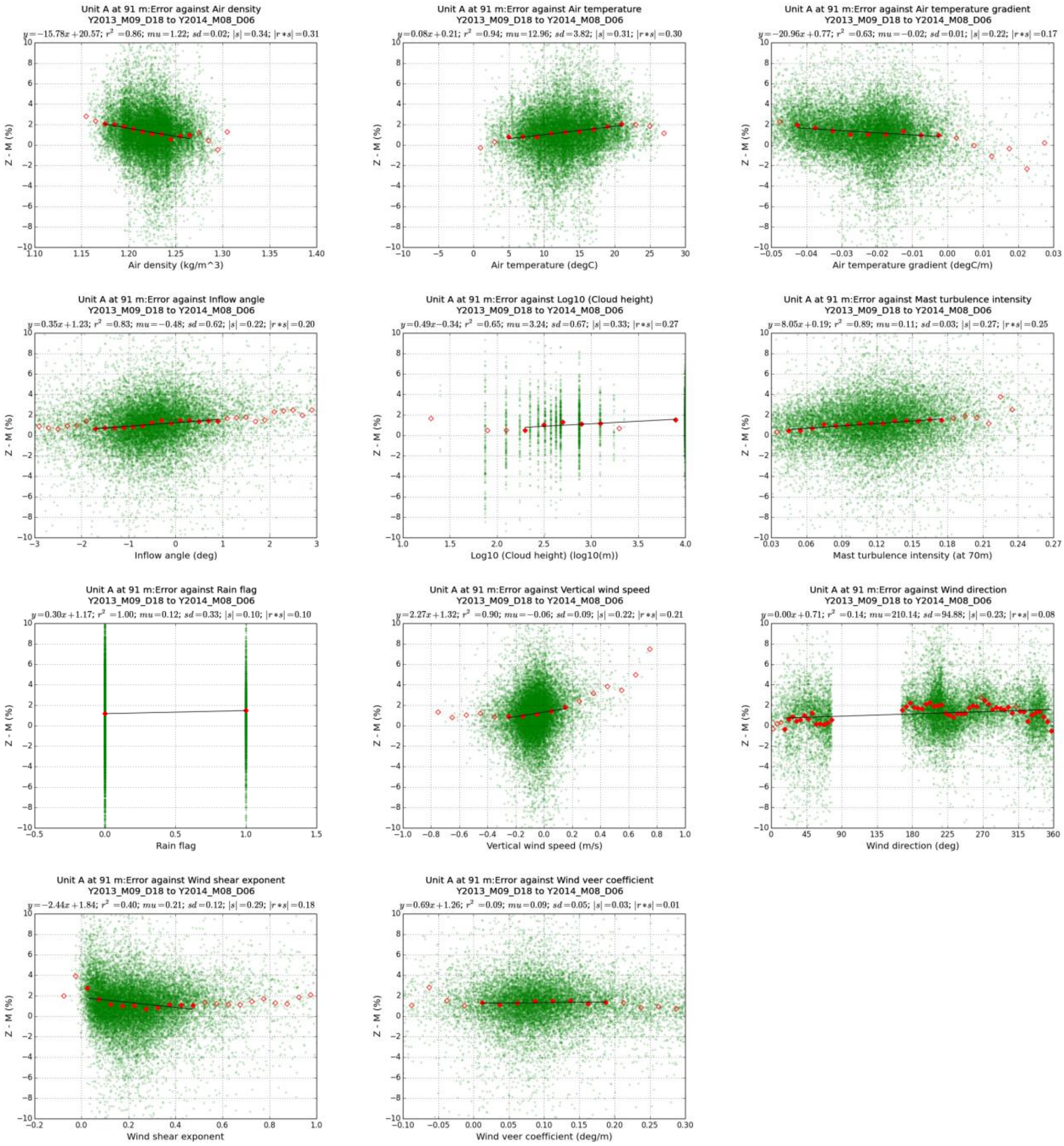



**Figure D-4: Correlating differences between ZephIR and Mast measurements at 91 m with environmental parameters**

# APPENDIX E CORRELATIONS BETWEEN PARAMETERS

Table E-1: Correlations between parameters for data set used for assessment of Unit A at 91 m

