Product Traceability and Uncertainty for the GRUAN RS92 radiosonde humidity product

Version 2.0

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Gap Analysis for Integrated
Atmospheric ECV Climate Monitoring
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Work Package 2; Complied by David Medland
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Version history

Version	Principal updates	Owner	Date
1.0	First issue	NPL	22.09.2017
2.0	Issued as annex C to D2.6	NPL	30.11.2017

1 Product overview

Product name: In-situ radiosonde RS92 relative humidity
Product technique: Capacitive humidity sensor
Product measurand: relative humidity
Product form/range: profile (ground to 30km, 1sec sampling)
Product dataset: GRUAN Reference level sonde dataset
Site/Sites/Network location:

SITE	LAT	LON	HEIGHT(m)	LOCATION	COUNTRY
BEL	39.05	-76.88	53	Beltsville	US
BOU	71.32	-156.61	8	Boulder	US
CAB	51.97	4.92	1	Cabauw	NL
LAU	-45.05	169.68	370	Lauder	NZ
LIN	52.21	14.12	98	Lindenberg	DE
NYA	78.92	11.92	5	Ny-Ålesund	NO
PAY	46.81	6.95	491	Payerne	CH
POT	40.60	15.72	720	Potenza	IT
SOD	67.37	26.63	179	Sodankylä	FI

Product time period: 20 May 2006 to present
Data provider: GRUAN
Instrument provider: Site operators, see www.gruan.org.
Product assessor: David Medland, NPL
Assessor contact email: david.medland@npl.co.uk

1.1 Guidance notes

For general guidance see the Guide to Uncertainty in Measurement & its Nomenclature, published as part of the GAIA-CLIM project.

This document is a measurement product technical document which should be stand-alone i.e. intelligible in isolation. Reference to external sources (preferably peer-reviewed) and documentation from previous studies is clearly expected and welcomed, but with sufficient explanatory content in the GAIA-CLIM document not to necessitate the reading of all these reference documents to gain a clear understanding of the GAIA-CLIM product and associated uncertainties entered into the Virtual Observatory (VO).

In developing this guidance, we have created a convention for the traceability identifier numbering as shown in Figure 1. The ‘main chain’ from raw measurand to final product forms the axis of the diagram, with top level identifiers (i.e. 1, 2, 3 etc.). Side branch processes add sub-levels components to the top level identifier (for example, by adding alternate letters & numbers, or 1.3.2 style nomenclature).

The key purpose of this sub-level system is that all the uncertainties from a sub-level are summed in the next level up.

For instance, using Figure 1, contributors 2a1, 2a2 and 2a3 are all assessed as separate components to the overall traceability chain (have a contribution table). The contribution table for (and uncertainty associated with) 2a, should combine all the sub-level uncertainties (and any additional uncertainty intrinsic to step 2a). In turn, the contribution table for contributor 2, should include all uncertainties in its sub-levels.

Therefore, only the top level identifiers (1, 2, 3, etc.) shown in bold in the summary table need be combined to produce the overall product uncertainty. The branches can therefore be considered in isolation, for the more complex traceability chains, with the top level contribution table transferred to the main chain. For instance, see Figure 2 & Figure 3 as an example of how the chain can be divided into a number of diagrams for clearer representation.

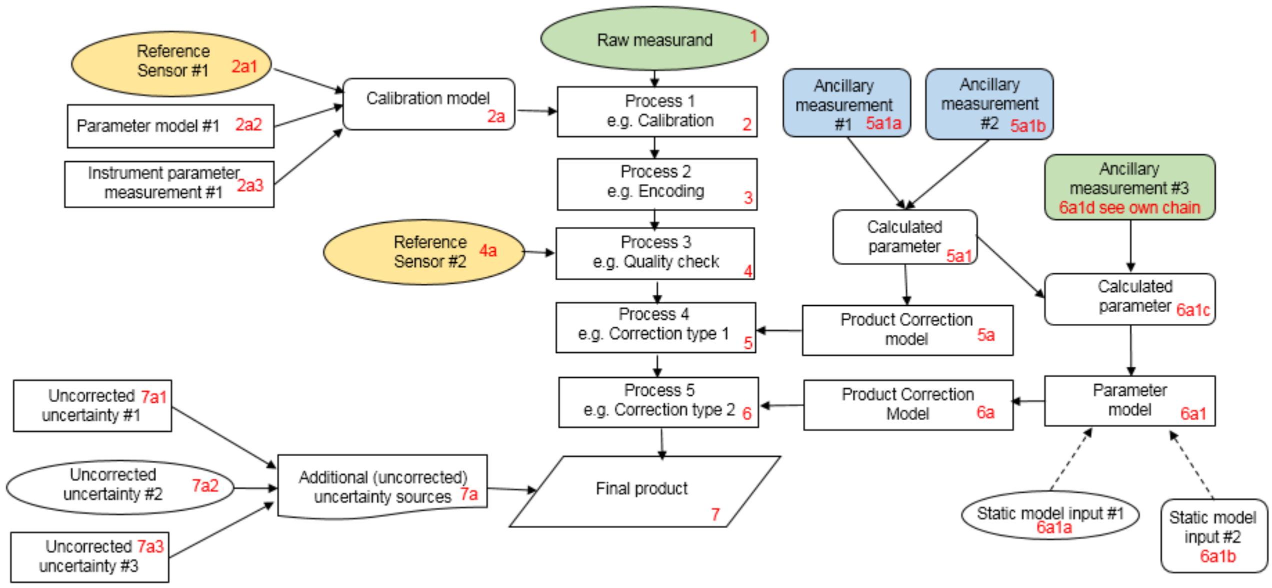

Figure 1. Example traceability chain. Green represents a key measurand or ancillary measurand recorded at the same time with the product raw measurand. Yellow represents a source of traceability. Blue represents a static ancillary measurement

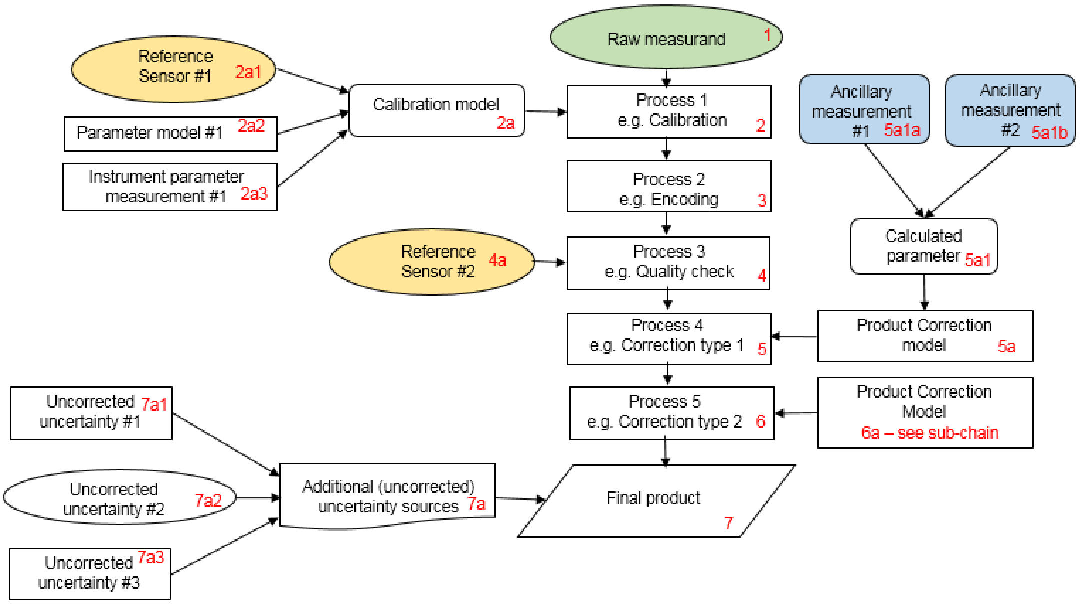

Figure 2. Example chain as sub-divided chain. Green represents a key measurand or ancillary measurand recorded at the same time with the product raw measurand. Yellow represents a source of traceability. Blue represents a static ancillary measurement

When deciding where to create an additional sub-level, the most appropriate points to combine the uncertainties of sub-contributions should be considered, with additional sub-levels used to illustrate where their contributions are currently combined in the described process.

A short note on colour coding. Colour coding can/should be used to aid understanding of the key contributors, but we are not suggesting a rigid framework at this time. In Figure 1, green represents a key measurand or ancillary or complementary measurand recorded at the same time with the raw measurand; yellow represents a primary source of traceability & blue represents a static ancillary measurement (site location, for instance). Any colour coding convention you use, should be clearly described.

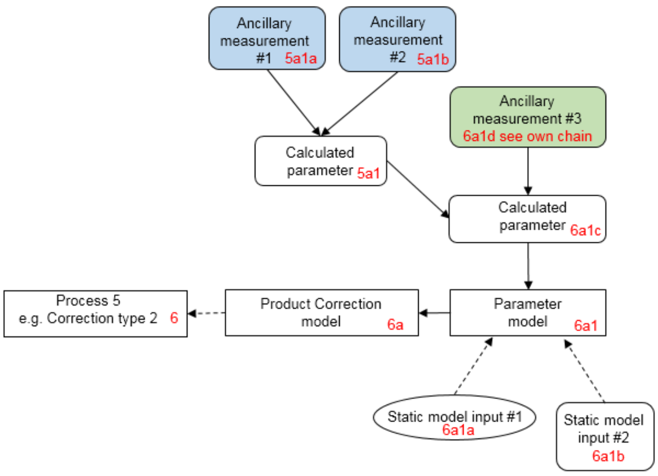

Figure 3. Example chain contribution 6a sub-chain. Green represents a key measurand or ancillary measurand recorded at the same time with the product raw measurand. Blue represents a static ancillary measurement

The contribution table to be filled for each traceability contributor has the form seen in Table 1.

Table 1. The contributor table.

Information / data	Type / value / equation	Notes / description
Name of effect		
Contribution identifier		
Measurement equation parameter(s) subject to effect		
Contribution subject to effect (final product or sub-tree intermediate product)		
Time correlation extent & form		
Other (non-time) correlation extent & form		
Uncertainty PDF shape		
Uncertainty & units		
Sensitivity coefficient		
Correlation(s) between affected parameters		
Element/step common for all sites/users?		
Traceable to …		
Validation		

Name of effect – The name of the contribution. Should be clear, unique and match the description in the traceability diagram.

