Investigation of the quality of wind speed and direction measurements from the Monitor Sensor AWS and the effect of air density on measured wind speed.

2nd May 2007

Warren Skidmore, Sebastian Els

Contents

Chapter 1

Introduction

1.1 The purpose of this document

This document is not intended to be a final report regarding the accuracy and calibration of the wind speed and direction measurements collected during TMT site testing. It is a working document for the TMT sites group and is available for use when processing and analysing wind speed and direction measurements from the sites and interpreting these results. The quality of measurements from the sites can be assessed using the methods outlined in this document, the sites group monitors the operation of the wind sensors accordingly and carries out maintenance work as necessary to ensure the best possible data quality.

Some knowledge of the sites, the site testing equipment and the measurement aims of the site testing group are assumed for readers of this report.

1.2 Overall sensor layout

At the TMT candidate sites listed in Table 1.1, a Monitor Sensors Automated Weather Station (AWS) and a CSAT3 sonic anemometer have been installed. The location of the sonic anemometer on the 7m tower and the location of the AWS with respect to the tower are also listed in Table 1.1. The sonic anemometers are oriented to point away from the dome and can be at either end of the side of the tower on which they are attached (see Figure 2.3 of [1]). The top horizontal cross member of the AWS units are all oriented approximately East-West. Listed in Table 1.1 is a distance and approximate bearing of the AWS from the centre of the base of the 7m tower.

1.3 Description of the AWS

The Monitor Sensors AWS are equipped with a cup anemometer and a wind vane (see [1]). The present sensor readings are read out through a data logger and stored in a file on the Supervisor Computer every 2 minutes [1]. The wind speed readings are supposed to be 1 minute averages from the previous minute, but the sensor settings have not always been consistent. In the worst case the readings were averaged over a few seconds. All AWS systems were systematically setup in 2006 09 and very few significant changes were necessary to any of the AWS sensor settings. It is not possible to change, check or set the wind direction sensor settings, so the averaging period is not known. However all candidate sites are equipped with the same type of wind direction sensors, so all data are equivalent.

[1]At sites where a 30m tower is installed (T2 as of 2006 09, T3 as of 2007 03), the sensors are read every 60s

Table 1.1: The TMT candidate sites and details of the sonic anemometer location and orientation at the 7m level on the telescope tower and AWS orientation and location with respect to the centre of the tower base. Note: The T4 sonic anemometer is positioned further from the dome than at the other sites, the AWS was moved by 2005 10 31 (possibly one or two days before that date) from 170^o 12m to the present location. Trees around the T4 site were cut down on 2005 09 13.

Site	Altitude	Sonic anemometer location/orientation	AWS location
T1-Tolar	2290m	West side south end	280^o 10m
T2-Armazones	3064m	North side east end	45^o 10m
T3-Tolonchar	4480m	South side west end	0^o 10m
T4-SPM	2830m	South side west end	110^o 10m
T6-Hawaii	4050m	South side east end	0^o 10m

1.4 Description of the sonic anemometer

The CSAT3 sonic anemometers give a continuous 60Hz output of the three dimensional wind vectors, V_x, V_y, V_z and sonic temperature T_s [1]. These measurements are averaged in to 60 second bins and the horizontal wind speed and direction are calculated. The write time of the sonic anemometer measurement and the AWS measurement is the same. The sonic anemometers were installed, positioned and oriented to point in to the prevailing wind or, as in the case at T6, to be perpendicular to the two main wind directions so as to minimise the effect of the dome. The CSAT3 heads are approximately 1.3m from the dome, except for the T4 unit that is about 2m from the dome. See [1] for a more detailed description.

Chapter 2

Wind speed

2.1 Assessment of AWS anemometer operation

First we include a summary of all known wind speed calibration measurements and sensor changes, services and operational observations. Then we look at how the weather station wind speed measurements compare to those from the sonic anemometers placed on the 7m tower. We describe how this comparison appears in the cases where the AWS wind speed sensor is fine and when it is affected by problems with the bearings around the vertical axis. Finally we describe the development of a statistical method to assess the effect of problems with the AWS wind speed sensor on the wind speed measurements. We list the results of this method for all data collected up until this date.

2.1.1 Summary of configuration file notes and on site work reports

Below are extracts of site calibration reports that concern wind speed measurements. On site comparison measurements with the AWS are made using an SM28 hand held weather station [2, 3]. Wind speeds are in km/h.

T1-Tolar

```
2005 01 26 AWS 22+-8 SM28 15+-5
2005 03 09 AWS 18+-3 SM28 17+-3
2005 08 28 AWS 30    SM28 33
2005 08 29 AWS 13.64 SM28 13.9
2005 10 07 AWS wind speed sensor giving lots of zero values (noticed 2005 10 10)
2005 10 18 17:20:04 Wind speed sensor changed
2005 11 10 AWS 26.9  SM28 30+-4
2006 02 16 AWS 17+-1 SM28 11.5+-1
2006 07 05 AWS 11.2  SM28 12.0
2006 07 05 AWS 10.5  SM28 11.4
```

T2-Armazones

```
2005 01 24 AWS 36+-2  SM28 32+-3
2005 01 30 AWS 27+-7  SM28 27+-3
2005 01 31 AWS 15+-10 SM28 8+-5
2005 03 05 AWS 8+-2   SM28 2+-2
2005 03 07 AWS 38+-2  SM28 38+-2
2005 03 11 AWS 40+-10 SM28 38+-5
2005 08 24 AWS 32.59  SM28 34.4
```

```
2006 02 12 AWS 75     SM28 60
2006 04 17 AWS anemometer squeaking
2006 07 04 AWS 29.2   SM28 26.1
2006 07 04 AWS 24.1   SM28 25.0
2006 08 19 SM28 WS = 21.0 K/HR (16:04 local)
2006 10 15 SM28 WS = 56.7 Km/H (14:58 local), 65.0 Km/H  (15:00 local),
51 Km/H (18:32 local)
2007 03 02 Wind speed sensor bearings replaced
```

T3-Tolonchar

```
2005 11 19 AWS 11.6      SM28 9.2
2006 01 28 AWS 13.5+-1.8 SM28 12.6+-1
2006 02 01 Wind speed units confirmed to be km/h
2006 02 18 AWS 37+-2     SM28 35+-5
2006 03 28 Wind speed sensor changed, old one apparently not rotating smoothly
2006 07 06 Wind speed sensor changed
2006 07 06 AWS 26.8      SM28 24
2006 07 06 AWS 26.5      SM28 22
2006 08 17 SM28 21.2 - 25 Km/Hr (13:02 local), 27.4 K/Hr (15:50 local),
36.4 K/Hr Max = 47.3 K/Hr Average = 36.5 K/Hr (17:05 local)
2006 10 06 AWS wind speed sensor makes squeaking noises
2007 03 09 Wind speed sensor bearings replaced
```