| | Air density | Air temperature | Air temperature gradient | Inflow angle | Log10 (Cloud height) | Mast turbulence intensity | Rain flag | Vertical wind speed | Wind direction | Wind shear exponent | Wind veer coefficient |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Air density | | 1.00 | 1.00 | 0.72 | 0.14 | 0.97 | 1.00 | 0.46 | 0.02 | 0.97 | 0.87 |
| Air temperature | 1.00 | | 0.99 | 0.80 | 0.53 | 0.98 | 1.00 | 0.61 | 0.00 | 0.87 | 0.98 |
| Air temperature gradient | 0.98 | 0.96 | | 0.62 | 0.06 | 0.98 | 1.00 | 0.36 | 0.05 | 0.98 | 0.95 |
| Inflow angle | 0.83 | 0.92 | 0.95 | | 0.20 | 0.44 | 1.00 | 1.00 | 0.22 | 0.90 | 0.82 |
| Log10 (Cloud height) | 0.02 | 0.56 | 0.16 | 0.29 | | 0.66 | 1.00 | 0.90 | 0.63 | 0.62 | 0.82 |
| Mast turbulence intensity | 0.97 | 0.92 | 0.99 | 0.35 | 0.74 | | 1.00 | 0.48 | 0.72 | 0.98 | 0.95 |
| Rain flag | 0.07 | 0.80 | 0.49 | 0.63 | 0.87 | 0.76 | | 0.80 | 0.41 | 0.30 | 0.17 |
| Vertical wind speed | 0.86 | 0.89 | 0.94 | 1.00 | 0.34 | 0.38 | 1.00 | | 0.21 | 0.71 | 0.85 |
| Wind direction | 0.15 | 0.14 | 0.06 | 0.11 | 0.77 | 0.89 | 1.00 | 0.71 | | 0.02 | 0.89 |
| Wind shear exponent | 0.99 | 0.93 | 0.98 | 0.74 | 0.89 | 0.97 | 1.00 | 0.48 | 0.30 | | 0.91 |
| Wind veer coefficient | 0.95 | 0.95 | 0.97 | 0.84 | 0.69 | 0.94 | 1.00 | 0.73 | 0.13 | 0.96 | |

**Table E-2: Correlations between parameters for data set used for assessment of Unit B at 91 m**

| | Air density | Air temperature | Air temperature gradient | Inflow angle | Log10 (Cloud height) | Mast turbulence intensity | Rain flag | Vertical wind speed | Wind direction | Wind shear exponent | Wind veer coefficient |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Air density | | 0.99 | 1.00 | 0.68 | 0.34 | 0.97 | 1.00 | 0.35 | 0.05 | 0.98 | 0.88 |
| Air temperature | 0.97 | | 0.98 | 0.58 | 0.30 | 0.96 | 1.00 | 0.11 | 0.22 | 0.81 | 0.99 |
| Air temperature gradient | 1.00 | 0.99 | | 0.74 | 0.13 | 0.96 | 1.00 | 0.33 | 0.37 | 0.98 | 0.95 |
| Inflow angle | 0.70 | 0.77 | 0.83 | | 0.37 | 0.62 | 1.00 | 1.00 | 0.26 | 0.44 | 0.46 |
| Log10 (Cloud height) | 0.61 | 0.12 | 0.21 | 0.41 | | 0.82 | 1.00 | 0.80 | 0.83 | 0.28 | 0.80 |
| Mast turbulence intensity | 0.99 | 0.92 | 0.99 | 0.61 | 0.75 | | 1.00 | 0.53 | 0.73 | 0.98 | 0.97 |
| Rain flag | 0.63 | 0.62 | 0.31 | 0.55 | 0.93 | 0.92 | | 0.96 | 0.50 | 0.26 | 0.74 |
| Vertical wind speed | 0.87 | 0.12 | 0.85 | 1.00 | 0.41 | 0.42 | 1.00 | | 0.14 | 0.28 | 0.29 |
| Wind direction | 0.72 | 0.01 | 0.65 | 0.91 | 0.80 | 0.84 | 1.00 | 0.82 | | 0.11 | 0.88 |
| Wind shear exponent | 0.95 | 0.97 | 0.97 | 0.91 | 0.79 | 0.95 | 1.00 | 0.64 | 0.31 | | 0.90 |
| Wind veer coefficient | 0.96 | 0.90 | 0.96 | 0.89 | 0.82 | 0.91 | 1.00 | 0.77 | 0.69 | 0.99 | |