Contribution identifier - Unique identifier to allow reference in the traceability chains.

Measurement equation parameter(s) subject to effect – The part of the measurement equation influenced by this contribution. Ideally, the equation into which the element contributes.

Contribution subject to effect – The top level measurement contribution affected by this contribution. This can be the main product (if on the main chain), or potentially the root of a side branch contribution. It will depend on how the chain has been sub-divided.

Time correlation extent & form – The form & extent of any correlation this contribution has in time.

Other (non-time) correlation extent & form – The form & extent of any correlation this contribution has in a non-time domain. For example, spatial or spectral.

Uncertainty PDF shape – The probability distribution shape of the contribution, Gaussian/Normal Rectangular, U-shaped, log-normal or other. If the form is not known, a written description is sufficient.

Uncertainty & units – The uncertainty value, including units and confidence interval. This can be a simple equation, but should contain typical values.

Sensitivity coefficient – Coefficient multiplied by the uncertainty when applied to the measurement equation.

Correlation(s) between affected parameters – Any correlation between the parameters affected by this specific contribution. If this element links to the main chain by multiple paths within the traceability chain, it should be described here. For instance, SZA or surface pressure may be used separately in a number of models & correction terms that are applied to the product at different points in the processing. See Figure 1, contribution 5a1, for an example.

Element/step common for all sites/users – Is there any site-to-site/user-to-user variation in the application of this contribution?

Traceable to – Describe any traceability back towards a primary/community reference.

Validation – Any validation activities that have been performed for this element?

The summary table, explanatory notes and referenced material in the traceability chain should occupy <= 1 page for each element entry. Once the summary tables have been completed for the full end-to-end process, the uncertainties can be combined, allowing assessment of the combined uncertainty, relative importance of the contributors and correlation scales both temporally and spatially. The unified form of this technical document should then allow easy comparison of techniques and methods.

2 Introduction

This document contains the product traceability and uncertainty information for the Global Climate Observing System (GCOS) Reference Upper-Air Network (GRUAN) Vaisala RS92 radiosonde relative humidity product.

The RS92 radiosonde measure relative humidity using two Humicaps which contain a hydro active polymer thin-film dielectric between two electrodes on a glass substrate. There is no protective cap on the humidity sensor but the two Humicaps are alternately heated to prevent icing. This heating is switched off below -60 ^{o}C or above 100 hPa, whichever is reached first, to prevent overheating. The Humicaps are initially calibrated at Vaisala's CAL4 facility and before launch there is a ground check with a GC25 unit and ideally a second ground check using a Standard Humidity Chamber (SHC). The raw relative humidity data is corrected for a temperature-related dry bias, radiative heating of the sensor and time lag experienced by the sensor at low temperatures. Vaisala and GRUAN processing both use the Hyland and Wexler 1983 formulation of saturation vapour pressure over water.

The GRUAN data processing was developed to meet the requirements of reference measurements including the collection of metadata, documentation of applied algorithms and estimates of uncertainty. The process by which the GRUAN processing collects raw relative humidity data as well as the calibrations and corrections applied are described in the paper Dirksen et al. 2014, which has been used in the creation of this document. The estimates for uncertainty provided here are those given in Dirksen et al. 2014[1] except in the case of elements where no uncertainty estimate is given where they have been calculated using the methods they describe. Dirksen et al. gives an estimate for total uncertainty in relative humidity of ±6 % RH.

3 Product Traceability Chain

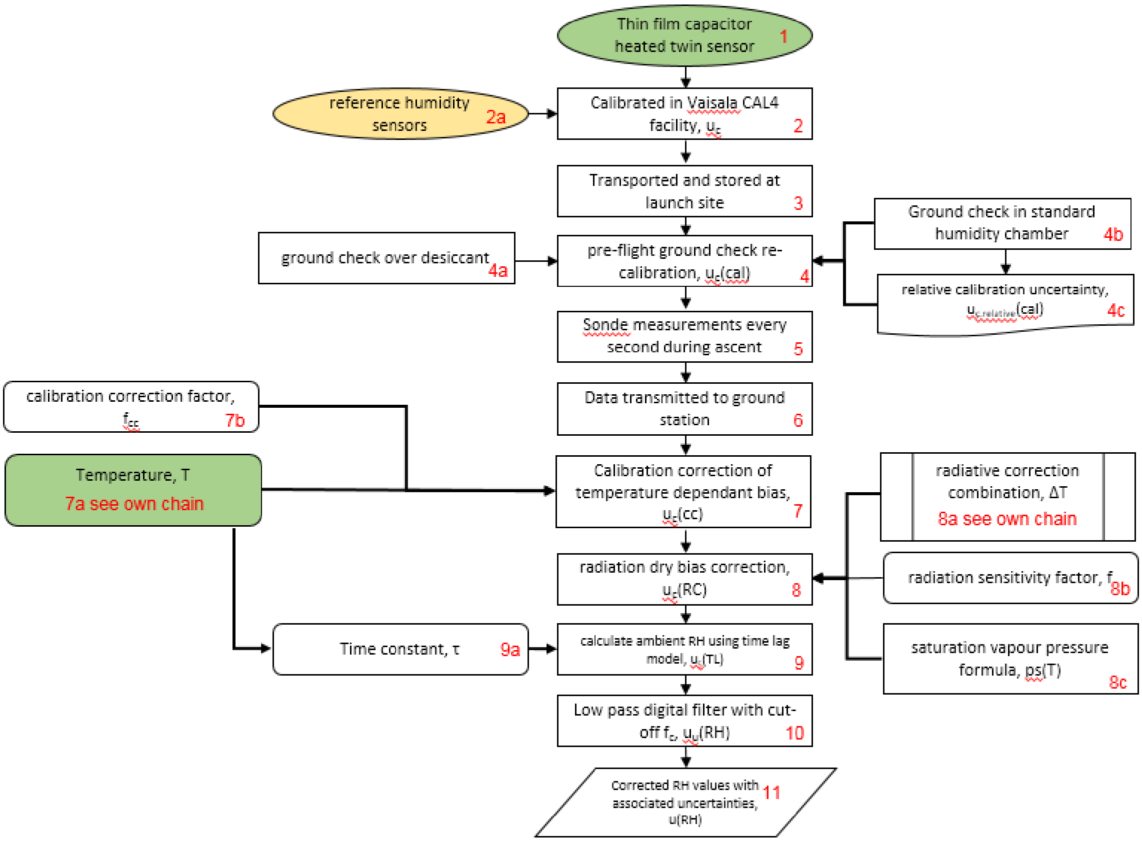

Figure 4 the traceability chain of the GRUAN relative humidity product excluding the radiative correction sub chain.

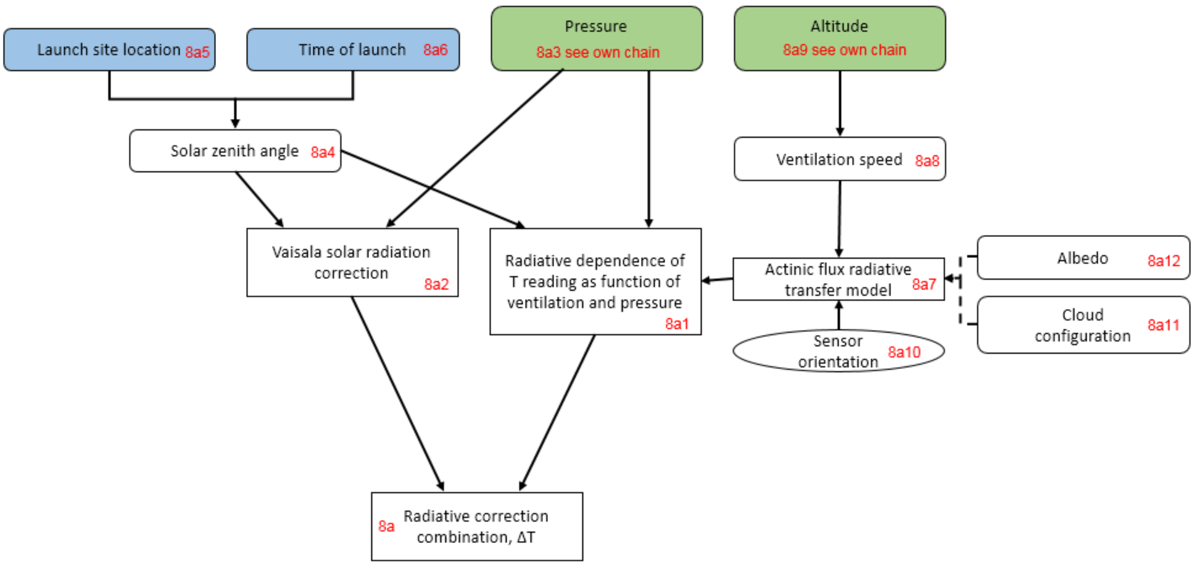

Figure 5 the radiative correction sub chain of the traceability chain for the GRUAN relative humidity product.

4 Element Contributions

4.1 Thin film capacitor heated twin sensor (1)

The Vaisala RS92 radiosonde carries two thin film polymer capacitive moisture sensors and the measurements from these sensors are merged. These have a thin polymer layer between two porous electrodes. Water molecules are captured at binding sites in the polymer, altering the capacitance of the sensor. The number of occupied binding sites is proportional to the ambient air water vapour density. The sensors have a measurement range of 0 to 100 % RH and a resolution of 1 % RH.

The uncertainty shown here is the reproducibility in soundings determined by Vaisala using the standard deviation between twin soundings as determined by Vaisala[2], although it is not used in the GRUAN product uncertainty, but GRUAN calculate the equivalent elsewhere in 10.