T4-SPM

```
2006 02 23 AWS 13.4  SM28 11.2
2006 01 25 20:52UT AWS anemometer replaced (old sensor left for comparison tests)
```

T6-Hawaii

```
2005 12 02 AWS 9.2   SM28 9.7+-0.2
2006 01 02 Wind speed units confirmed to be km/h
2006 12 08 20:26:06UT AWS anemometer replaced
2007 01 21 AWS 13.92 SM28 13.1
```

2.1.2 Comparison with sonic anemometer

The sonic anemometer and AWS are physically in different locations and at different altitudes (7m (close to the telescope) and 2m, respectively). We expect the wind speed to be greater at the altitude of the sonic anemometer by some factor, but in general if there is wind at the AWS then there should be wind at the sonic anemometer and vice versa. The difference in wind speeds is described by a multiplicative factor that has some dependence on wind direction due to the local topography and structures, this factor is not strictly known for any of the sites. For the purposes here it is not necessary to know it as long as we can assume that its absolute value is always roughly 1 regardless of wind direction. Its value is expected to be around $V_{2m}/V_{7m} \sim 0.7$ (this value is an approximation based on discussions with Konstantinos Vogiatzis about his wind flow models).

There is no expectation that the sonic anemometer ever reads zero wind speed in a non-zero wind. If we ignore local effects of the dome and topography on the wind flow, the multiplicative wind speed factor mentioned above encompasses any incorrect calibration factors between the AWS and sonic

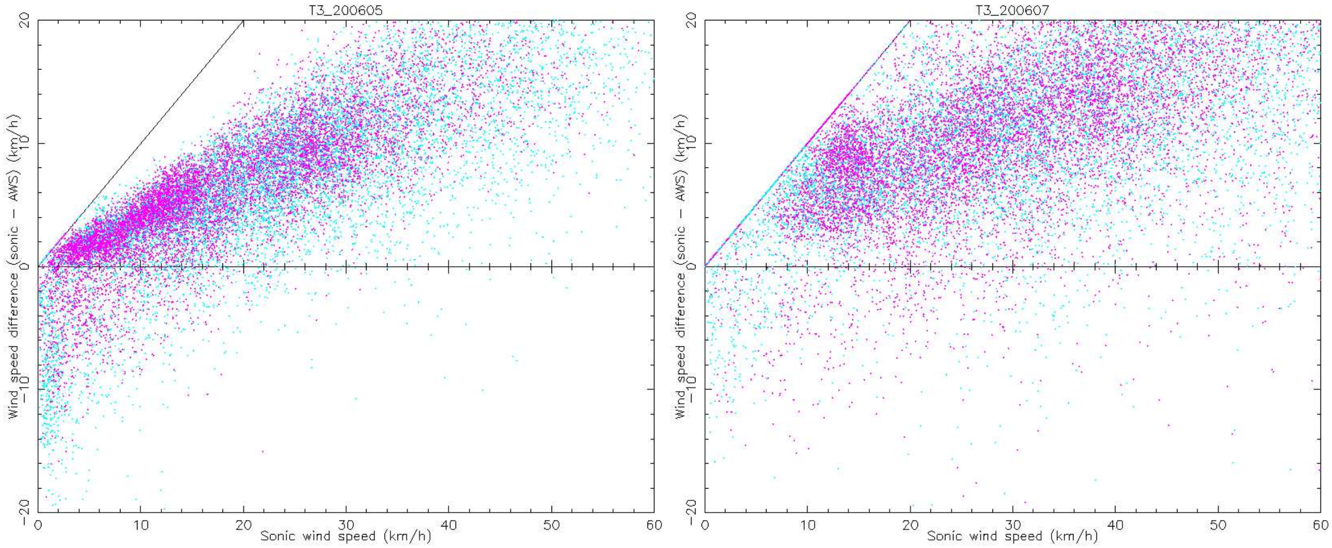

Figure 2.1: Plots of the sonic wind speed minus the AWS wind speed versus the sonic wind speed for two months from T3-Tolonchar. Blue points are daytime, purple points are nighttime. **Left:** During this month there is no evidence that the AWS anemometer is sticking or stiff, there is no evidence that the AWS anemometer is underestimating the wind speed. The mean slope indicates that the sonic anemometer measures proportionally higher wind speeds due its higher location, as expected. **Right:** This month shows that often the AWS anemometer is measuring zero wind speed when the sonic anemometer measures high wind speeds. Also note the much poorer correlation of AWS and sonic wind speed, evidenced by the increased scatter of points. Thus there is evidence that the AWS anemometer has a mechanical problem.

anemometer.

The mechanical AWS anemometer has to overcome internal friction before it registers any wind (see Section 4.1). This internal friction should be low, so the number of zero wind speed points should also be low. The AWS anemometer's manufacturer's specification is for a startup wind speed of 0.36km/h [1]. A disproportionately high number of zero wind speed points from the AWS anemometer indicates a probable problem, as does a strong deviation from a simple form of multiplicative relation between AWS wind speed and sonic wind speed.

If the above assumptions are correct, then we can check for periods when the AWS anemometer has a mechanical problem that affects its ability to rotate, such as when the vertical rotational axis bearing becomes stiff, by plotting the difference in speeds ($V_{sonic} - V_{AWS}$) versus the wind speed measured by the sonic anemometer. A plot of the difference in speeds versus the wind speed should on average have a positive slope (as the sonic anemometer, being higher, measures higher wind speeds) that goes through the origin. A clear 45° line will extending well above several km/h indicates that the AWS anemometer is sticking.

Scripts and code were written that downloaded all AWS and sonic anemometer data from all sites and created the type of plots mentioned in the paragraph above ($V_{sonic} - V_{AWS}$ vs V_{sonic}), one new plot for each month. Examples of these comparison plots are shown in Figure 2.1. Table 2.1 lists the sites and months during which an assessment of the AWS anemometer operation has been made.