# APPENDIX F UNIT A SENSITIVITY ANALYSIS AFTER ACCOUNTING FOR CORRELATION: NUMERICAL RESULTS

Table F-1: Revised sensitivity analysis for Unit A measurement at 20 m

| Parameter | Base parameter removed | Slope (m) | $R^2$ | Sensitivity | Sensitivity × R | m × Range |
|---|---|---|---|---|---|---|
| Air density | Air temperature | -1.29 | 0.10 | -0.03 | -0.01 | -0.32 |
| Air temperature | | 0.01 | 0.18 | 0.05 | 0.02 | 0.58 |
| Air temperature gradient | Air temperature | 2.06 | 0.00 | 0.02 | 0.00 | 0.17 |
| Inflow angle | | 0.01 | 0.00 | 0.00 | 0.00 | 0.04 |
| Log10 (Cloud height) | | 1.20 | 0.45 | 0.89 | 0.60 | 3.59 |
| Mast turbulence intensity | Wind shear exponent | 3.27 | 0.58 | 0.09 | 0.07 | 0.69 |
| Rain flag | | 1.18 | 1.00 | 0.39 | 0.39 | 1.18 |
| Vertical wind speed | Inflow angle | -0.31 | 0.33 | -0.03 | -0.02 | -0.62 |
| Wind direction | | 0.00 | 0.22 | 0.22 | 0.11 | 0.46 |
| Wind shear exponent | | 2.35 | 0.72 | 0.22 | 0.19 | 2.82 |
| Wind veer coefficient | Wind shear exponent | 3.88 | 0.98 | 0.15 | 0.15 | 1.55 |

Table F-2: Revised sensitivity analysis for Unit A measurement at 45 m

| Parameter | Base parameter removed | Slope (m) | $R^2$ | Sensitivity | Sensitivity × R | m × Range |
|---|---|---|---|---|---|---|
| Air density | Air temperature | -1.89 | 0.11 | -0.04 | -0.01 | -0.47 |
| Air temperature | | 0.03 | 0.54 | 0.12 | 0.09 | 1.26 |
| Air temperature gradient | Air temperature | 6.27 | 0.05 | 0.06 | 0.01 | 0.50 |
| Inflow angle | | -0.09 | 0.37 | -0.05 | -0.03 | -0.51 |
| Log10 (Cloud height) | | 1.26 | 0.59 | 0.93 | 0.72 | 3.77 |
| Mast turbulence intensity | Wind shear exponent | 0.05 | 0.00 | 0.00 | 0.00 | 0.01 |
| Rain flag | | 0.72 | 1.00 | 0.23 | 0.23 | 0.72 |
| Vertical wind speed | Inflow angle | 0.42 | 0.49 | 0.05 | 0.03 | 0.85 |
| Wind direction | | 0.00 | 0.17 | 0.21 | 0.09 | 0.42 |
| Wind shear exponent | | 1.47 | 0.33 | 0.16 | 0.09 | 1.76 |
| Wind veer coefficient | Wind shear exponent | 3.24 | 0.86 | 0.14 | 0.13 | 1.29 |