Information / data	Type / value / equation	Notes / description
Name of effect	Thin film capacitor heated twin sensor reproducibility	Multiple sounding std dev.
Contribution identifier	1	
Measurement equation parameter(s) subject to effect	Relative Humidity. RH' = RH	
Contribution subject to effect (final product or sub-tree intermediate product)	Relative Humidity.	
Time correlation extent & form	point-to-point	
Other (non-time) correlation extent & form	None.	
Uncertainty PDF shape	Normal.	
Uncertainty & units (2σ)	2 % RH	Reproducibility in sounding.
Sensitivity coefficient	1	Not used in the GRUAN uncertainty calculation. An equivalent calculated in step 10 is used instead.
Correlation(s) between affected parameters	None.	
Element/step common for all sites/users?	Yes	
Traceable to …	Vaisala	
Validation		

4.2 Calibrated in Vaisala CAL4 facility (2), u_c

Vaisala's CAL4 calibration facility has four chambers dedicated to humidity calibration operating at relative humidities between 0 % RH and over 90 % RH and a fifth chamber used to check humidity readings at low temperatures. Dew point meters which are calibrated every 12 months are used as humidity measurement references (see 2a). The relative humidity of the chambers are calculated using the measured dew point temperature and chamber temperature. The temperature references are calibrated every 6 months[3].

The calibration uncertainty is determined by Vaisala using the measurement uncertainties and the process uncertainties.

Information / data	Type / value / equation	Notes / description
Name of effect	Calibrated in Vaisala CAL4 facility	
Contribution identifier	2, u_c	
Measurement equation parameter(s) subject to effect	Relative Humidity RH' = aRH + b	Assumed measurement equation
Contribution subject to effect (final product or sub-tree intermediate product)	Relative Humidity	
Time correlation extent & form	Long term	Reference hygrometers are calibrated every 12 months.
Other (non-time) correlation extent & form	Over sounding	
Uncertainty PDF shape	normal	
Uncertainty & units (2σ)	2 % RH	Repeatability in calibration
Sensitivity coefficient	1	
Correlation(s) between affected parameters	none	
Element/step common for all sites/users?	Yes	
Traceable to …	Reference humidity sensors.	2a
Validation		

4.3 Reference Humidity Sensors (2a)

High precision dewpoint hygrometers are used as reference sensors for humidity. These are calibrated every 12 months in the Finnish National Measurements Standards Laboratory for Humidity (MIKES)[3].

Figure 6 shows the year-on-year variation in calibration bias for each batch of Vaisala sondes.

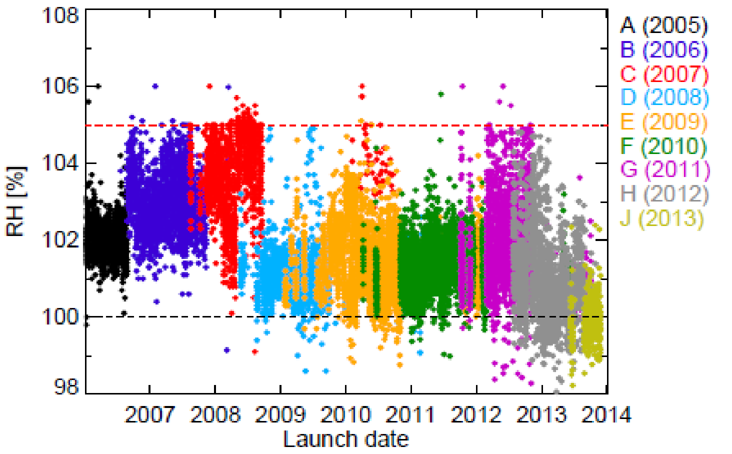

Figure 12. Time series of reading of the RS92 humidity sensor when inserted in the SHC (100 % relative humidity) prior to launch, as part of the additional manufacturer-independent ground check. The colours depict the radiosonde's production year. The black dashed line represents the 100 % level, whereas the red dashed line indicates 105 %, the rejection criterion for humidity readings in the SHC.

Figure 6. Dirksen 2014, figure 12.

Information / data	Type / value / equation	Notes / description
Name of effect	Reference humidity sensors.	
Contribution identifier	2a	
Measurement equation parameter(s) subject to effect	Relative Humidity RH' = RH	
Contribution subject to effect (final product or sub-tree intermediate product)	Calibration in CAL4 facility.	
Time correlation extent & form	Long term	Calibrated every 12 months, temperature references calibrated every 6 months
Other (non-time) correlation extent & form	Over sounding	
Uncertainty PDF shape	normal	
Uncertainty & units (2σ)	0.8 % RH @ 0 % RH to 90 % RH calibration. 1.2 % RH, 30 % RH at -33 °C check.	From Vaisala 2002.
Sensitivity coefficient	unknown	Included in given Vaisala calibration uncertainty.
Correlation(s) between affected parameters	None	
Element/step common for all sites/users?	Yes.	
Traceable to …	MIKES	http://www.mikes.fi/en/services-

		for-industry/calibration-services
Validation		

4.4 Transported and stored at Launch Site (3)

Impurities can build up on the RS92 sensor boom during storage but these should be removed by heating the sensor boom before launch. Therefore in the GRUAN data processing it is assumed that transportation and storage do not attribute to the uncertainty of the measurements [1].

Information / data	Type / value / equation	Notes / description
Name of effect	Transported and stored at launch site.	
Contribution identifier	3	
Measurement equation parameter(s) subject to effect	Relative Humidity	
Contribution subject to effect (final product or sub-tree intermediate product)	Relative Humidity	
Time correlation extent & form	none	Proportional to length of storage
Other (non-time) correlation extent & form	none	
Uncertainty PDF shape	none	
Uncertainty & units (1σ)	0	
Sensitivity coefficient	0	
Correlation(s) between affected parameters	none	
Element/step common for all sites/users?	Yes.	
Traceable to …	n/a	
Validation		

4.5 Pre-flight Ground Check Recalibration (4), $u_c(cal)$

The GRUAN ground check includes a check over desiccant using the Vaisala GC25 unit and an advised check using a Standard Humidity Chamber (SHC). The uncertainty in the ground check calibration is calculated from these ground checks and from Vaisalas initial calibration. If no ground check is performed the uncertainty defaults to 4 % RH.

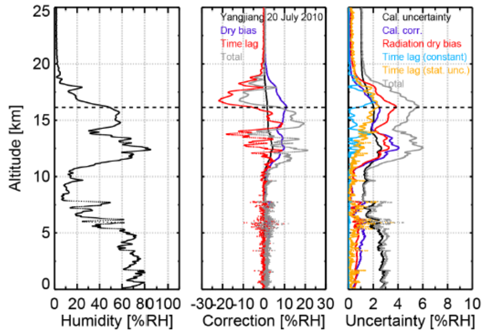

Figure 16. Corrections and their estimated uncertainties to the relative humidity. Left panel: humidity profile. Middle panel: profiles of the corrections for the temperature-dependent calibration correction (black), radiation dry bias (blue), and time-lag (red). The grey trace represents the total correction. Right panel: estimates of the total uncertainty (grey) and the various contributions due to the correction for calibration uncertainty (black), the correction for the temperature-dependent calibration correction (blue), radiation dry bias (red), time-lag constant $u(\tau)$ (light blue), and the statistical uncertainty of the time-lag correction (orange). The horizontal dashed line at 16.1 km represents the tropopause.

Figure 7 Dirksen 2014, figure 16

Information / data	Type / value / equation	Notes / description
Name of effect	Pre-flight Ground check recalibration	
Contribution identifier	4, $u_c(Cal)$	
Measurement equation parameter(s) subject to effect	Relative Humidity	
Contribution subject to effect (final product or sub-tree intermediate product)	Relative Humidity	
Time correlation extent & form	Long term	Between replacement of the desiccant used in the GC25 unit.
Other (non-time) correlation extent & form	Over sounding	
Uncertainty PDF shape	normal	
Uncertainty & units (2σ)	$u_c(Cal) = \sqrt{u_c^2 + u_{c,GC25}^2 + u_{c,absolute\ SHC}^2 + u_{c,relative}^2(Cal)RH}$	2-3 % RH, from Dirksen et al. figure 16, see figure 4.
Sensitivity coefficient	1	

Correlation(s) between affected parameters		
Element/step common for all sites/users?	yes	
Traceable to …	Vaisala calibration, GC25, SHC	
Validation		

4.6 Ground Check over Desiccant (4a), $u_{c,GC25}$

The readings of the radiosonde over a desiccant in near 0 % RH are used to determine possible drifts in the calibration of the sensors. The sensor readings are usually around 0.1 % RH after the desiccant is replaced but drift over time up to 1 % RH, indicating that they can detect the degradation of the desiccant. Because of this the ground check readings are not used to recalibrate the humidity sensors as in the standard Vaisala data processing, but are used in quality checks and the uncertainty estimate.

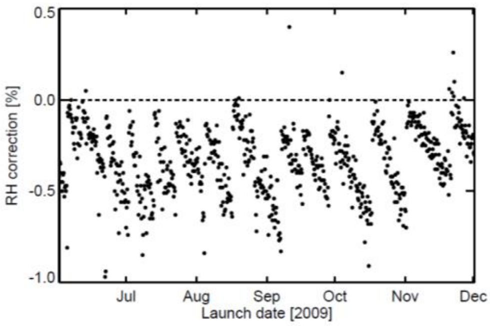

Figure 11. RH-sensor recalibration during ground check in the GC25 for RS92 radiosondes launched at Lindenberg in the second half of 2009. The desiccant is replaced bi-weekly, or when the re-calibration exceeds 1 % RH.

Figure 8 Dirksen 2014, figure 11

Information / data	Type / value / equation	Notes / description
Name of effect	Ground check over desiccant	
Contribution identifier	4a, $u_{c,GC25}$	
Measurement equation parameter(s) subject to effect	Corrected RH values with associated uncertainty	
Contribution subject to effect (final product or sub-tree intermediate product)	Pre-flight ground check recalibration	
Time correlation extent & form	Long term	Over length of time between replacement of the desiccant.
Other (non-time) correlation extent & form	Over sounding	
Uncertainty PDF shape	rectangular	

Uncertainty & units (2σ)	$u_{c,GC25} = \sqrt{(\frac{\Delta U_1}{3})^2 + (\frac{\Delta U_2}{3})^2 + (U_1 - U_2)^2_{GC25}}$	<1 % RH. ΔU is usually less than 0.5 % RH. (Dirksen et al figure 11, see figure 5).
Sensitivity coefficient	1	
Correlation(s) between affected parameters		
Element/step common for all sites/users?	Yes	
Traceable to …		
Validation		

4.7 Ground check in Standard Humidity Chamber (4b), $u_{c,absolute\ SHC}$

The SHC contains saturated (100 % RH) air above distilled water. Supersaturation is not expected because of condensation nuclei present in the ambient air. The uncertainty determined from the SHC check has an absolute and relative part. The absolute part is calculated from the difference between the two humidity sensor readings while in the SHC. Using a SHC during ground check is advised but not possible at every GRUAN site. In cases where the SHC check is not possible, 2.5 % RH is added to the calibration uncertainty.