Table 2.1: The sites and dates for which the sonic anemometer/AWS comparison allows the AWS anemometer operation to be assessed. When a plot of the wind speed difference vs sonic anemometer wind speed is inspected, OK means that the AWS anemometer appears to be working fine, BAD means that there is strong evidence that the AWS anemometer is sticking in low wind speeds and measuring below the real wind speed, POOR means that there is a lot of scatter. All months listed for T2-Armazones show a majority of points indicating good operation of the AWS anemometer but the plots show a lot of scatter. The ratio values are derived as described in Section 2.1.3.

Month	T1	Ratio	T2	Ratio	T3	Ratio	T4	Ratio	T6	Ratio	Notes
2005 12	-		-		-		-		BAD	2.7	1
2006 01	-		-		-		-		BAD	1.0	2
2006 02	OK	27.9	POOR	4.8	-		-		BAD	0.46	
2006 03	OK	4.1	BAD	1.5	OK	12.2	-		BAD	0.023	
2006 04	OK	6.6	BAD	2.3	OK	5.0	-		BAD	0.12	
2006 05	OK	15.7	POOR	6.4	OK	7.3	OK	15.5	BAD	0.38	
2006 06	OK	5.7	POOR	9.2	BAD	0.26	OK	21.4	BAD	0.58	3
2006 07	OK	13.9	POOR	28.3	BAD	0.54	OK	7.0	BAD	0.26	
2006 08	BAD	0.30	BAD	2.5	BAD	0.15	BAD	0.045	BAD	0.24	4
2006 09	BAD	0.84	BAD	0.96	BAD	0.12	BAD	0.12	BAD	0.14	
2006 10	-		-		BAD	0.10	BAD	0.14	BAD	0.11	
2006 11	-		-		BAD	0.10	BAD	0.16	BAD	0.10	
2006 12	-		-		BAD	2.2	BAD	0.11	BAD	0.50	5,6
2007 01	-		-		OK	28.6	BAD	0.37	BAD	1.6	
2007 02	-		-		OK	21.5	OK	1.5	OK	2.2	
2007 03	-		-		OK	5.4	OK	3.5	OK	1.0	
2007 04	-		-		OK	2.6	OK	18.5	OK	8.8	

1). T6- one population of points looks OK
2). T6- a second population is clearly off
3). T3- one population of points looks OK
4). T4- one population of points looks OK
5). T3- one population of points looks OK
6). T6- sensor replaced in early Dec 2006

2.1.3 Statistical analysis

The periods where we have overlapping wind speed measurements with the AWS and the sonic anemometer only cover relatively short sections of the full AWS data sets. Several years of AWS measurements have no simultaneous sonic anemometer measurements. The method of manual comparison with the sonic anemometer in Section 2.1.2 is thus limited in its time coverage. We required a more quantitative method of defining whether we could consider AWS wind speed data to be good or bad, a method that would not be biased during periods of calm or harsh conditions. So a method based on the statistical distribution of wind speeds was developed.

The distribution of wind speeds is expected to follow a standard statistical distribution, generally a log normal distribution. But independent of the form of the wind speed distribution we always know the wind is never exactly zero, that at low wind speeds, well below the mean or median wind speed, the number of points in each wind speed bin will increase as the bin wind speed increases and most measurements approach the mean or median wind speed.

We derived the following statistical method for assessing whether the distribution of wind speeds was similar to that expected, i.e. the AWS anemometer has low internal friction, or whether there was evidence of high friction in the AWS anemometer causing a disproportionately large number of zero wind speed points.

For a particular period of AWS measurements (all analysis in this report uses month-long periods):

1). Determine the mean wind speed and standard deviation around the mean for all non-zero measurements.
2). Set a wind speed bin width of $\frac{\mathrm{V_{mean}}}{5}$.
3). Count the number of zero wind speed measurements and the number of finite measurements in the first bin (greater than 0 and less than or equal to $\frac{\mathrm{V_{mean}}}{5}$).
4). Report the ratio of the number of points in the first bin to those with zero wind speed.

The ratios for the corresponding examples from T3-Tolonchar in Figure 2.1 are 7.3 for 2006 05 and 0.54 for 2006 07. Corresponding ratios are reported in Table 2.1 for those months with simultaneous sonic anemometer measurements. By comparing the ratios and manual assessments (Section 2.1.2) in Table 2.1 we see that higher ratios correspond to 'OK' assessments of the AWS anemometer operation, low ratios occur when the AWS wind speed sensor is 'BAD'. For the reported ratios in Table 2.1, only AWS wind speed measurements that were coincident with CSAT3 sonic anemometer measurements were included in the calculations.

The effect of having a disproportionately large number of points with zero wind speed on the measured mean wind speed is quantified using the following method:

1). Determine the mean wind speed including and excluding points with zero wind speed, i.e. determine $\overline{\mathrm{V_{nonzero}}}$ and $\overline{\mathrm{V_{all}}}$.
2). Take the difference of the mean wind speeds ($\Delta\mathrm{V} = \overline{\mathrm{V_{nonzero}}} - \overline{\mathrm{V_{all}}}$) to get a velocity shift, divide the shift by the two mean values, $\overline{\mathrm{V_{nonzero}}}$ and $\overline{\mathrm{V_{all}}}$, separately to get a relative shift for the non-zero wind speeds and all wind speed cases.

Figure 2.2 shows the ratio of the number of points in the lowest wind speed bin over the number of zero wind speed points against the relative shift on the mean wind speed in the left plot and median wind speed in the right plot. A clear anti-correlation exists between the statistical ratio and relative

