UNCERTAINTY ANALYSIS OF SOLAR MONITORING STATION: A CASE STUDY

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Summary

The present work describes the type B uncertainty analysis for the environmental quantities monitored by a solar station. Type B in our case represents the random effects of sensor and data logger on the measuring system by rounding resolution and noise, and should be as low as possible. It is performed in order to comply with ISO technical recommendations and also academic purposes. Special care should be taken if this report is used as an example for uncertainty analysis of similar stations because it depends on configuration, calibration certificates, data loggers specs, acquisition setup and so on. By the end of work it will be possible to include the determined system uncertainty to the overall measured repeated data.

Key-words: Uncertainty analysis, ISO, monitoring station

1. Introduction

Uncertainty is a part of any measurement and should be presented together with data in order to comply with existent standards like WMO (2008, sec 1.5), NASA (2010), NIST - Taylor e Kuyatt (1994) and so on. It is not common in meteorology area the full uncertainty analysis of the measurement system, according to recommended by WMO (2008, sec 1.6). In general, it is presented only the statistical errors of repeated data observations. But uncertainties are grouped on two categories: types A and B ISO BIPM (2008). Type A as previously mentioned, is the uncertainty obtained from statistical errors of repeated data observations. Type B is the uncertainty obtained from technical specifications, manuals, data sheets of sensors combined with the measuring system features. Several countries by their national institutes or similar counterparts established standardization guidelines on their own language. Most are essentially similar, because are derived from ISO-based standards. In the present text, a combination of references above mentioned and other complementary sources will be used as guidelines to determine our case type B uncertainties. By the end of present work, it will be possible to include the determined system uncertainty to the overall measured repeated data. The monitoring station is deployed at Fotovoltaica Lab, at Universidade Federal de Santa Catarina, Florianópolis SC Brazil [http://fotovoltaica.ufsc.br/sistemas/fotov/en/] lat. 27º25’50.34” S lon. 48º26’28,81” W.

2. Material and methods

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The uncertainty will be performed in the following steps: **a.** describe the measuring processes, **b.** do the analysis of sources of uncertainty, **c.** quantify its systematic and random effects, **d.** perform its combined correction, **e.** determine expanded uncertainty to finally obtain the expression measurement results. The first step is the schematic representation of the monitoring station in figure 1. The second step is the description of data logger scales, sensors type, model and characteristics taken from manual and calibration certificates described in tables 1 and 2. Data logger analog reading resolution, accuracy and response time could be obtained from specs [https://www.campbellsci.com/cr3000]. Four reading scales available for use were analyzed: 5V and 1V single ended (se) and 200, 50 and 20 mV differential (df) with input reversal (rev). Reversion is important to reduce offsets and long length cable effects.