Information / data	Type / value / equation	Notes / description
Name of effect	Ground check in standard humidity chamber	
Contribution identifier	4b, $u_{c,absolute\ SHC}$	
Measurement equation parameter(s) subject to effect	Relative Humidity	
Contribution subject to effect (final product or sub-tree intermediate product)	Pre-flight ground check re-calibration	
Time correlation extent & form	none	
Other (non-time) correlation extent & form	Over sounding	
Uncertainty PDF shape	Triangular	
Uncertainty & units (2σ)	$u_{c,absolute\ SHC} = \sqrt{(U_1 - U_2)^2_{SHC}}$	U can be between 99 % RH and 105 % RH (Dirksen et al. figure 12, see figure 2).
Sensitivity coefficient	1	
Correlation(s) between affected parameters	Relative calibration uncertainty	
Element/step common for all sites/users?	no	A pre-flight check using a SHC is recommended but not possible at every site.

Traceable to …		
Validation		

4.8 Relative Calibration uncertainty (4_c) $u_{c,relative}(cal)$

The relative calibration uncertainty is using the difference between the readings of the two humidity sensors inside the SHC and the expected reading of 100 % RH.

Information / data	Type / value / equation	Notes / description
Name of effect	Relative calibration uncertainty	
Contribution identifier	4c, $u_{c,relative}(cal)$	
Measurement equation parameter(s) subject to effect	Relative Humidity	
Contribution subject to effect (final product or sub-tree intermediate product)	Pre-flight ground check re-calibration	
Time correlation extent & form	none	
Other (non-time) correlation extent & form	Throughout sounding	
Uncertainty PDF shape		
Uncertainty & units (2σ)	$u_{c,relative}(cal) = \sqrt{(U_1 - U_{SHC})^2 + (U_2 - U_{SHC})^2} / U_{SHC}$	Recently produced sondes usually have a U of <102 % RH (Dirksen et al. figure 12) and U_{SHC} = 100 %, giving an uncertainty of 0.028*RH.
Sensitivity coefficient	1	
Correlation(s) between affected parameters	Ground check in the Standard Humidity Chamber	
Element/step common for all sites/users?	No	
Traceable to …		
Validation		

4.9 Sonde measurements every second during ascent (5)

The uncertainty in these measurements is the statistical noise of the measurements, here represented by the standard deviation.

Information / data	Type / value / equation	Notes / description

Name of effect	Sonde measurements every second during ascent.	
Contribution identifier	5, σ(RH)	
Measurement equation parameter(s) subject to effect	Relative Humidity	
Contribution subject to effect (final product or sub-tree intermediate product)	Relative Humidity	
Time correlation extent & form	none	
Other (non-time) correlation extent & form	none	
Uncertainty PDF shape	normal	
Uncertainty & units (1σ)	0.5 – 1 % RH	Standard deviation of measurements.
Sensitivity coefficient	1	Not used in final combination
Correlation(s) between affected parameters	none	
Element/step common for all sites/users?	yes	
Traceable to …		
Validation		

4.10 Data Transmitted to Ground Station (6)

It is assumed there are no issues/uncertainties associated with data transmission from the radiosonde to the ground station.

Information / data	Type / value / equation	Notes / description
Name of effect	Data Transmitted to ground station.	
Contribution identifier	6	
Measurement equation parameter(s) subject to effect	Relative humidity	
Contribution subject to effect (final product or sub-tree intermediate product)	Relative humidity	
Time correlation extent & form	none	
Other (non-time) correlation extent & form	none	
Uncertainty PDF shape	none	
Uncertainty & units (1σ)	0 % RH	

Sensitivity coefficient	1	Not used in final combination
Correlation(s) between affected parameters	none	
Element/step common for all sites/users?	yes	
Traceable to …		
Validation		

4.11 Calibration Correction of Temperature Dependent Bias (7), $u_c(cc)$

The RS92 radiosonde has a temperature-dependant dry bias that cannot be attributed to radiative heating or time-lag and is attributed to inaccuracies in the Vaisala calibration of the humidity sensors[4]. This dry bias is predominantly between -40 and -60 °C and peaks at around -50 °C. The GRUAN processing corrects the dry bias by multiplying by a correction factor interpolated between reference points shown in table 1.

Table 2 Parameters for the temperature-dependent calibration correction of humidity values, from Dirksen et al. table 3.

Temperature (°C)	20	0	-15	-30	-50	-60	-70	-100
Correction Factor, f_{cc}	1.00	1.00	1.02	1.04	1.06	1.07	1.05	1.00
Uncertainty, $u(f_{cc})$	0.01	0.02	0.03	0.03	0.06	0.07	0.05	0.10

Information / data	Type / value / equation	Notes / description
Name of effect	Calibration of temperature dependent bias.	
Contribution identifier	7, $u_c(cc)$	
Measurement equation parameter(s) subject to effect	$RH^* = f_{cc}\, RH$	RH* are the corrected RH values.
Contribution subject to effect (final product or sub-tree intermediate product)	Relative humidity	
Time correlation extent & form	Long term	Between re-assessment of the correction factor
Other (non-time) correlation extent & form	Between reference temperatures.	
Uncertainty PDF shape	normal	
Uncertainty & units (2σ)	$u_c(cc) = \frac{u(f_{cc})}{f_{cc}} RH^*$	Usually about 2 % RH but can peak at 4 % RH.
Sensitivity coefficient	1	
Correlation(s) between affected parameters	Time lag correction	Both have a dependence on T.

Element/step common for all sites/users?	Yes	
Traceable to …		
Validation	Coincident frost-point hygrometer data	

4.12 Temperature (7a), T

The temperature is used to determine the correction factor that is applied to correct the temperature-dependent bias and to determine time constant used in the time-lag correction.

It is assumed that the uncertainty in temperature does not propagate into the uncertainty in relative humidity.

Information / data	Type / value / equation	Notes / description
Name of effect	Temperature	
Contribution identifier	7a, T	
Measurement equation parameter(s) subject to effect	f_{cc}, τ	
Contribution subject to effect (final product or sub-tree intermediate product)	Calibration correction of the temperature dependant bias, time lag correction	
Time correlation extent & form	Long term	
Other (non-time) correlation extent & form	Throughout sounding	
Uncertainty PDF shape	normal	
Uncertainty & units (2σ)	0.15 K (night time) 0.6 K (daytime)	0.02 % RH at night. 0.08 % RH at day.
Sensitivity coefficient	1	Not used in uncertainty assessment.
Correlation(s) between affected parameters	Time constant, τ Calibration correction factor, f_{cc}	
Element/step common for all sites/users?	yes	
Traceable to …	PTU of GRUAN temperature product	
Validation		

4.13 Calibration Correction Factor (7b)

The measured relative humidity is multiplied by a calibration correction factor to correct for the temperature-dependent dry bias.

Information / data	Type / value / equation	Notes / description
Name of effect	Calibration correction factor	
Contribution identifier	7b	
Measurement equation parameter(s) subject to effect	$RH^* = f_{cc}RH$	
Contribution subject to effect (final product or sub-tree intermediate product)	Calibration correction of temperature dependant bias	
Time correlation extent & form	Long term	
Other (non-time) correlation extent & form	Between reference temperatures	
Uncertainty PDF shape	rectangular	
Uncertainty & units (2σ)	0.01 to 0.10 unitless	See table 1
Sensitivity coefficient	RH^*/f_{cc}	
Correlation(s) between affected parameters		
Element/step common for all sites/users?	yes	
Traceable to …		
Validation		

4.14 Radiation dry bias correction (8), $u_c(RC)$

Solar radiation heats the humidity sensor and introduces a dry bias. Relative error can range from 9% at the surface to 50% at 15 km to correct this bias the measured profile is multiplied by a correction factor derived from the ratio of saturation pressure over water in the heated sensor and in ambient air.

$$RH_c = RH_m \frac{p_s(T + f\Delta T)}{p_s(T)}$$

The GRUAN processing uses the Hyland and Wexler 1983 formulation[5] for calculating saturation pressure over water. ΔT is the same as in the correction of the temperature product multiplied by a factor to represent the greater sensitivity of the humidity sensor to radiative warming. Because of this sections 3.15-3.27 are excerpted from the temperature PTU document, with some changes made to represent the humidity product.

Information / data	Type / value / equation	Notes / description
Name of effect	Radiation dry bias correction	
Contribution identifier	8	

Measurement equation parameter(s) subject to effect	$RH_c = RH_m \frac{p_s(T + f\Delta T)}{p_s(T)}$	
Contribution subject to effect (final product or sub-tree intermediate product)	Relative humidity	
Time correlation extent & form	Long term, between soundings.	
Other (non-time) correlation extent & form	Over profile	
Uncertainty PDF shape		
Uncertainty & units (2σ)	$u_c(RC) = \sqrt{u_c(RC_f)^2 + u_c(RC_t)^2}$	Can be over 5 % RH for mid-day launches but not present for night time soundings.
Sensitivity coefficient	1	
Correlation(s) between affected parameters	none	
Element/step common for all sites/users?	yes	
Traceable to …		
Validation		

4.15 Radiation correction combination (8a), ΔT

The radiative correction combination is the same as in the GRUAN temperature product. For daytime measurements it is the mean of the GRUAN and Vaisala radiation corrections but at nighttime only the Vaisala correction is used. Because the same temperature correction is used as in the temperature product, sections are the same as in the temperature product document.