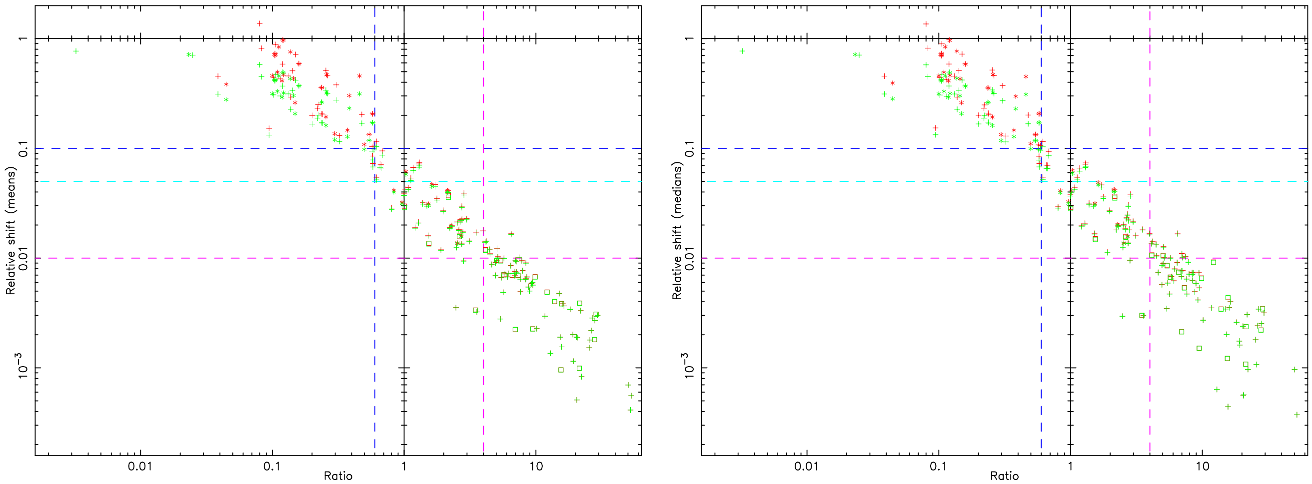

Figure 2.2: **Left:** Plot of the relative shift of mean wind speed versus ratio of number of points in lowest wind speed bin over number of points of zero wind speed. Green points are for wind speed difference over mean of all non-zero wind speeds, red points are for difference over mean of all wind speeds. **Right:** Same plot for median speeds.

effect on the mean and median wind speeds. The horizontal lines indicate the 10%, 5% and 1% effects, the vertical lines and the vertical axis indicate corresponding bin ratios of 0.6, 1 and 4 (blue, cyan and purple) respectively. We can say that, for a ratio of 1, the effect on both the mean and median wind speeds is about 5%. Green points are for wind speed differences divided by the mean (left hand panel) or median (right hand panel) calculated using the all non-zero wind speeds, red points are for all wind speed measurements. + signs are for all months on all sites (see Table 2.2), squares are for those points in Table 2.1 that are labelled as OK, stars are for points labelled BAD (points labelled POOR are omitted). The stars and squares fall within the same body of points as the + signs.

A conclusion could be that for months with ratios below 1.0 that we can say the wind speed measurements may be significantly biased or affected by problems with the AWS wind speed sensor that cause an underestimation of the wind speed by a maximum of 5%. The relation of relative shift and ratio only give an upper limit on the bias because some zero wind speed measurements occur during winds lower than the specified start up wind speed for a normally functioning anemometer [1]. In 2006 09, an AWS-AWS comparison at T2-Armazones ([5]) showed that the AWS anemometer used for all measurements in this report compared very well to a second brand new new cup anemometer. The ratio for the original AWS anemometer measurements during this month was 7.1.

2.2 Long term time line of wind speed data quality

The full listing of the ratios for all AWS data so far obtained is listed in Table 2.2. These ratios include all AWS wind speed measurements and are shown in Figure 2.2 against the relative effect as + symbols. The equivalent ratios in Tables 2.1 and 2.2 are almost equal in most cases. The ratios in Table 2.1 are calculated using only those AWS wind speed measurements with simultaneous sonic anemometer measurements, the amount of sonic anemometer data can be small during the first and last month of operation and the sonic anemometers have sometimes had significant down times, so there are some explainable inconsistencies.

Table 2.2: List of all months of AWS wind speed measurements and their statistical ratios.

Month	T1-Tolar	T2-Armazones	T3-Toloncher	T4-SPM	T6-Hawaii
2003 10	2.6	-	-	-	-
2003 11	3.1	-	-	-	-
2003 12	5.6	-	-	-	-
2004 01	2.5	-	-	-	-
2004 02	1.4	-	-	-	-
2004 03	2.0	-	-	-	-
2004 04	2.8	-	-	-	-
2004 05	2.5	-	-	-	-
2004 06	1.2	-	-	-	-
2004 07	1.3	-	-	-	-
2004 08	9.4	-	-	-	-
2004 09	-	-	-	-	-
2004 10	4.1	-	-	0.32	-
2004 11	7.0	21	-	0.083	-
2004 12	4.0	9.0	-	0.58	-
2005 01	2.7	5.5	-	0.58	-
2005 02	2.7	5.8	-	0.0032	-
2005 03	3.0	4.5	-	0.094	-
2005 04	6.5	1.9	-	1.5	-
2005 05	1.8	15	-	2.5	-
2005 06	2.7	8.4	-	20	0.025
2005 07	5.1	8.4	-	10	0.67
2005 08	5.1	11	-	-	2.2
2005 09	0.48	50	-	-	4.9
2005 10	0.20	27	-	0.22	4.6
2005 11	7.6	5.0	6.9	53	1.1
2005 12	9.3	9.5	7.8	15	1.0
2006 01	6.1	8.8	3.5	22	0.59
2006 02	19	7.1	4.2	52	0.25
2006 03	4.5	1.5	7.0	2.8	0.080
2006 04	7.6	2.3	5.0	1.2	0.12
2006 05	16	6.4	8.4	13	0.31
2006 06	6.2	5.7	0.24	19	0.58
2006 07	8.5	26	0.54	5.4	0.26
2006 08	0.24	2.7	0.14	0.039	0.24
2006 09	0.66	7.1	0.11	0.13	0.14
2006 10	1.1	25	0.10	0.15	0.12
2006 11	2.7	22	0.10	0.16	0.10
2006 12	1.7	26	2.2	0.11	0.62
2007 01	1.0	18	29	0.22	1.3
2007 02	0.62	20	28	0.80	0.68
2007 03	0.57	16	7.5	3.6	1.3
2007 04	-	232	7.9	15	2.8
2007 05	-	-	-	-	-

Chapter 3

Wind direction

3.1 Assessment of wind vane operation

The operation of the AWS wind direction sensor and wind vane is expected to be less affected by mechanical problems than the wind speed measurements. If the vertical axis bearing is stiff then the response of the wind vane will be slightly slower in low wind speeds but on average there should be no difference when compared to a new wind direction sensor.

The problems with the wind direction sensors are dominated by alignment issues (both alignment errors at the time of installation and alignment changes when the locking bolts on the sensor body come loose), incorrect wind direction offset parameters and incorrect application of the offset parameters. The sonic anemometer software simply outputs the results of the analysis of the raw sonic anemometer data stream relative to the internal coordinate system [1]. This has to be corrected later depending on the orientation of the sonic anemometer on the telescope tower. No correction was carried out during the analysis reported in this document and the expected offset is listed in Table 3.1. The AWS wind direction measurements are modified by a wind angle parameter, this has been zero at all sites except T2-Armazones and the history of this parameter and configuration tests are listed Section 3.1.2. The WIND_ANGLE offset is added to the AWS wind direction measurement by the `weather` script on the supervisor computer as the script reads out the AWS and the values are added to the `weather_station.[SITE].[DATE]` file. No record of the unmodified wind direction measurement is made.