**Table F-3: Revised sensitivity analysis for Unit A measurement at 70 m**

| Parameter | Base parameter removed | Slope (m) | $R^2$ | Sensitivity | Sensitivity × R | m × Range |
|---|---|---|---|---|---|---|
| Air density | Air temperature | -2.30 | 0.08 | -0.05 | -0.01 | -0.57 |
| Air temperature | | 0.04 | 0.68 | 0.16 | 0.13 | 1.62 |
| Air temperature gradient | Air temperature | 0.66 | 0.00 | 0.01 | 0.00 | 0.05 |
| Inflow angle | | 0.10 | 0.43 | 0.07 | 0.04 | 0.62 |
| Log10 (Cloud height) | | 1.37 | 0.65 | 1.01 | 0.81 | 4.11 |
| Mast turbulence intensity | Wind shear exponent | 1.47 | 0.13 | 0.05 | 0.02 | 0.31 |
| Rain flag | | 0.30 | 1.00 | 0.10 | 0.10 | 0.30 |
| Vertical wind speed | Inflow angle | -0.40 | 0.34 | -0.04 | -0.02 | -0.79 |
| Wind direction | | 0.00 | 0.47 | 0.46 | 0.32 | 0.89 |
| Wind shear exponent | | 0.87 | 0.11 | 0.10 | 0.03 | 1.04 |
| Wind veer coefficient | Wind shear exponent | 1.46 | 0.43 | 0.07 | 0.04 | 0.58 |

**Table F-4: Revised sensitivity analysis for Unit A measurement at 91 m**

| Parameter | Base parameter removed | Slope (m) | $R^2$ | Sensitivity | Sensitivity × R | m × Range |
|---|---|---|---|---|---|---|
| Air density | Air temperature | -2.63 | 0.16 | -0.06 | -0.02 | -0.66 |
| Air temperature | | 0.08 | 0.94 | 0.31 | 0.30 | 3.23 |
| Air temperature gradient | Air temperature | -5.47 | 0.12 | -0.06 | -0.02 | -0.44 |
| Inflow angle | | 0.35 | 0.83 | 0.22 | 0.20 | 2.10 |
| Log10 (Cloud height) | | 0.49 | 0.65 | 0.33 | 0.27 | 1.47 |
| Mast turbulence intensity | Wind shear exponent | 2.35 | 0.46 | 0.08 | 0.05 | 0.49 |
| Rain flag | | 0.30 | 1.00 | 0.10 | 0.10 | 0.30 |
| Vertical wind speed | Inflow angle | -0.64 | 0.49 | -0.06 | -0.04 | -1.29 |
| Wind direction | | 0.00 | 0.14 | 0.23 | 0.08 | 0.44 |
| Wind shear exponent | | -2.44 | 0.40 | -0.29 | -0.18 | -2.93 |
| Wind veer coefficient | Wind shear exponent | 2.63 | 0.66 | 0.12 | 0.10 | 1.05 |