Information / data	Type / value / equation	Notes / description
Name of effect	Radiation correction combination	
Contribution identifier	8a, ΔT	
Measurement equation parameter(s) subject to effect	$RH_c = RH_m \frac{p_s(T + f\Delta T)}{p_s(T)}$ Where $\Delta T = \frac{\Delta T_{GRUAN} + \Delta T_{Vaisala}}{2}$	
Contribution subject to effect (final product or sub-tree intermediate product)	Radiation dry bias correction	
Time correlation extent & form	Across soundings	
Other (non-time) correlation extent & form	Throughout profile	
Uncertainty PDF shape	normal	
Uncertainty & units (2σ)	$u_c(RC_T) =$	Low near the surface,

	$RH_m \frac{p_s(T+f(\Delta T+u(\Delta T)))-p_s\,(T+f(\Delta T-u(\Delta T)))}{2*p_s(T)}$	peaks at about 4 % RH near the tropopause for mid-day launches.
Sensitivity coefficient	1	
Correlation(s) between affected parameters	Radiation sensitivity factor	
Element/step common for all sites/users?	yes	
Traceable to …	Vaisala temperature correction	
Validation		

4.16 Radiative dependence of T reading as function of ventilation and pressure (8a1), $u_{c,RC(\Delta T)}$

During daytime the radiosonde sensor boom is heated by solar radiation, which introduces biases in temperature and humidity. The net heating of the temperature sensor depends on the amount of absorbed radiation and on the cooling by thermal emission and ventilation by air flowing around the sensor. Luers[6] used customized radiative transfer calculations and detailed information on the actual cloud configuration to accurately compute the radiation temperature error for selected soundings.

$$\Delta T(I_a, p, v) = a \cdot x^b \qquad \text{with } x = \frac{I_a}{p \cdot v},$$

a = 0:18 ± 0.03 and b = 0:55 ± 0:06, the uncertainty due to these parameters in a, b and the radiation correction is typically <0.2 K (2σ) daytime only. For nigh time the Vaisala correction of 0.04 K at 5 hPa is used.

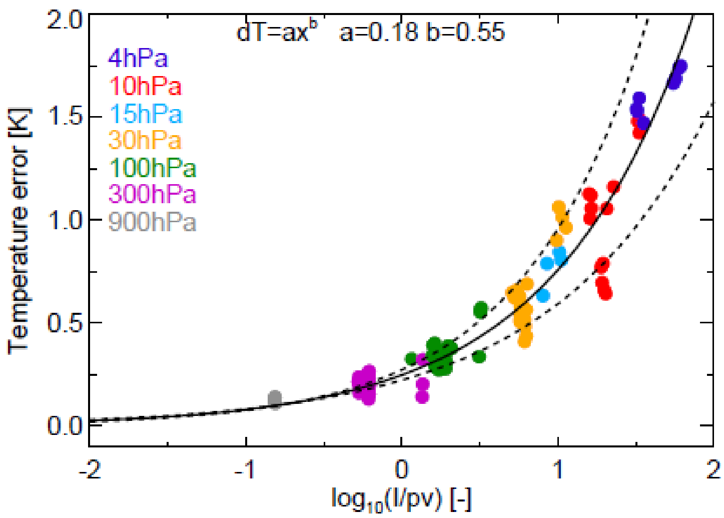

Figure 9. Dirksen et al[1] figure 4

Information / data	Type / value / equation	Notes / description
Name of effect	Radiative dependence of T f(ventilation, pressure)	

Contribution identifier	8a1, $u_{c,RC(\Delta T)}$	
Measurement equation parameter(s) subject to effect	$RH_c = RH_m \frac{p_s(T + f(\frac{\Delta T_{GRUAN} + \Delta T_{Vaisala}}{2}))}{p_s(T)}$ $where\ \Delta T_{GRUAN} = a.\left(\frac{I_a}{p.v}\right)^b$	
Contribution subject to effect (final product or sub-tree intermediate product)	Radiation correction	
Time correlation extent & form	None	Point to point correction
Other (non-time) correlation extent & form	N/A	
Uncertainty PDF shape	Normal	
Uncertainty & units (1σ)	0.5 % RH	Combination of uncertainty from pressure (8a3) and ventilation (8a8) uncertainties.
Sensitivity coefficient	1	
Correlation(s) between affected parameters	None	
Element/step common for all sites/users?	Yes	
Traceable to …		
Validation		

4.17 Vaisala radiation correction (8a2), $\Delta T_{Vaisala}$

The Vaisala correction for the radiation temperature error is available as a table for various pressures and solar elevation angles [7]. The ascent speed is assumed to be 5 m/s, so does not use the measured values.

There is no separate uncertainty associated with the DigiCora correction in Dirksen et al [1]. However, validation experiments shows a standard deviation of 0.1 K in the troposphere, rising to between 0.3 K and 0.4 K in the stratosphere.

Temperature sensor solar radiation correction table RSN2010

	Elevation angle, degrees									
	Night	-4	-2	0	3	10	30	45	60	90
Sea level	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.07	0.09	0.10
500 hPa	0.00	0.00	0.00	0.00	0.00	0.04	0.12	0.15	0.17	0.19
200 hPa	0.00	0.00	0.00	0.02	0.05	0.20	0.25	0.27	0.29	0.31
100 hPa	0.00	0.00	0.06	0.11	0.20	0.32	0.36	0.37	0.38	0.39
50 hPa	0.00	0.00	0.21	0.28	0.35	0.45	0.46	0.47	0.48	0.48
20 hPa	-0.02	0.05	0.37	0.45	0.51	0.60	0.60	0.60	0.60	0.60
10 hPa	-0.03	0.18	0.48	0.55	0.59	0.69	0.69	0.69	0.69	0.69
5 hPa	-0.04	0.37	0.56	0.64	0.70	0.78	0.78	0.78	0.78	0.78
2 hPa	-0.06	0.55	0.68	0.77	0.84	0.89	0.89	0.89	0.89	0.89
1 hPa	-0.07	0.64	0.77	0.86	0.94	0.98	0.98	0.98	0.98	0.98

NOTES:

- RS92 solar radiation correction table RSN2010 for DigiCORA® Sounding Software version 3.64
- The correction values in the table are as a function of pressure and sun elevation angle. Actual correction takes into account radiosonde ventilation in flight, presented table values are calculated for typical 5 m/s ventilation.
- The corrections are subtracted from the measured temperature.

Figure 10. DigiCora radiation correction table[8]

Information / data	Type / value / equation	Notes / description
Name of effect	Vaisala radiation correction	
Contribution identifier	8a2, $\Delta T_{Vaisala}$	
Measurement equation parameter(s) subject to effect	$RH_c = RH_m \frac{p_s(T + f(\frac{\Delta T_{GRUAN} + \Delta T_{Vaisala}}{2}))}{p_s(T)}$	
Contribution subject to effect (final product or sub-tree intermediate product)	Radiation dry bias correction	
Time correlation extent & form	None	
Other (non-time) correlation extent & form	None	
Uncertainty PDF shape	Normal	
Uncertainty & units (1σ)	Up to 4 % RH below the tropopause, 1 % RH above it.	Based on sensitivity tests using change of 0.1 K below the tropopause to 0.4 K above.
Sensitivity coefficient	1	Unused in final calculation.
Correlation(s) between affected parameters	None	
Element/step common for all sites/users?	Yes	
Traceable to …		

Validation	Vaisala validation experiments	

4.18 Pressure (8a3)

The pressure derived from the GRUAN sonde pressure measurement is used in both the GRUAN and Vaisala solar radiation correction models.

The quoted pressure uncertainty is ±0.2 hPa (1σ). When applied to the GRUAN solar correction model the typical temperature uncertainties are <0.001 K (1σ) in the troposphere, rising to ±0.03 K (1σ) in the stratosphere. See the GRUAN pressure product traceability uncertainty document for details of this uncertainty contribution.

Information / data	Type / value / equation	Notes / description
Name of effect	Pressure	
Contribution identifier	8a3	
Measurement equation parameter(s) subject to effect	Input into both solar radiation correction models	For the GRUAN correction takes form $\Delta T(I_a, p, v) = a \cdot x^b \quad \text{with } x = \frac{I_a}{p \cdot v},$
Contribution subject to effect (final product or sub-tree intermediate product)	Radiation dry bias correction	
Time correlation extent & form	Systematic over part of ascent	
Other (non-time) correlation extent & form	Systematic over part of ascent	
Uncertainty PDF shape	Normal & offset	
Uncertainty & units (2σ)	0.0035 % RH below the tropopause and <0.05 % RH above.	Based on sensitivity tests using 0.001 K below the tropopause and 0.03 K above.
Sensitivity coefficient	1	Unused in final calculation.
Correlation(s) between affected parameters	Altitude	
Element/step common for all sites/users?	Yes	
Traceable to …		
Validation		

4.19 Solar Zenith Angle (8a4)

The uncertainty is not considered separately, but is effectively incorporated into the 8a2 Actinic flux radiative transfer model fit uncertainty.

Information / data	Type / value / equation	Notes / description
Name of effect	Solar Zenith Angle	
Contribution identifier	8a4	
Measurement equation parameter(s) subject to effect	-	
Contribution subject to effect (final product or sub-tree intermediate product)	Actinic flux radiative transfer model	
Time correlation extent & form	None	
Other (non-time) correlation extent & form	None	
Uncertainty PDF shape	Static	
Uncertainty & units (1σ)	0	
Sensitivity coefficient	1	
Correlation(s) between affected parameters		
Element/step common for all sites/users?		
Traceable to …		
Validation		

4.20 Launch site location (8a5)

The uncertainty is not considered separately.

Information / data	Type / value / equation	Notes / description
Name of effect	Launch site location	
Contribution identifier	8a5	
Measurement equation parameter(s) subject to effect	-	
Contribution subject to effect (final product or sub-tree intermediate product)	SZA	Uses site longitude/latitude & altitude
Time correlation extent & form	None	
Other (non-time) correlation extent & form	None	
Uncertainty PDF shape	Static	

Uncertainty & units (1σ)	0	
Sensitivity coefficient	1	
Correlation(s) between affected parameters		
Element/step common for all sites/users?		
Traceable to …		
Validation		

4.21 Time of launch (8a6)

The uncertainty is not considered separately.