3.1.1 Comparison with sonic anemometer

Correlation plots of month-long segments of the AWS and sonic anemometer wind direction measurements show the stability of the two instruments and demonstrate whether their respective measurements agree. Table 3.1 lists the months that give a consistent offset, numbers in bold indicate that the offset between AWS and sonic anemometer wind direction is as expected based on the orientation of the sonic anemometer and, in the case of T2-Armazones, on the wind angle offset parameter. The error in the alignment estimations of the AWS wind direction sensors and sonic anemometers from correlation plots is $\pm 8^\circ$. Up until 2006 03 27, the logic used to derive the sonic anemometer wind direction was incorrect, after this time the software on all sites was updated to give correct wind directions. All analysis reported here includes recalculated sonic anemometer wind directions, measurements in the TMT sites database are not correctly calculated [as of the time of writing this report]. The logic used to calculate the wind direction is detailed in Appendix B. Measurements of the sonic wind direction made before 2006 03 27 should be recalculated from the V_x and V_y velocity components in the sonic anemometer results files.

The internal coordinate system of the sonic anemometer [1] is such that when facing north into a wind from the north, the output reading will be 270°, i.e. a +90 degree offset should be added to the output from the CSAT3 analysis software. See Figure 2.2 in [1], if north is to the right in the negative x direction and the wind is from the north, the output will be 270°.

To correct the sonic anemometer horizontal wind direction to true north, apply the offset values in Table 3.1 (sonic-AWS) to the calculated wind direction as shown in Equation (3.1).

$$\theta_{\text{true}} = \theta_{\text{measured}} - \text{offset} \tag{3.1}$$

3.1.2 Summary of configuration file notes and on site work reports

Summarised notes of calibration measurements, checks and changes of the WIND_ANGLE parameter and instrument installation and orientation notes for the five sites are listed below. The original information came from a variety of sources, mainly from Sebastian Els's AWS calibration notes, Warren Skidmore's configuration status files, from the archives of the software and configuration files, the CTIO site testing memos and from old emails. The AWS calibration measurements are the output of the *weather* script on the SC unless otherwise noted, times are in UT.

T1-Tolar

```
2003 04 10 AWS first installed on Tolar
2005 01 26  AWS 227+-10  Compass 236+-10
2005 03 09  AWS 305+-5   Compass 308+-5
2005 08 28  AWS 190.65   Compass 198
2005 08 28 WIND_ANGLE=0
2005 08 29  AWS 343.22   Compass 343
2005 11 10  AWS 193      Compass 190.5
2006 02 16  AWS 333+-5   Compass 340+-5
2006 02 16 Sonic anemometer installed pointing west
2006 03 23 WIND_ANGLE=0
2006 03 29 Sonic anemometer software modified to give wind direction w.r.t.
direction unit is pointing
2006 07 05  AWS 1.2      Compass 0
```

T2-Armazones

```
2003 12 17           AWS 210  Compass 0
2004 11 06 Standard AWS operations begin
2005 01 03  18:30-33  AWS 248  Compass 250
[2005-01-23 20:18:02  wind direction adjusted for sensor error direction is now -210
from the original direction] - from electronic note on batman, date stamp 2005 10 24
2005 01 23  20:10:02 WIND_ANGLE correction parameter implemented. -210 added to AWS
wind vane output when written.
2005 01 24  21 00     AWS 160  Compass 162
2005 01 31  12 15     AWS 360  Compass 5   windgusts
2005 03 05  19 07     AWS 350  Compass 350 low wind
2005 03 11  09:35     AWS 358  Compass 2   gusts
```

Table 3.1: The mean approximate offset (sonic anemometer direction minus AWS direction) for each month of simultaneous AWS and sonic anemometer data and the expected offset if WIND_ANGLE=0. Bold values are those consistent with the sonic anemometer orientation and wind angle offset parameter according to the notes in Section 3.1.2. Estimates on the values of the offsets are accurate to within about ±8°. Also listed are dates of commencement of AWS measurements as part of the TMT sites system and the start and end dates of the AWS/sonic anemometer overlap periods.

Month	T1-Tolar	T2-Armazones	T3-Toloncher	T4-SPM	T6-Hawaii	Notes
Start date	2003 10 11	2004 11 06	2005 11 17	2004 10 02	2005 06 28	
Overlap start	2006 02 16	2006 02 11	2006 03 30	2006 05 06	2005 11 29	
Overlap end	2006 09 10	2006 09 09	-	-	-	
Offset (sonic-AWS)	0	-90	90	90	90	
2005 12	-	-	-	-	**95**	
2006 01	-	-	-	-	**95**	1
2006 02	**0**	60	-	-	**90**	2
2006 03	**0**	55	**80**	-	**90**	3
2006 04	**0**	20	10	-	**100**	4
2006 05	**0**	20	0	**70**	**100**	
2006 06	**0**	25	0	**80**	**100**	
2006 07	**0**	-90	85	**75**	**100**	5
2006 08	**0**	**-85**	**80**	**75**	**100**	
2006 09	**0**	**-90**	**90**	**70**	**97**	
2006 10	-	-	**90**	**80**	**97**	
2006 11	-	-	**90**	**80**	**96**	6
2006 12	-	-	**90**	**80**	**96**	
2007 01	-	-	**90**	-	**100**	