# APPENDIX G UNIT A SENSITIVITY ANALYSIS AFTER ACCOUNTING FOR CORRELATION: SELECTED GRAPHICAL RESULTS

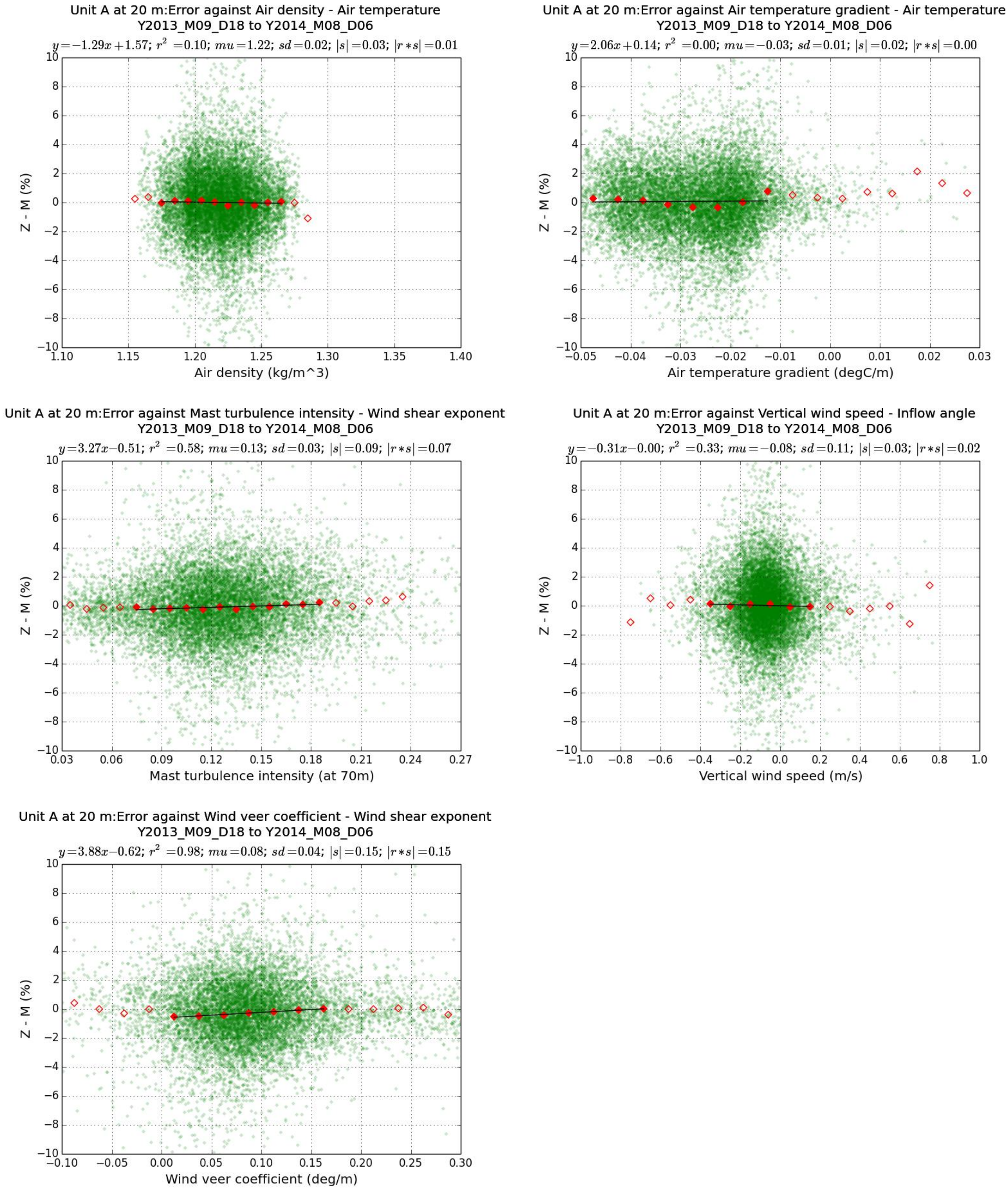



**Figure G-1: Modified correlations: differences between ZephIR and Mast measurements at 20 m against environmental parameters (after removing dependence on base parameters)**