Information / data	Type / value / equation	Notes / description
Name of effect	Time of launch	
Contribution identifier	8a6	
Measurement equation parameter(s) subject to effect	-	
Contribution subject to effect (final product or sub-tree intermediate product)	SZA	
Time correlation extent & form	None	
Other (non-time) correlation extent & form	None	
Uncertainty PDF shape	Static	
Uncertainty & units (1σ)	0	
Sensitivity coefficient	1	
Correlation(s) between affected parameters		
Element/step common for all sites/users?		
Traceable to …		
Validation		

4.22 Actinic flux radiative transfer model (8a7)

The dominant systematic error is due to solar radiative heating. Using a heat transfer model, the radiative error for the RS92 temperature sensor was estimated to be approximately 0.5 K at 35 km[9]. This number is comparable to the correction of up to 0.63 K at 5 hPa that was applied by the DigiCora software (prior to version 3.64) in the pro- cessing of RS92 routine soundings until 2010, when this was increased to 0.78 K[10].

The 8th World Meteorological Organization (WMO) radiosonde intercomparison in Yangjiang, China, indicates that the Vaisala-corrected temperature measurements of the RS92 may exhibit a warm bias of up to 0.2 K[11].

A recent comparison between radiosoundings and spaceborne GPS radio occultation measurements reports a 0.5–1K warm bias at 17 hPa for Vaisala-corrected RS92 temperature profiles[12]. The accuracy of the satellite-retrieved temperature is approximately 0.2–0.3K in the middle stratosphere[13,14].

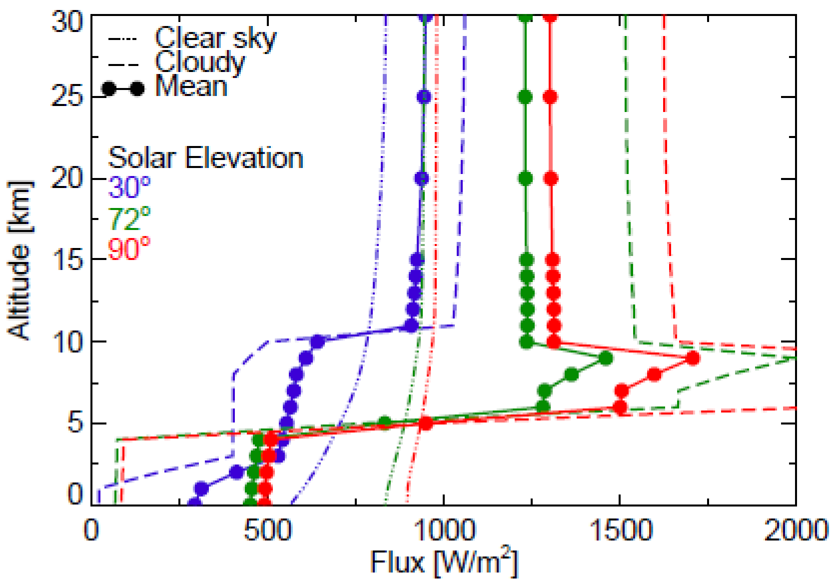

Figure 11. Dirksen figure 5

Information / data	Type / value / equation	Notes / description
Name of effect	Actinic flux model	
Contribution identifier	8a7	
Measurement equation parameter(s) subject to effect	Radiation correction temperature correction $$\Delta T = a.\left(\frac{I_a}{p.v}\right)^b$$	
Contribution subject to effect (final product or sub-tree intermediate product)	Radiation correction	
Time correlation extent & form	Corrected point by point. correlates with time of day (SZA)	
Other (non-time) correlation extent & form	None	
Uncertainty PDF shape	Rectangular	

Uncertainty & units (2σ)	60-250 W/m^2 in the troposphere, 30-200 W/m^2 in the stratosphere dependant on SZA	$$u(I_a) = \frac{\lvert I_{a,\,\text{cloudy}} - I_{a,\,\text{clear sky}} \rvert}{2\sqrt{3}}.$$ Low end of range at low SZA, high end of range at high SZA
Sensitivity coefficient	$\Delta T \sim {I_a}^b$	
Correlation(s) between affected parameters	SZA	
Element/step common for all sites/users?	Yes	
Traceable to …		
Validation		

4.23 **Ventilation speed (8a8) u_v & $u_{vent(\Delta T)}$**

The correction of the radiation temperature error also depends on the ventilation speed v. The temperature correction is a function of pressure & ventilation speed, given in Figure 12.

In the GRUAN processing the actual ventilation speed is used, rather than assuming a fixed value. The actual ventilation speed is the sum of the ascent speed, which is derived from the altitude data, plus an additional contribution due to the sonde's pendulum motion.

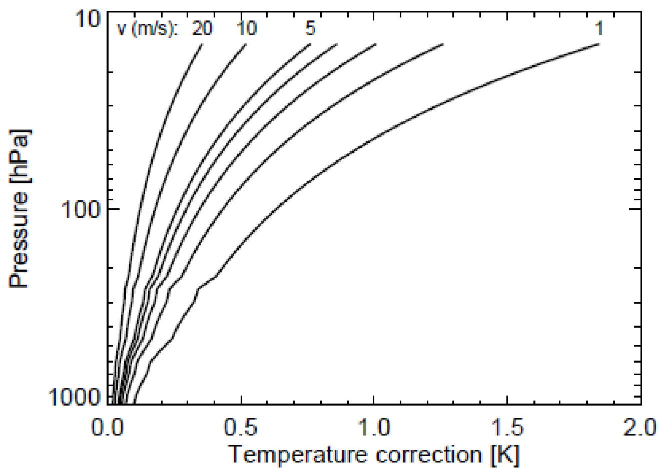

Figure 6. Profiles of the GRUAN radiation temperature correction for ventilation speeds between 1 and 20 m s^{-1}. The correction was calculated for a radiosounding performed in Lindenberg on 17 September 2013 at 12:00 UTC. The kinks in the profiles between 900 and 200 hPa result from the cloud configuration that was used in the Streamer simulations, with cloud layers between 4 and 6 and between 7 and 10 km, which introduces jumps in the simulated radiation profile at the top of the cloud (see the dashed traces in Fig. 5). The maximum solar zenith angle during the sounding was 36.5°.

Figure 12. Ventilation speed temperature correction, from Dirksen et al[1] figure 6

u(v) = ±1m/s (2σ), with the temperature dependence given by:

$$\Delta T \cdot u(v)/v$$

This is equivalent to 0.01 K in the troposphere, rising up to 0.3 K in the stratosphere (2σ).

Information / data	Type / value / equation	Notes / description
Name of effect	Ventilation speed correction	
Contribution identifier	8a8, u_v & $u_{vent(\Delta T)}$	
Measurement equation parameter(s) subject to effect	Relative Humidity	
Contribution subject to effect (final product or sub-tree intermediate product)	Radiation correction (8)	$\Delta T \cdot u(v)/v$
Time correlation extent & form	Systematic	Over ascent
Other (non-time) correlation extent & form	Systematic with Altitude measurement and assumed pendulum motion	Correlated to altitude systematic errors.
Uncertainty PDF shape	Rectangular in velocity, but treated as random in ΔT.	Increase in ventilation speed correction is +1 m.s^{-1} ± 1m.s^{-1} suggesting a defined limit uncertainty.
Uncertainty & units (2σ)	u(v) = ±1m/s (2σ), with the temperature dependence given by $\Delta T \cdot u(v)/v$ Equivalent to 0.2-0.4 % Rh below the tropopause and <0.5 % RH above.	Based on sensitivity tests using 0.01 K (in the trop. upto 0.3 K in the strat (2σ)
Sensitivity coefficient	1	
Correlation(s) between affected parameters	Altitude measurement	
Element/step common for all sites/users?	Yes	
Traceable to …		
Validation		

4.24 Altitude (8a9)

Not considered separately – only uncertainty on derived vertilation speed (8a5).

The altitude product from the GRUAN sondes have a typical uncertainty of ±1 m (1σ) in the troposphere, increasing to ±1.5 m (1σ) in the stratosphere.

Information / data	Type / value / equation	Notes / description

Name of effect	Altitude	
Contribution identifier	8a9	
Measurement equation parameter(s) subject to effect	-	
Contribution subject to effect (final product or sub-tree intermediate product)	Ventilation speed	
Time correlation extent & form	None	
Other (non-time) correlation extent & form	None	
Uncertainty PDF shape	Normal	
Uncertainty & units (1σ)	1.5 m	
Sensitivity coefficient	1	Unused in final calculation.
Correlation(s) between affected parameters	None	
Element/step common for all sites/users?	Yes	
Traceable to …	No	
Validation	Ventilation speed validation experiments.	

4.25 Sensor orientation (8a10)

Due to the fact that the RS92 temperature sensor is a wire rather than a sphere, the direct solar flux onto the sensor depends on its orientation. The geometry factor g accounts for the reduction of the exposed area of the temperature sensor due to spinning of the radiosonde, which causes the orientation of the sensor wire to cycle between being parallel and perpendicular to the solar rays. Currently, a value of 0.5 is used for g, but this may change in the next version of the GRUAN processing.

Information / data	Type / value / equation	Notes / description
Name of effect	Sensor orientation	
Contribution identifier	8a10	
Measurement equation parameter(s) subject to effect	-	
Contribution subject to effect (final product or sub-tree intermediate product)	Radiation correction	
Time correlation extent & form	None	
Other (non-time) correlation extent & form	None	
Uncertainty PDF shape	Static	

Uncertainty & units (1σ)	0	
Sensitivity coefficient	1	
Correlation(s) between affected parameters		
Element/step common for all sites/users?		
Traceable to …		
Validation		

4.26 **Cloud configuration (8a11)**

No separate contribution – the uncertainty is effectively included as part of the radiative model fit uncertainty (8a1).