1). T6-Hawaii has periods with fixed AWS direction
2). T2-Armazones very chaotic
3). T4-SPM has a lot of noise in all months
4). T2-Armazones has minor population at -55. T3-Tolonchar has minor population at 80
5). T2-Armazones has lesser population at 120 and very few points at -20. T3-Tolonchar has a lesser population at 0
6). T6-Hawaii has periods with fixed AWS direction

```
2005 05 18  14:25     AWS 320  Compass 320
2005 05 18  14:25     AWS 326  Compass 335
2005 08 03 First mention of WIND_ANGLE=-210 in site-config archive
From archives: site-config.T2-Armazones.20050803: WIND_ANGLE=-210 before this date
2005 08 24  12:52     AWS 224 Compass 17 [From minicom - consistent with AWS-210]
2005 09 10 WIND_ANGLE=-210
2005 11 04 13:36      AWS 155.22-155.35 Compass 156.9
2006 02 11 - sonic data starts, sonic pointing north
2006 02 12 15.45      AWS 210  Compass 210
2006 03 23 WIND_ANGLE=-210
2006 03 27 - sonic software update, instrument plots before this date not correct
2006 03 29 Sonic anemometer software modified to give wind direction w.r.t.
direction unit is pointing
From archives: site-config.T2-Armazones.20060330:WIND_ANGLE=-210 before this date
2006 03 31 - Offset noted after correction of AWS-sonic ~-30 deg
2006 04 03  15 45-50 AWS 140  Compass 112 offset because sensor body loose,
tightened screw
2006 04 03  17 05    AWS 139  Compass 110 offset because sensor body loose,
tightened screw
2006 04 03  17 10    AWS 222  Compass 192 offset because sensor body loose,
tightened screw
2006 04 03 - direction of the sonic OK +-5 to 10 deg.
2006 04 03 WIND_ANGLE=-240 updated from -210 (set incorrectly for a short time to -180)
2006 04 04 Noted that WIND_ANGLE correction not being applied for some time before this date
2006 04 04 WIND_ANGLE changed from -240 to +30 [LOOKS LIKE THIS SHOULD HAVE BEEN
+120 NOT +30]
From archives: site-config.T2-Armazones.20060404: WIND_ANGLE=-240 before this date
From archives: site-config.T2-Armazones.20060405:WIND_ANGLE=30 before this date
2006 06 06 WIND_ANGLE changed from +30 to 0
From archives: site-config.T2-Armazones.20060607:WIND_ANGLE=30 before this date
2006 07 03 - Offset noted of AWS-sonic ~-15 deg
2006 07 04 On site inspection - Sensor body at 25 degrees east of north. Vane connected
at 250 degrees with respect to fiducial mark. Orientation of wind vane corrected,
measures 0 when pointed North 17:45 UT
From archives: site-config.T2-Armazones.20060715: WIND_ANGLE=0 before this date
From archives: Date stamp 2006 11 18 site-config WIND_ANGLE=0
2006 12 07 22.08     AWS 357.34 Compass 0
```

T3-Tolonchar

```
2005 11 19  AWS 188.8     Compass 190
2005 12 29 WIND_ANGLE=0
2006 01 28  AWS 1.7+-1.0  Compass 0.0
2006 02 18  AWS 323       Compass 320+-5
2006 02 19 Sonic anemometer installed pointing south
2006 03 29 Sonic anemometer software modified to give wind direction w.r.t.
direction unit is pointing
2006 04 05 AWS sensor rotated to match the sonic anemometer
```

```
2006 07 06  AWS 358       Compass 0 Measurements made after rotating unit to North.
```

T4-SPM

```
2005 04 29  AWS 210+-2    Compass 208+-4
2005 09 13 Trees cut down around site
2005 10 05 AWS back on line after lightning damage
2005 10 30 AWS moved and telescope operations restarted
2006 03 07 Sonic anemometer installed pointing south but not collecting data
2006 03 23 Instrument computer fixed and sonic taking data
```

T6-Hawaii

```
2005 06 28 Wind vane set to give 0 when pointing North (checked with GPS)
2005 07 12 Wind direction sensor died due to static discharge
2005 09 13 WIND_ANGLE set to 180 after replacement of wind direction sensor
oriented south, wind direction sensor died straight away due to static discharge
2005 11 29 Sonic anemometer installed pointing south, aligned with compass
2005 12 02 Wind direction sensor replaced on, WIND_ANGLE set to zero
2005 12 02  AWS 0         Compass 0
2006 01 27 Sonic processing software updated.
2006 03 29 Sonic anemometer software modified to give wind direction w.r.t.
direction unit is pointing
```

3.2 Correction factors and uncertain periods for the wind direction measurements

Listed in the following subsections are dates and correction offsets for the AWS wind direction measurements, dates where the AWS wind direction output cannot be confirmed or is undetermined, and justification and conclusions about the wind direction measurements.

3.2.1 T1-Tolar

The sonic anemometer/AWS wind direction comparison always yielded the expected offset. All on site calibration measurements listed in Section 3.1.2 confirm the wind vane orientation. The WIND_ANGLE offset parameter has always been zero.

We conclude that no correction AWS wind direction offsets need to be applied.

3.2.2 T2-Armazones

The T2-Armazones wind direction measurements have given course for concern, as evidenced by the notes in Section 3.1.2. Numbers in bold in Table 3.1 are for the periods during which we have confidence in the measurements based on the notes in Section 3.1.2 and the information in Table 3.1.

A problem with the application of an offset parameter to the T2-Armazones AWS wind direction measurements is that it is not certain that the parameter was applied correctly, i.e., it is not known whether the offset parameter should have been added or subtracted from the AWS data. There is also an undetermined period when the application of the offset by the *weather* script was not being carried out due to a software error. With this in mind, it is possible to make some sense of the information in Section 3.1.2, but it is not possible to reconcile the information in Section 3.1.2 and in Table 3.1 until the 2006 07 04 reorientation of the wind direction sensor. Therefore, all data obtained before 2007 07 04 must be considered to be unreliable.

Because of the large amount of weather station wind direction measurements obtained before 2007 07 04 we have attempted to correct the measurements based on a comparison with sonic anemometer measurements. This work is detailed in Section 3.3.

3.2.3 T3-Tolonchar

Generally the sonic anemometer/AWS wind direction comparison yielded the expected offset of 90 degrees. However at approximately 2006 04 05 19:38UT the AWS wind direction jumps by $+90^o$, at approximately 2006 07 06 22:00UT the AWS wind direction jumps back by -90^o. These jumps are explained in Section 3.1.2 when, on 2006 04 05, the AWS wind direction sensor was erroneously rotated so that the wind direction measurements would match that of the sonic anemometer and was rotated back on 2006 07 06. The time series of sonic anemometer wind direction measurements is smooth where these jumps occur. The WIND_ANGLE offset has always been zero. Records of these AWS wind direction sensor orientation changes are listed in the CTIO memos.

The correction to the T3-Tolonchar AWS wind direction measurements would be to subtract 90 degrees between 2006 04 05 19:38UT and 2006 07 06 22:00UT. See Figure 3.1 to see the effect that applying this offset and the sonic-AWS offset has on the wind direction correlation.