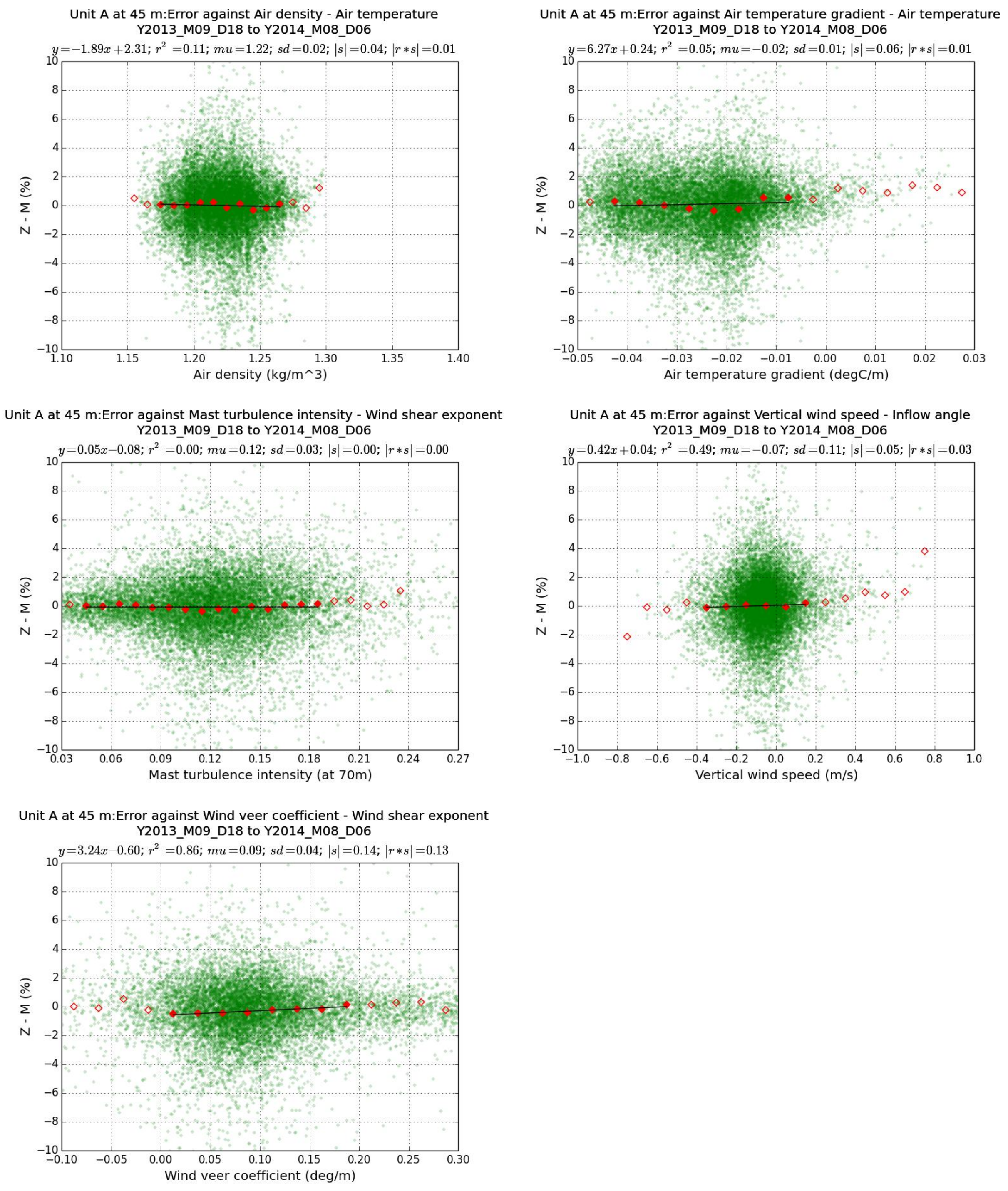



**Figure G-2: Modified correlations: differences between ZephIR and Mast measurements at 45 m against environmental parameters (after removing dependence on base parameters)**

