Product Traceability and Uncertainty for the GRUAN RS92 radiosonde temperature product

Version 2.0

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Gap Analysis for Integrated
Atmospheric ECV Climate Monitoring
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Dissemination level: PU

Work Package 2; Complied by Paul Green & Tom Gardiner (NPL)

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Version history

Version	Principal updates	Owner	Date
0.1 draft	First draft	NPL	06.02.2017
0.2 draft	Second draft	NPL	18.04.2017
0.3 draft	Third draft	NPL	18.05.2017
0.4 draft	Sent for initial external comments	NPL	24.05.2017
1.0	First issue	NPL	02.06.2017
2.0	Minor changes to chain diagram §5.5 & §5.6 edits. Issued as annex B to D2.6	NPL	30.11.2017

1 Product overview

Product name: In-situ radiosonde RS92 temperature
Product technique: Capacitive temperature sensor
Product measurand: Temperature
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 – present
Data provider: GRUAN
Instrument provider: Site operators, see www.gruan.org
Product assessor: Paul Green, NPL
Assessor contact email: paul.green@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.

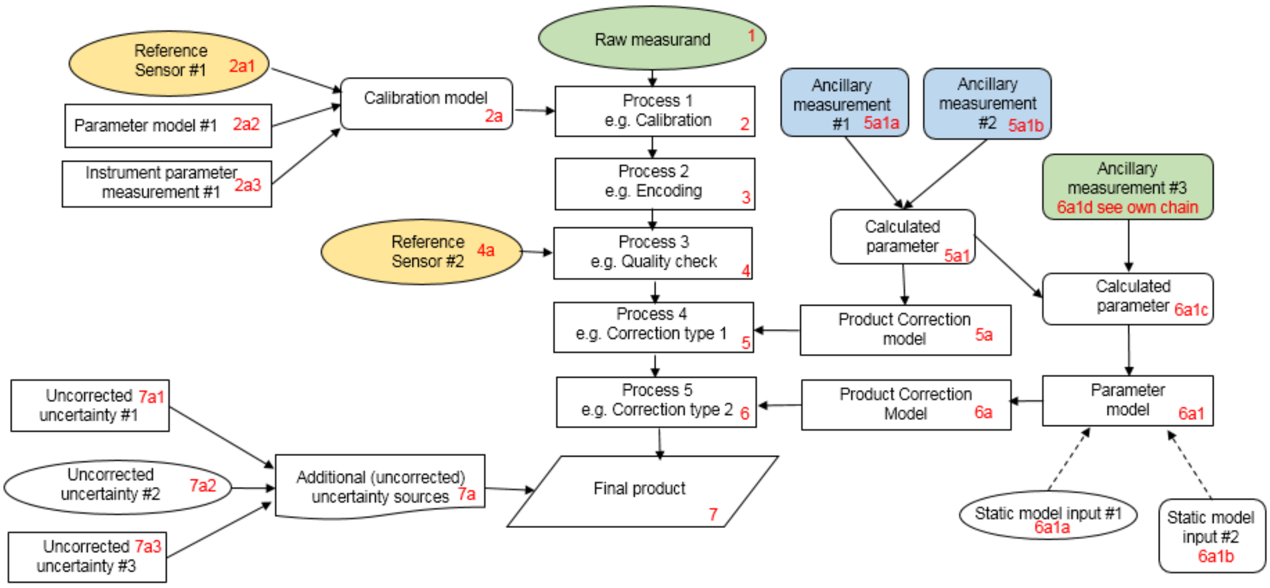


Figure 1. Example traceability chain. Green represents a key measurand or ancillary measurand recorded at the same time with the product raw measurand. Yellow represents a source of traceability. Blue represents a static ancillary measurement

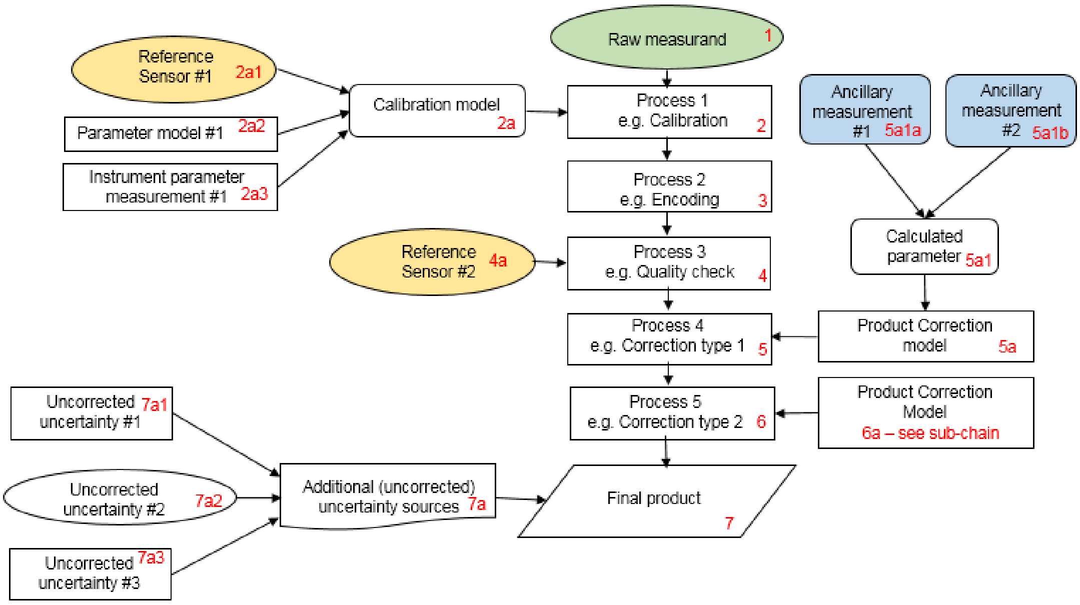


Figure 2. Example chain as sub-divided chain. Green represents a key measurand or ancillary measurand recorded at the same time with the product raw measurand. Yellow represents a source of traceability. Blue represents a static ancillary measurement

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.