Information / data	Type / value / equation	Notes / description
Name of effect	Cloud configuration	
Contribution identifier	8a11	
Measurement equation parameter(s) subject to effect	-	
Contribution subject to effect (final product or sub-tree intermediate product)	Actinic flux Radiative transfer model	
Time correlation extent & form	None	
Other (non-time) correlation extent & form	None	
Uncertainty PDF shape	Static	
Uncertainty & units (1σ)	0	
Sensitivity coefficient	1	
Correlation(s) between affected parameters		
Element/step common for all sites/users?		
Traceable to …		
Validation		

4.27 **Albedo (8a12) $u_{c,(Ia)}$ & $u_{u,Ia(\Delta T)}$**

$$\Delta T \cdot u_{\mathrm{c}}(I_{\mathrm{a}})/I_{\mathrm{a}}$$

where ΔT is the solar radiation correction term and

$$u_c(I_a) = \frac{1}{2\cdot\sqrt{3}}\left|I_a^{\text{clear sky}} - I_a^{\text{cloudy}}\right|$$

Information / data	Type / value / equation	Notes / description
Name of effect	Albedo	
Contribution identifier	8a12	
Measurement equation parameter(s) subject to effect	Radiation correction temperature correction $$\Delta T = a.\left(\frac{I_a}{p.v}\right)^b$$ Where Albedo is used to determine I_a	
Contribution subject to effect (final product or sub-tree intermediate product)	Radiation correction	
Time correlation extent & form	Corrected point by point. correlates with time of day (SZA)	
Other (non-time) correlation extent & form	None	
Uncertainty PDF shape	Rectangular	
Uncertainty & units (2σ)	0.8 % RH below the tropopause and 0.2 % RH above.	60-250 W/m^2 in the troposphere, 30-200 W/m^2 in the stratosphere dependant on SZA, RH uncertainty found using sensitivity tests using uncertainty in ΔT of <0.05 K (2σ) throughout the ascent.
Sensitivity coefficient	$$\Delta T \sim {I_a}^b$$	
Correlation(s) between affected parameters	SZA	
Element/step common for all sites/users?	Yes	
Traceable to …		
Validation		

4.28 Radiation sensitivity factor (8b), f

The radiation sensitivity factor, f, accounts for the greater sensitivity of the humidity sensor to radiative heating than the temperature sensor[15]. As a result of changes made to the radiosonde design the sensitivity factor depends on the year of production, different values are shown in table 2.

Table 3 Radiative heating sensitivity factor value and uncertainty for different production years

Production year	Sensitivity factor, f	U(f)
<2006	13	4
2006-2008	10	3
2009-present	6.5	2

Information / data	Type / value / equation	Notes / description
Name of effect	Radiation sensitivity factor	
Contribution identifier	8b, f	
Measurement equation parameter(s) subject to effect	$RH_c = RH_m \frac{p_s(T + f\Delta T)}{p_s(T)}$	
Contribution subject to effect (final product or sub-tree intermediate product)	Radiation dry bias correction	
Time correlation extent & form	Across all sondes within production year ranges.	
Other (non-time) correlation extent & form	Over sounding	
Uncertainty PDF shape	normal	
Uncertainty & units (2σ)	$u_c(RC_f) = RH_m \frac{p_s(T+(f+u(f))\Delta T) - p_s(T+(f-u(f))\Delta T)}{2*p_s(T)}$	From 0.5 to 2 % RH below the tropopause and <0.25 % RH above.
Sensitivity coefficient	1	
Correlation(s) between affected parameters	Radiation correction combination.	
Element/step common for all sites/users?	yes	
Traceable to …		
Validation		

4.29 Saturation Vapour Pressure Formula (8c), ps(T)

The radiative dry bias correction uses the Hyland and Wexler formulation of saturation vapour pressure, ps.

$$p_s = \exp[\sum_{i=-1}^{3} h_i T^i + h_4 \ln(T)]$$

Where T is the temperature in kelvin and the coefficients h_i are as shown in table 3.

Table 4 The coefficients used for calculating saturation vapour pressure in the Hyland and Wexler 1983 formulation.

Coefficient	value
h_{-1}	$-0.58002206 \times 10^{4}$
h_0	0.13914993×10^{1}
h_1	$-0.48640239 \times 10^{-1}$
h_2	$0.41764768 \times 10^{-4}$
h_3	$-0.14452093 \times 10^{-7}$
h_4	0.65459673×10^{0}

The uncertainty contribution from using this formulation was determined using sensitivity test with changes in the uncertainty in the radiation correction, calculated as shown in section 4.14 observed for changes in the coefficients. From this it was seen that unless the changes to the coefficients were large enough to affect the fifth significant figure then the changes in the uncertainty of the radiation correction where less than 1% of the overall uncertainty contribution.

Information / data	Type / value / equation	Notes / description
Name of effect	Saturation vapour pressure calculation	
Contribution identifier	8c, ps(T)	
Measurement equation parameter(s) subject to effect	RH = e/ew	
Contribution subject to effect (final product or sub-tree intermediate product)	Radiation dry bias correction	
Time correlation extent & form	Across all soundings	
Other (non-time) correlation extent & form	none	
Uncertainty PDF shape	normal	
Uncertainty & units (1σ)	<0.02 % RH	Assuming the uncertainty in the coefficients only affects beyond the fifth significant figure.
Sensitivity coefficient	1	Unused in final calculation.
Correlation(s) between affected parameters		
Element/step common for all sites/users?	yes	
Traceable to …	Hyland and Wexler 1983	
Validation		

4.30 Time Lag Correction (9), $u_c(TL)$

The response of the humidity sensor slows with decreasing temperature which flattens gradients and smooths structure in the profile. This results from the need for water molecules to diffuse into or out of the sensor[4]. This effect starts to be significant at -40 °C. To correct the time lag the GRUAN processing models it as a low-pass filter with exponential kernel, as shown below:

$$RH_i^m = \frac{\sum_{j=0}^{i} RH_j^a \exp(\frac{t_j - t_i}{\tau_i})}{\sum_{j=0}^{i} \exp(\frac{t_j - t_i}{\tau_i})}$$

Where RH^m is the measured humidity and RH^a is the ambient humidity. T is the temperature dependent time constant and t is time. The correction for the time-lag error then follows from inverting this equation to find RH^a:

$$RH_i^{a^*} = RH_i^m + \sum_{j=0}^{i-1} (RH_i^m - RH_i^{a^*}) \exp(\frac{t_j - t_i}{\tau_i})$$

Where RH^{a*} is the corrected ambient humidity.

The correction of the time-lag as described in section 3.29 is applied to the measured RH humidity profile before the low-pass digital filter. The uncertainty here is the correlated uncertainty of the time-lag correction and results from the uncertainty of the time constant, τ.

Information / data	Type / value / equation	Notes / description
Name of effect	Calculate ambient RH using time-lag model	
Contribution identifier	9, RH^{a*}, $u_c(TL)$	
Measurement equation parameter(s) subject to effect	$RH_i^{a^*} = RH_i^m + \sum_{j=0}^{i-1} (RH_i^m - RH_i^{a^*}) \exp(\frac{t_j - t_i}{\tau_i})$	
Contribution subject to effect (final product or sub-tree intermediate product)	Time lag correction	
Time correlation extent & form	Long-term	
Other (non-time) correlation extent & form	Throughout profile	
Uncertainty PDF shape	rectangular	
Uncertainty & units (2σ)	$u_c(TL) = 0.5\lvert RH(\tau + u(\tau)) - RH(\tau - u(\tau))\rvert$	Usually <0.5 % RH, peaks at 2 % RH. From Dirksen et al. figure 16, see figure 4.

Sensitivity coefficient	1	
Correlation(s) between affected parameters		
Element/step common for all sites/users?		
Traceable to …		
Validation		

4.31 Time constant (9a), τ

The time constant is used to describe the time lag response and it is the time required for the sensor to respond to 63 % of an instantaneous change in ambient relative humidity. The time constant is related to temperature, T.

$$\tau = A * \exp(c_0 + c_1 * T)$$

With the parameters A = 0.8, c_0 = -0.7399, c_1 = -0.07718. It is assumed that the time constant is the same for increasing and decreasing humidity.

Information / data	Type / value / equation	Notes / description
Name of effect	Time constant	
Contribution identifier	9a, τ	
Measurement equation parameter(s) subject to effect	$RH_i^{a^*} = RH_i^m + \sum_{j=0}^{i-1}(RH_i^m - RH_i^{a^*})\exp(\frac{t_j - t_i}{\tau_i})$	
Contribution subject to effect (final product or sub-tree intermediate product)	Time lag correction	
Time correlation extent & form	Long term	
Other (non-time) correlation extent & form	Throughout sounding	
Uncertainty PDF shape		
Uncertainty & units (2σ)	$u(\tau) = 0.5 * \tau(1 - A) \approx 0.1\tau$ or 1.5-3 s	
Sensitivity coefficient	unspecified	
Correlation(s) between affected parameters	Calibration correction factor	Both depend on temperature.
Element/step common for all sites/users?	Yes	

Traceable to …		
Validation		

4.32 Low pass digital filter with cut-off (10), fc

The correction used for the time-lag error also amplifies noise in the profile. This is removed using a low pass digital filter. The cut-off for the filter, $f_c=3/\tau$ and is less than 0.1 Hz. The factor of 3 is to prevent the removal of genuine structures in the profile when τ is large.

The uncertainty is the statistical noise calculated as part of the smoothing step. This is calculated as:

$$u(\bar{s_i}) = \sqrt{\frac{N'}{N'-1} \sum_{j=-M}^{M} c_j^2 (s_{i+j} - \bar{s_i})^2}$$

Where s is the smoothed data point an N' corresponds to the width of the Gaussian-shaped kernel function.

Information / data	Type / value / equation	Notes / description
Name of effect	Low pass digital filter	
Contribution identifier	10, U_u(RH)	
Measurement equation parameter(s) subject to effect	Relative humidity	
Contribution subject to effect (final product or sub-tree intermediate product)	Time lag correction	
Time correlation extent & form	none	
Other (non-time) correlation extent & form	50 points up and down profile	Uses a sample of 100 points.
Uncertainty PDF shape	normal	
Uncertainty & units (2σ)	0.5 – 2 % RH	From Dirksen et al. figure 16, see figure 4.
Sensitivity coefficient	1	
Correlation(s) between affected parameters		
Element/step common for all sites/users?		
Traceable to …		
Validation		

4.33 Corrected RH values with associated uncertainties (11)

The total uncertainty of the corrected relative humidity profile is the sum in quadrature of the calibration, dry bias correction, radiative heating correction, time lag correction and statistical uncertainties.