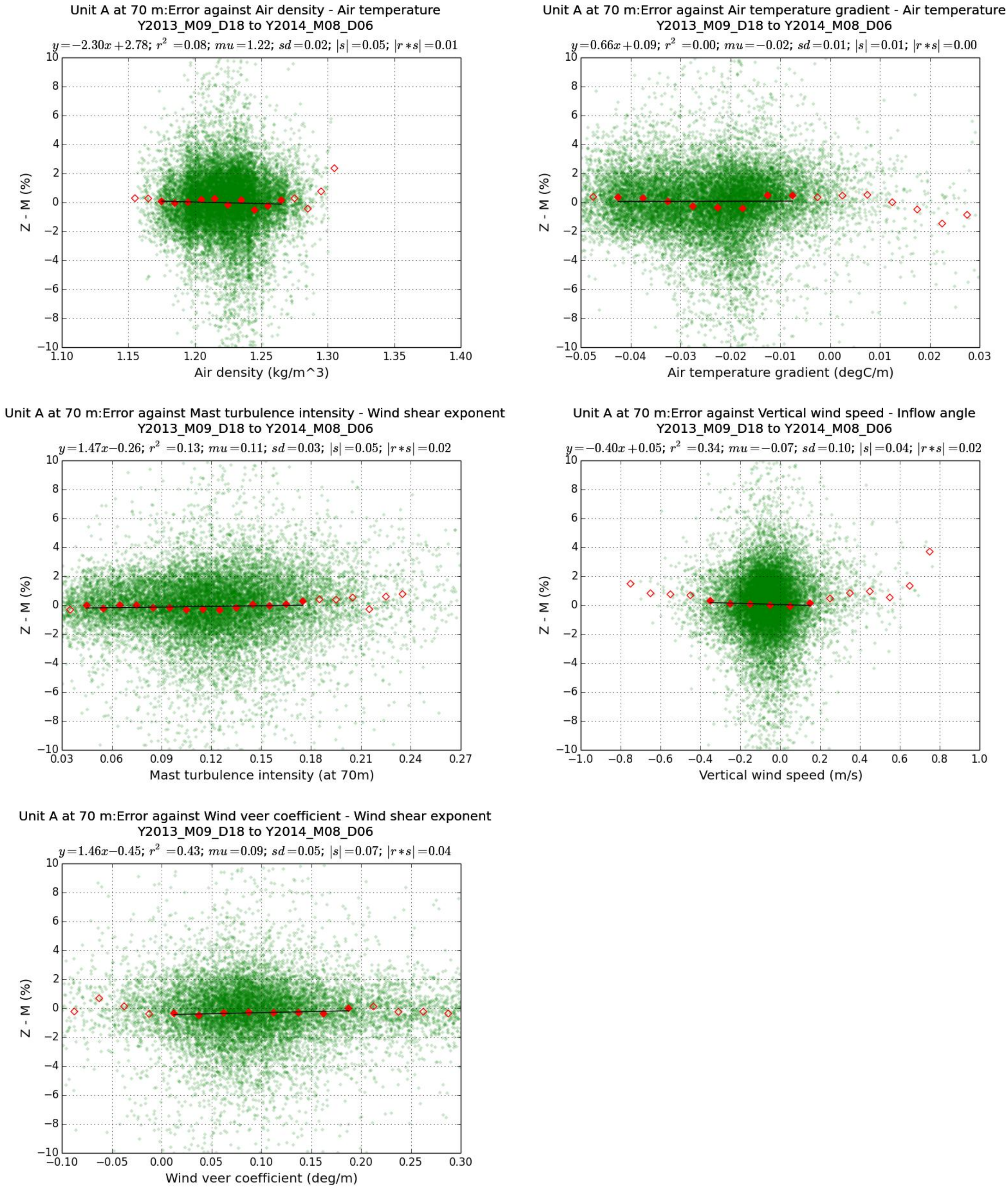



**Figure G-3: Modified correlations: differences between ZephIR and Mast measurements at 70 m against environmental parameters (after removing dependence on base parameters)**