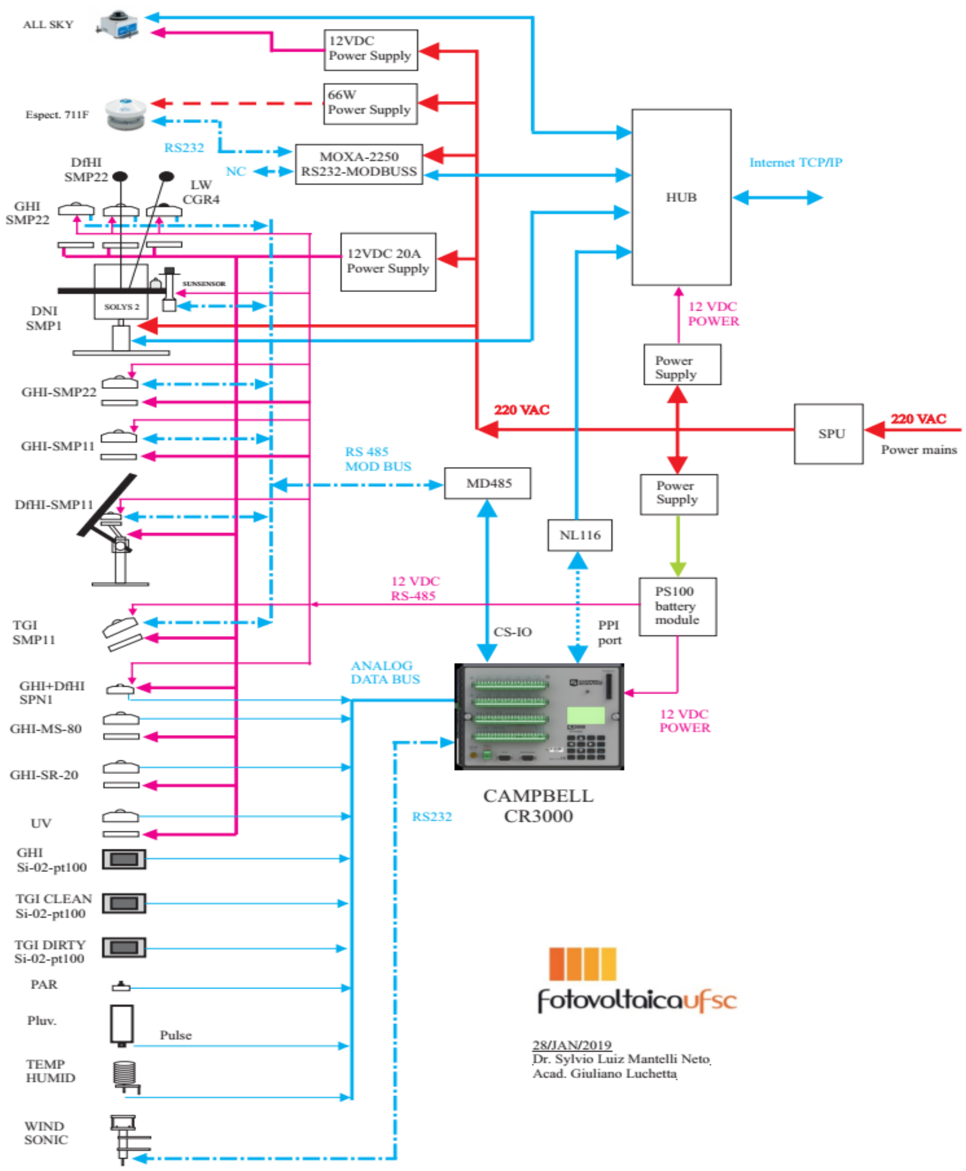

Fig. 1: Simplified schematic representation of solar station, indicating the principal variables monitored.

Sensors and data logger uncertainties must be combined to obtain system type B uncertainty. The combination of analog sensors and data logger sources of errors are considered multiplicative due to signal amplification by multiple scales. In that case, it is used the maximum error sum of squares under a chosen reading condition. They are uncorrelated variables because their sources of errors are statistically independent. Examples of correlated errors are the directional and spectral response, leveling, pointing errors, temperature compensation, wind dependency quantities and so on. Correlation is very detailed because the coefficient should be determined and taken into account. It is a too long topic to be considered in the present work and is left for future analysis. Sensors resolution or sensitivity are obtained from specs or calibration certificates. The sensor uncertainty used is usually one half of its resolution. On “Max. reading” column of table 2 values used are taken from sensors specs. matched to data logger reading scales. For Si-02-PT100, 200mV scale is correspondent to 1742W.m^{-2} irradiance. The pyranometers SR-20, MS-80 and SPN1 are respectively maximum readings of 36mV, 32mV and 2000mV @2000W.m^{-2}. For PAR it is 17mV @3000µmol.sm^{-2} and UV 138 mV@400Wm^{-2}. The same criteria was used for temperature 1V @60ºC, humidity 1V@100% and pressure 2.5V @1100hPa.

Tab. 1: Data logger CR3000 measuring uncertainty features taken from specs.

Scale	accuracy	Offset according to scale	Resolution
20 mV	± 0.04% of reading + offset	1.5*resolution+1µV =2.005µV	0.67 µV
50mV	± 0.04% of reading + offset	1.5*resolution+1µV =3,505µV	1.67 µV
200mV	± 0.04% of reading + offset	1.5*resolution+5µV =9,95µV	3.33 µV
1000mV	± 0.04% of reading + offset	3.0*resolution+5µV= 105.2µV	33.4 µV
5000mV	± 0.04% of reading + offset	3.0*resolution+1µV =502µV	167 µV