3.2.4 T4-SPM

The sonic anemometer/AWS wind direction comparison always yielded the expected offset within expected errors in the orientation of the sonic anemometer and AWS wind vane and the uncertainty of the estimation - the uncertainty of the offset estimations are worse than at the other sites as the local effects of trees and rocks disrupts the ground air flow. Again WIND_ANGLE has always been zero. Calibration measurements before the AWS was moved show correct sensor alignment.

We conclude that no correction offsets should be applied to the AWS wind direction measurements.

3.2.5 T6-Hawaii

The sonic anemometer/AWS wind direction comparison always yielded the expected offset within expected errors in the orientation of the sonic anemometer and AWS wind vane. Again WIND_ANGLE has always been zero.

We conclude that no AWS wind direction correction offsets are needed.

Table 3.2: Dates and approximate amplitudes for the offset (sonic anemometer wind direction - AWS wind direction) and jumps in the offset for T2-Armazones. This offset should be -90°. On 2006 07 04 the wind sensor was correctly oriented and WIND_ANGLE=0 already on 2006 06 06.

Start date	End date	Jump date	Offset amplitude and changes
2006 02 11	2006 02 20	-	+40°†
2006 02 20	2006 02 28	-	+40°
2006 03 01	2006 03 31	-	+40°
-	-	2006 04 04.5	jumps from +40° to +20°
2006 05 01	2006 05 31	-	+20°
2006 06 01	2006 06 30	-	+20°
2006 07 01.5	2006 07 04.5	-	+20°
2006 07 06	2006 07 13	-	-130°
2006 07 17	2006 07 31	-	-100° after a gap
2006 08 01	2006 08 31	-	-100°
2006 09 01	2006 09 10	-	-100°

† Sonic anemometer measurements in local time, not UT, UT = local + 5hr. Before 2006-02-22 13:14UT add 5 hours to the times to turn local time into UT.

3.3 Correction of the T2-Armazones AWS wind direction measurements

The difference between the T2-Armazones sonic anemometer and AWS wind direction measurements as a function of time was closely inspected to detect jumps in the difference that may identify and confirm the date and size of the recorded changes. When a jump was noted the relevant log file, weather and instrument plot was inspected to identify the exact time and amplitude of the jump and if an identification was made the time was noted in Table 3.2.

The sonic-AWS offset and the offsets in Table 3.2 were applied to the T2-Armazones sonic anemometer and AWS wind direction measurements, the effects of this are seen in Figure 3.1. Apart from a few small groups of points, the vast majority of points are satisfactorily corrected and the correlation appears as expected.

3.4 Effects of the dome on the wind flow at the sonic anemometer

The right hand plot in Figure 3.1 shows the corrected wind direction correlations from the sonic anemometer and AWS. Deviations in a linear 1:1 relation can be explained by the effects of the dome on the wind flow near the sonic anemometer. Clear discontinuities can be seen at about 80° at T1-Tolar, 220° at T2-Armazones, 30° at T3-Tolonchar and 330° at T6-Hawaii. These correspond quite closely with wind directions that hit the corner of the dome directly opposite the sonic anemometer, see Table 1.1. Smaller amplitude larger scale effects are probably due to the local topography of the various sites.

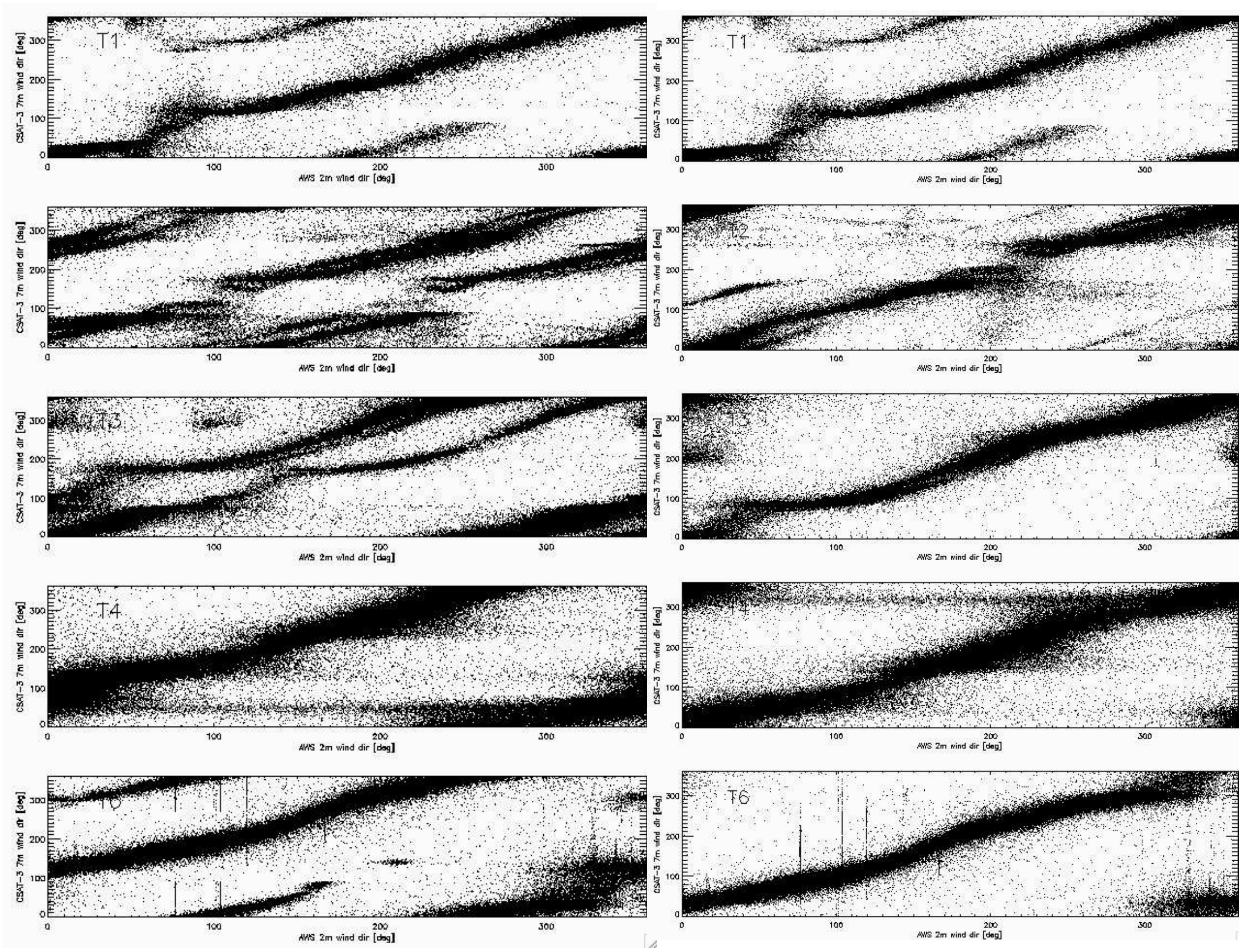

Figure 3.1: **Left:** Scatter plot showing the correlation of sonic anemometer wind direction against AWS wind direction measurements before the application of any correction offsets as described in Tables 3.1 and 3.2 and Section 3.2.3. **Right:** Same plot after corrections are applied.