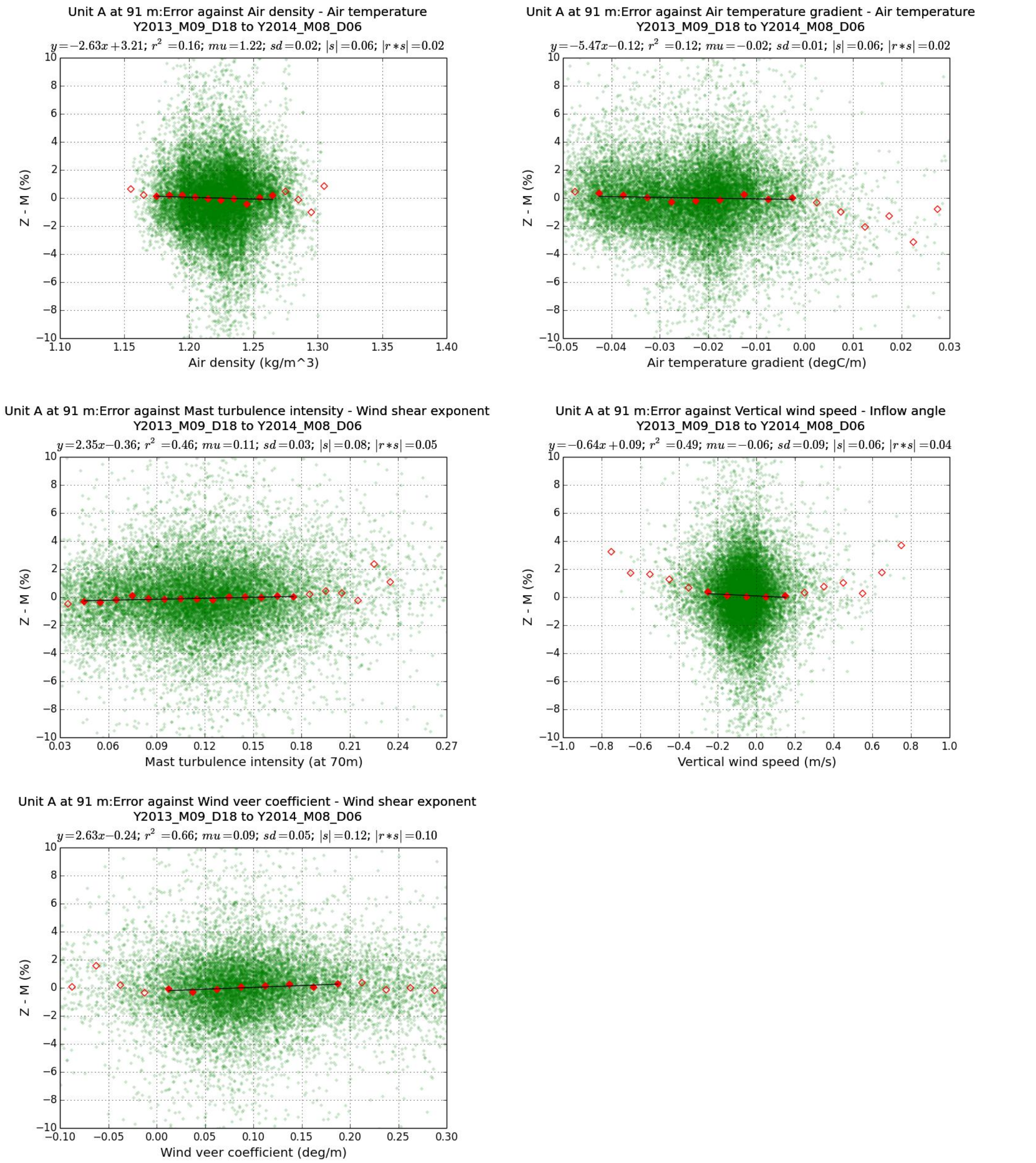



**Figure G-4: Modified correlations: differences between ZephIR and Mast measurements at 91 m against environmental parameters (after removing dependence on base parameters)**