Data logger uncertainty is obtained by using “Max. reading” and “resolution” values from table 2 on table 1 at described measuring conditions for every analog reading. The reader should pay attention on the units and the right moment to use the sensitivity. As an example it will be described the MS-80 data logger scale and total type B uncertainty as illustrated on equations 1 to 3. The data logger also reads the digital RS-485, RS-232C sensor types. It is important to notice that spectrophotometer, smart digital pyranometers and wind sonic amplify and convert signals to physical units. These sources of uncertainty are independent of data logger analysis and are used as described in its features and in table 2. It is important to notice that in most cases it is not possible to compare digital and analog sensors in a fair common base. Detailed uncertainty analysis of digital sensors is not always available because of delays caused by A/D conversion and communication protocols. In the present case, the combination of sources of errors are restricted to data logger analog readings.

$$U_{CR3000,MS80}=\frac{0.04}{100}\times 32000+3.505=\pm 16.305\,\mu V \quad \text{(eq. 1)}$$

$$U_{MS80}=\frac{5.29}{10.59}=\pm 0.5\,W/m^2 \quad \text{(eq. 2)}$$

Tab. 2: Type B sensors uncertainty obtained from sensors calibration certificates, data logger specs and reading conditions.

Quantity	Model	Sensitivity or resolution	Sensor uncertainty	Max reading	Data logger scale	Datalogger uncertainty	Type B uncertainty
$U_{Espect:300-350}$	MS711F		±17.2 %			NA	±17.2 % §
$U_{Espect:350-450}$	MS711F		±4.7 %			NA	±4.7 % §
$U_{Espect:450-1050}$	MS711F		±3.8 %			NA	±3.8 % §
$U_{Espect:1050-1100}$	MS711F		±5.2 %			NA	±5.2 % §
Global Diffuse Tilted Bean Long Wave	2x SMP22 3x SMP11 SMP10 SHP1 SGR4		±0.1 Wm^{-2}			NA	±0.1 Wm^{-2} §
Global	Si-02	55.55µV/Wm^{-2}	±0.5Wm^{-2}	@1782Wm^{-2}	200mV	±89.95 µV	±1.70Wm^{-2}
Tilted	Si-02	56.11µV/Wm^{-2}	±0.5Wm^{-2}	@1782Wm^{-2}	200mV	± 89.95 µV	±1.68Wm^{-2}
Dirty	Si-02	56.16µV/Wm^{-2}	±0.5Wm^{-2}	@1782Wm^{-2}	200mV	± 89.95 µV	±1.68Wm^{-2}
Global	SR-20	17.72µV/Wm^{-2}	±0.5Wm^{-2}	36mV@2000Wm^{-2}	50mV	±14.04µV	± 0.94Wm^{-2}
Global	MS-80	10.59µV/Wm^{-2}	±0.5Wm^{-2}	32mV@2000Wm^{-2}	50mV	±16.30 µV	±1.62Wm^{-2}
Global -Diffuse	SPN1	1 mV/Wm^{-2}	±10.58Wm^{-2}	2V@2000Wm^{-2}	5V	±1302µV	±10.65Wm^{-2}
PAR	PQS1	5.4µV/µmol.sm^{-2}	±0.5µmol.sm^{-2}	17mV@3000 µmol.sm^{-2}	20mV	±8.80 µV	±1.70 µmol.sm^{-2}
UV	CUV5	345µV/Wm^{-2}	±0.55Wm^{-2}	138mV@400Wm^{-2}	200mV	±65.15µV	±0.58Wm^{-2}
Temp	HMP155	0.14 mV/ºC	± 0.1ºC	1V@ 60ºC	1V	±505.2µV	±3.58ºC
Humid.	HMP155	0.1mV/%RH	±1.7%	1V@100%	1V	±505.2µV	±3.92%
Press.	CS106	0.25mV/hPa	±0.6hPa	2.5V@1100hPa	5V	±1502µV	±0.6hPa
Wind dir	WINDSONIC1		±3º	NA	NA	NA	±3º §
Wind Speed			±2 % @ 12 m/s			NA	±2% §
Pluv.	TBL-4	0.1mm	±0.05mm			-	±0.05mm

§ Read observations on conclusions.

$$U_{G-MS80}=\sqrt{0.5^2+(\frac{16.305}{10.59})^2}=\pm 1.62\, W/m^2 \quad \text{(eq. 3)}$$

When the sensor indicates more than one source of uncertainty like SPN1 and CUV5, it is necessary to take them in account as indicated on equation 4 for SPN1 case.

$$U_{SPN1}=\frac{0.5}{1}+\frac{8}{100}+10=\pm 10.58\, W/m^2 \quad \text{(eq. 4)}$$