Information / data	Type / value / equation	Notes / description
Name of effect	Corrected RH values with associated uncertainties.	
Contribution identifier	11,u(RH)	
Measurement equation parameter(s) subject to effect	Relative Humidity	
Contribution subject to effect (final product or sub-tree intermediate product)	Relative Humidity	
Time correlation extent & form	none	
Other (non-time) correlation extent & form	>10s, usually <40s	Varies according to low pass digital filter, available as res_rh.
Uncertainty PDF shape	normal	
Uncertainty & units (2σ)	$u(RH) = \sqrt{u_c(cal)^2 + u_c(cc)^2 + u_c(TL)^2 + u_c(RC)^2 + u_u(RH)^2}$	6 % RH
Sensitivity coefficient	1	
Correlation(s) between affected parameters	none	
Element/step common for all sites/users?	Yes	
Traceable to …		
Validation		

5 Uncertainty Summary

Element identifier	**Contribution name**	**Uncertainty contribution form**	**Typical value**	**Traceability level (L/M/H)**	**Random, structured random, quasi-systematic or systematic?**	**Correlated to**
1	Thin film capacitor heated twin sensor	constant	0	H	random	none
2, u_c	Calibrated in Vaisala CAL4 facility	constant	2 % RH	H	systematic	4
2a	Reference humidity sensors	constant	0.8-1.2 % RH	H	systematic	
3	Transported and stored at launch site	constant	0	L	systematic	none
4, $u_c(cal)$	Pre-flight ground check re-calibration	$\sqrt{u_c^2 + u_{c,GC25}^2 + u_{c,absolute\ SHC}^2 + u_{c,relative}^2}(Cal)RH$	1-3 % RH	H	Quasi-systematic	10
4a, $u_{c,GC25}$	Ground check over desiccant	$\sqrt{(\frac{\Delta U_1}{3})^2 + (\frac{\Delta U_2}{3})^2 + (U_1 - U_2)_{GC25}^2}$	<1 % RH	H	Quasi-systematic	4
4b, $u_{c,absolute\ SHC}$	Ground check in standard humidity chamber	$\sqrt{(U_1 - U_2)_{SHC}^2}$		H	Quasi-systematic	4, 4c
4c, $u_{c,relative}(cal)$	Relative calibration uncertainty	$\sqrt{(U_1 - U_{SHC})^2 + (U_2 - U_{SHC})^2} / U_{SHC}$	0.028* RH	H	Quasi-systematic	4, 4b
5	Sonde measurements every second during ascent	Statistical uncertainty	0.05-0.1 % RH		random	None
6	Data transmitted to ground station	constant	0	L	systematic	None
7, $u_c(cc)$	Calibration correction	$\frac{u(f_{cc})}{f_{cc}} RH^*$	0.5 – 4 % RH		systematic	10

	of temperature dependant bias					
7a	Temperature	See temperature PTU documents				7b,9a2
7b	Calibration correction factor	Constant, interpolated between reference temps	0.01-0.1		systematic	7
8, $u_c(RC)$	Radiation dry bias correction	$\sqrt{u_c(RC_f)^2 + u_c(RC_t)^2}$	5 % RH	M		10
8a, $u_c(RC_T)$	Radiative correction combination	$RH_m \frac{p_s(T+f(\Delta T+u(\Delta T))) - p_s(T+f(\Delta T-u(\Delta T)))}{2 * p_s(T)}$	4 % RH	M	Systematic	8
8a1	Radiative dependence of T reading as a function of ventilation and pressure	constant	0.5 % RH	M	systematic	none
8a2	Vaisala solar radiation correction	constant	1 - 4 % RH	M	systematic	8a1
8a3	Pressure	constant	<0.05 % RH	M	Rand	Press PTU, 8a10
8a4	Solar zenith angle	Constant	0	M	Systematic (over ascent)	
8a5	Launch site location	Constant	0	H	Systematic	
8a6	Time of launch	constant	0	H	Systematic (over ascent)	
8a7, $u(I_a)$	Actinic flux radiative transfer model	$\frac{\lvert I_{a,cloudy} - I_{a,clear\ sky}\rvert}{2\sqrt{3}}$	<350 Wm^{-2}	M	Quasi-systematic	Altitude
8a8, $u_{u,vent}(\Delta T)$	Ventilation speed	$\Delta T(\frac{u(v)}{v})$	<0.5 % RH	M	Quasi-systematic	Altitude
8a9	Altitude	Constant	0	M	Quasi-systematic	Altitude PTU
8a10	Sensor orientation	constant	0	L	systematic	8a1
8a11	Cloud	constant	0	L	systematic	

	configuratio n					
8a12	Albedo	$\Delta T \frac{u_c(I_a)}{I_a}$	<0.8% RH	M	systematic	None
8b	Radiation sensitivity factor $u_c(RC_f)$	$\frac{p_{s(T+(f+u(f))\Delta T)} - p_{s(T+(f-u(f))\Delta T)}}{2 * p_s(T)}$	0.5 – 2 %	M	Systematic	
8c	Saturation vapour pressure	constant	<0.02 % RH	L	Systematic	None
9, u_c(TL)	Calculate ambient RH using time-lag model	$0.5\lvert RH(\tau + u(\tau)) - RH(\tau - u(\tau))\rvert$	1-2 % RH	M	Systematic	9a
9a, u(τ)	Time constant	$0.5 * \tau(1 - A)$		M	Sytematic	7a
10	Low pass digital filter	Statistical uncertainty	0.5 – 2 % RH	M	Random	9a
11, u(RH)	Corrected RH values	$\sqrt{u_c(cal)^2 + u_c(cc)^2 + u_c(TL)^2 + u_c(RC)^2 + u_u(R}$	6 % RH	M		

The total uncertainty in the GRUAN RS92 relative humidity product is the sum in quadrature of the uncertainties from the statistical uncertainty, calibration and the different corrections applied. This is shown in equation 1 below.

$$u(RH) = \sqrt{u_c(cal)^2 + u_c(cc)^2 + u_c(TL)^2 + u_c(RC)^2 + u_u(RH)^2} \qquad (1)$$

Where u_c(cal) is the uncertainty in calibration, u_c(cc) is the uncertainty in the calibration correction, u_c(TL) is the uncertainty in the time lag correction, u_c(RC) is the uncertainty in the radiative dry bias correction.

The total uncertainty in relative humidity, u(RH), is usually 6 % RH, but can peak above 10 % RH, and drops to between 2 and 2.5 % RH in the upper part of the profile, above the tropopause. However relative uncertainty is larger in the upper part of the profile because of how low the relative humidity measurements are. The total uncertainty takes into account four sources of correlated uncertainty and one source of statistical uncertainty. The statistical uncertainty, u_u(RH), is greatest below the tropopause and is usually below 5 % RH. Above the tropopause it is usually below 2 % RH. With the exception of narrow peaks in the statistical uncertainty, the correlated uncertainty contributes more to the total uncertainty throughout the profile. This include the calibration uncertainty, u_c(cal), which is itself a combination of manufacturer calibration uncertainty and ground check re-calibration uncertainty is between 2 and 3 % RH throughout most of the profile but is larger near the surface as a result of the relative uncertainty determined from the standard humidity chamber. The uncertainty contribution of the calibration dry bias correction, u_c(cc), increases from about 1.5 % RH near the surface to up to 5 % RH at the tropopause. Above this level u_c(cc) drops to below 0.5 % RH. The uncertainty contribution from the radiative heating correction, u_c(RC), starts below 2 % RH and rises to above 5 % RH near the tropopause. in soundings where it is present this is the largest contribution to the correlated uncertainty. The last contribution to the correlated uncertainty is from the time-lag correction, u_c(TL), is the smallest contributor to the correlated uncertainty and is usually below 2 %

RH. Three of the contributions to the correlated uncertainty are temperature related and correlated uncertainty peaks near the tropopause, where the temperature is low but there is still fairly high atmospheric RH. Most of the total uncertainty is correlated uncertainty.

5.1 Traceability uncertainty analysis

Traceability level definition is given in Table 5.

Table 5. Traceability level definition table

Traceability Level	Descriptor	Multiplier
High	SI traceable or globally recognised community standard	1
Medium	Developmental community standard or peer-reviewed uncertainty assessment	3
Low	Approximate estimation	10

Analysis of the summary table would suggest the following contributions, shown in Table 6, should be considered further to improve the overall uncertainty of the GRUAN temperature product. The entries are given in an estimated priority order.

Table 6. Traceability level definition further action table.

Element identifier	Contribution name	Uncertainty contribution form	Typical value	Traceability level (L/M/H)	Random, structured random, quasi-systematic or systematic?	Correlated to
8c	Saturation vapour pressure	constant	<0.02 % RH	L	Systematic	None
8a8, $u_{u,vent}(\Delta T)$	Ventilation speed	$\Delta T(\frac{u(v)}{v})$	<0.5 % RH	M	Quasi-systematic	Altitude
8a4	Solar zenith angle	Constant	0	M	Systematic (over ascent)	
8a5	Launch site location	Constant	0	H	Systematic	
8a6	Time of launch	constant	0	H	Systematic (over ascent)	
8a7, $u(I_a)$	Actinic flux radiative transfer model	$\frac{\lvert I_{a,cloudy} - I_{a,clear\ sky}\rvert}{2\sqrt{3}}$	<350 Wm^{-2}	M	Quasi-systematic	Altitude
8a9	Altitude	Constant	0	M	Quasi-	Altitude

					systematic	PTU
8a10	Sensor orientation	constant	0	L	systematic	8a1
8a11	Cloud configuration	constant	0	L	systematic	

5.2 Recommendations

An assessment of the Vaisala correction for radiative heating uncertainty should be evaluated, as currently the uncertainty is only calculated for the GRUAN correction and sensitivity tests indicate it may have a significant contribution.

It would also be useful for the ground-check information to be included in the data files, particularly as this influences whether calibration uncertainty is calculated from the ground check or just included assumed.

More detail about the saturation vapour pressure formula could be given in the documentation, since although Hyland and Wexler 1983 is widely referenced it can be hard to find.

There are contributions that do not have an assigned uncertainty. Some analysis to determine the magnitude of these potential contributions would better constrain the uncertainty budget.

Some contributions are discussed, but not used in the overall uncertainty calculation, e.g. uncertainty from the temperature product. The uncertainty contribution from these elements should be quantified and used.

6 Conclusions

The GRUAN RS92 radiosonde humidity product has been assessed against the GAIA CLIM traceability and uncertainty criteria.

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