Chapter 4

The dependence of measured wind speed on real wind speed and density

4.1 Cup anemometer operation assumptions

The angular rotational speed of a cup anemometer is given in Equation (4.1) that equates the energy density, i.e., power available in a column of moving air with the power needed to rotate the the cup anemometer.

$$0.5\rho \mathrm{V}_{\mathrm{air}}^2 = \omega^2 \mathrm{K}\rho + \omega^2 \mathrm{C}(\omega) \tag{4.1}$$

Where ρ is air density, V is wind speed, $\mathrm{K}\rho$ represents the air viscosity, ω is the angular velocity of the cup anemometer and $\mathrm{C}(\omega)$ represents the internal friction of the anemometer. We collect together terms and divide by ρ.

$$\mathrm{V}_{\mathrm{air}} = \omega \left[\mathrm{K} + \frac{\mathrm{C}(\omega)}{\rho}\right]^{\frac{1}{2}} \tag{4.2}$$

For a perfect cup anemometer with no internal friction, $\mathrm{C}(\omega)$=0, the measured wind speed is not a function of air density ρ and the angular velocity is proportional to wind speed. Several studies [6] show that angular velocity of a cup anemometer is directly proportional to wind speed except for very low speeds, as indicated in Equation 4.2.

If we have an anemometer with low internal friction, we can ignore the effects of air density or altitude on the measurements. If we have an anemometer that has significant internal resistance then we can identify this using the method described in Section 2.1.3 and estimate the bias induced, as long as the faulty anemometer is not transferred to another site of different altitude and air density then there is no problem in comparing cup anemometer measurements from different altitudes.

The real effect of internal friction is similar to sliding friction. It takes a lot to make the unit start moving but the unit will keep moving below the startup threshold before coming to a stop at a wind speed lower than the startup threshold. Once turning, the internal friction is greatly reduced, force needed to keep turning the anemometer is much lower than that needed to start it.

Appendix A

Wind speed and direction assessment software

Appendix B

Sonic anemometer wind direction calculation with respect to internal coordinate system

The sonic anemometer wind direction is derived using the following logic. Due to the internal coordinate system of the CSAT3 ([1], this logic means that for a sonic anemometer that is pointing West a wind direction of zero is derived for a wind from the North. For a sonic anemometer pointing north, a north wind gives 270°, an east wind gives 0°, south wind gives 90° and west wind gives 180°.

$$
\begin{array}{l}
\theta_{sonic} = tan^{-1}\left[\frac{V_x}{V_y}\right] \\
if\ V_x > 0\ and\ V_y > 0\ then\ \theta_{sonic} = \theta_{sonic} - 180 \\
if\ V_x < 0\ and\ V_y > 0\ then\ \theta_{sonic} = \theta_{sonic} - 180 \\
if\ V_x > 0\ and\ V_y < 0\ then\ \theta_{sonic} = \theta_{sonic} - 180 \\
if\ V_x < 0\ and\ V_y < 0\ then\ \theta_{sonic} = \theta_{sonic} - 180 \\
if\ \theta_{sonic} > 360\ then\ \theta_{sonic} = \theta_{sonic} - 360 \\
if\ \theta_{sonic} < 360\ then\ \theta_{sonic} = \theta_{sonic} + 360
\end{array}
\tag{B.1}
$$

Below is a section of Fortran 77 code that calculates the sonic wind direction from the 1 minute averaged x and y wind components. This is the logic that was applied to all measurements in this document and is applied to all remote site measurements as of 2006 03 29. Before this time, the on site measurements were not analysed correctly and the validity of the sonic wind direction measurements cannot be guaranteed.

```
      snwind_dir(num_son_points) = atan(svx(num_son_points)/
     & svy(num_son_points)) * 360.0 / (2.0 * 3.1415927)
      if (svx(num_son_points).gt.0.0.and.svy(num_son_points).gt.
     & 0.0) snwind_dir(num_son_points)=snwind_dir(num_son_points)-180.0
      if (svx(num_son_points).lt.0.0.and.svy(num_son_points).gt.
     & 0.0) snwind_dir(num_son_points)=snwind_dir(num_son_points)+180.0
      if (svx(num_son_points).gt.0.0.and.svy(num_son_points).lt.
     & 0.0) snwind_dir(num_son_points)=snwind_dir(num_son_points)+0.0
      if (svx(num_son_points).lt.0.0.and.svy(num_son_points).lt.
     & 0.0) snwind_dir(num_son_points)=snwind_dir(num_son_points)+0.0
      if (snwind_dir(num_son_points).gt.360.0)
     & snwind_dir(num_son_points) = snwind_dir(num_son_points) - 360.0
      if (snwind_dir(num_son_points).lt.0.0)
     & snwind_dir(num_son_points) = snwind_dir(num_son_points) + 360.0
```

Bibliography

[1] Skidmore W., 2006, Cross calibration of the CSAT3 sonic anemometer and automatic weather station - reports and plans, TMT internal report.

[2] Els E., 2005, First experiences with the SM28 weather station, TMT internal report.

[3] Skidmore W., Els s., Schöck M., 2005, Routine Maintenance at TMT Site Testing Installations, TMT internal report.

[4] Skidmore W., Travouillon T., Riddle R., 2006, SPIE, 6267, P. 64, Ed. Stepp L.

[5] Skidmore W., Travouillon T., Riddle R., 2007, Report of the calibration of the T2-Armazones 30m tower air temperature sensors and sonic anemometers, the cross comparison of weather stations and sonic anemometers and the turbulence measurements of sonic anemometers and finewire thermocouples, TMT internal report.

[6] Miller D., http://www.unca.edu/~dmiller/anemometry9_a320.ppt