The type B uncertainty obtained on the last column of table 2 is for an individual measurement. Environmental data are considered a variable measurand. In our station for example, global solar irradiation is sampled 60 times in a minute (n=60) with average ($\overline{m}$), maximum, minimum and standard deviation (u) correspondent to type A uncertainty. In that case the result of system measurement (RM) is the average and the combination of types A and B uncertainties according to equation 5 (Albertazzi 2013 § 6.6.1).

$$RM=\overline{m}\pm\sqrt{(t.u)^2-B^2} \quad \text{(eq. 5)}$$

Where t is the t-student coefficient for n-samples average or degrees of freedom, u the standard deviation, $\overline{m}$ is the average and B is the type B uncertainty determined in table 2.

For example the result of system measurement for GHI irradiance taken on 2019-06-13 at 13:21 GMT with SR-20 sensor 1-minute average sampled every second with n=60 degrees of freedom, α= 99% level of confidence, t-student=2.660, $\overline{m}_{sr\text{-}20}$=531.0 W/m^2 and standard deviation u= 2.251, is described on equation 6.

$$RM_{SR-20}=531\pm\sqrt{(2.660\times 2.251)^2-0.94^2}=531\pm 6.06\, W/m^2 \quad \text{(eq. 6)}$$

The equation 5 could be used as a result of measurement for all sensors in the system. The uncertainty determined in equation 6 is a combination of types A and B. Some measurands like temperature and humidity on table 3, presented large uncertainties. Although this effect could not be compensated, it could be reduced by averaged repeated measurements if measurand is considered invariable during some period of time. Irradiances could not be considered invariable during one minute interval, but temperature, humidity and pressure could. In that case the overall uncertainty is divided by $n^{1/2}$ as the gerenal expression illustrated on equation 7 (Albertazzi 2013 § 6.2). We will illustrate that considering again 1-minute average sampled every second with n=60 degrees of freedom, α= 99% level of confidence, t-student=2.660, $\overline{m}_{temp}$=19.03 ºC and standard deviation u= 0.082, as described on equation 8.

$$RM=\overline{m}\pm(\sqrt{(t.u)^2-B^2}/\sqrt{n}) \quad \text{(eq. 7)}$$

$$RM_{temp}=19.03\pm\sqrt{(2.660\times 0.082)^2-3.58^2}/\sqrt{60}=19.03\pm 0.46\, C \quad \text{(eq. 8)}$$

3. Conclusions

The values in last column of table 3 represent the type B uncertainty obtained from analog and digital sensors of Fotovoltaica-UFSC monitoring station. They could be used as a reference and should be combined to type A repeated data observations for WMO/ISO requirements, academic and monitoring purposes. Solar data is usually described in minute, hourly or daily averages, where statistical parameters could be easily determined. But for 1-second samplings only type B uncertainty is possible to be obtained, with outlines the importance of type B as unique uncertainty parameter available. Analog sensors combined with data logger specifications presented a more detailed uncertainty evaluation than digital ones. It is important to notice that the uncertainty varies according to scale used and the features existent on some data loggers like: input reversal, differential or single ended reading, integration time, etc and must be evaluated. The equations and values used on table 1 are different for other data logger reading modes. A special care should be taken on automatic scales for signal ranges. Smaller scales have lower uncertainties than bigger ones. If it is the case, the worst case maximum error should be used. It is possible to make a deeper uncertainty analysis, considering leveling errors, temperature dependencies, electronic noise, directional response and so on. But it is considerably more complex analysis and is left as a future work. Special care should be taken when comparing pyranometers with different response time. On one second data sampling their results may vary significantly among brands and type, i.e. thermopile and semiconductor. For one minute averages their differences are smoothed by mathematical averaging. Under certain conditions large uncertainties could be reduced if a measurand is considerable invariable during a certain measuring interval by averaging, as illustrated on equation 7. Smart and digital sensors have embedded features usually some sources of uncertainty are not available for analysis. Features like Analog to Digital resolution, electronic noise, offsets and so on are expressed in terms of maximum errors. In that case, it is used the half resolution described on sensor specs. But this analysis should be more detailed by manufacturers because no indication of A/D resolution uncertainty, amplification noise and so on is described the same way as the data logger specs. Therefore, authors believed they are not being taken into account, except when clearly indicated on data sheet. That could explain the uncertainty differences among analog sensors and digital irradiance sensor systems.

4. References

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