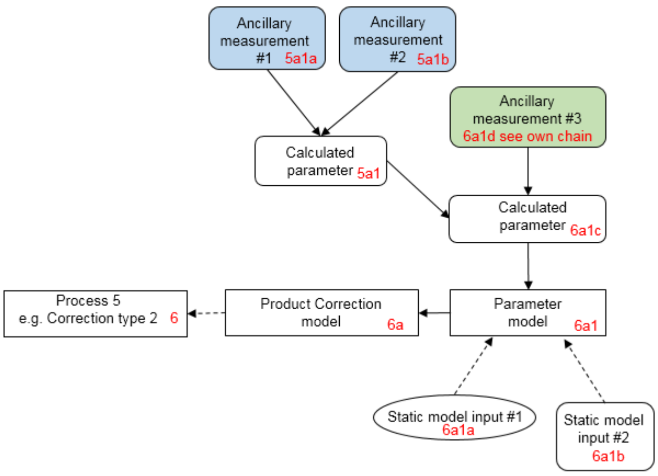


Figure 3. Example chain contribution 6a sub-chain. Green represents a key measurand or ancillary measurand recorded at the same time with the product raw measurand. Blue represents a static ancillary measurement

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 presents the Product Traceabililty and Uncertainty (PTU) information for the GRUAN RS92 radiosonde temperature product. The aim of this document is to provide supporting information for the users of this product within the GAIA-CLIM VO, and as an example PTU document for the suppliers of other VO data products. The uncertainty and traceability information contained in this document is based on the details given in Dirksen et al[1].

The GCOS (Global Climate Observing System) Reference Upper-Air Network (GRUAN) data processing for the Vaisala RS92 radiosonde was developed to meet the criteria for reference measurements. These criteria stipulate the collection of metadata, the use of well-documented correction algorithms, and estimates of the measurement uncertainty. An important and novel aspect of the GRUAN processing is that the uncertainty estimates are vertically resolved. Dirksen et al[1] describe the algorithms that are applied in version 2 of the GRUAN processing to correct for systematic errors in radiosonde measurements of pressure, temperature, humidity, and wind, as well as how the uncertainties related to these error sources are derived. Currently, the certified RS92 data product is available from 9 GRUAN sites. An additional GRUAN requirement for performing reference measurements with the RS92 is that the manufacturer- prescribed procedure for the radiosonde's preparation, i.e. heated reconditioning of the sensors and recalibration during ground check, is followed. In the GRUAN processing however, the recalibration of the humidity sensors that is applied during ground check is removed. For the dominant error source, solar radiation, laboratory experiments were performed to investigate and model its effect on the RS92's temperature and humidity measurements.

GRUAN uncertainty estimates are 0.15 K for night-time temperature measurements and approximately 0.6 K at 25 km during daytime. The other uncertainty estimates are up to 6 %

relative humidity for humidity, 10–50 m for geopotential height, 0.6 hPa for pressure, 0.4–1 m s^{-1} for wind speed, and 1° for wind direction. Daytime temperature profiles for GRUAN and Vaisala processing are comparable and consistent within the estimated uncertainty. GRUAN daytime humidity profiles are up to 15 % moister than Vaisala processed profiles, of which two-thirds is due to the radiation dry bias correction and one- third is due to an additional calibration correction. Redundant measurements with frost point hygrometers (CFH and NOAA FPH) show that GRUAN-processed RS92 humidity profiles and frost point data agree within 15 % in the troposphere. No systematic biases occur, apart from a 5 % dry bias for GRUAN data around −40 °C at night.

3 Instrument description

The Vaisala RS92 radiosonde, shown in Figure 4, measures vertical profiles of pressure, temperature, and humidity (PTU) from ground to the balloon-burst altitude limit of approximately 40 km. The RS92 is equipped with a wire-like capacitive temperature sensor (“Thermocap”); two polymer capacitive moisture sensors (“Humicap”); a silicon-based pressure sensor; and a GPS receiver to measure position, altitude, and winds. The RS92 transmits sensor data at 1-second intervals, which are received, processed, and stored by the DigiCora ground station equipment. A hydrophobic, reflective coating is applied to the sensor boom and the temperature sensor to reduce the RS92’s sensitivity to solar radiation, and to reduce the deposition of water or ice when flying through clouds. The GPS receiver on the RS92 transmits its position as xyz coordinates in the WGS-84 (World Geodetic System 1984) system. These xyz coordinates are then converted into latitude, longitude, and altitude data by the DigiCora system, while using the readings of the station GPS antenna as a reference for determining the geometric altitude of the radiosonde.

The sensors of the assembled radiosonde are calibrated in Vaisala’s CAL4 calibration facility[2]. The CAL4 contains reference sensors that are recalibrated at regular intervals against standards that are traceable to NIST (for pressure and temperature) and its Finnish equivalent, MIKES (for humidity). The respective operating ranges and accuracies of the PTU sensors are 3 (±0.6) to 1080 (±1) hPa, −90 (±0.5) to 60 (±0.5) ◦C, and 0 (±5) to 100 (±5) % RH, respectively[3].

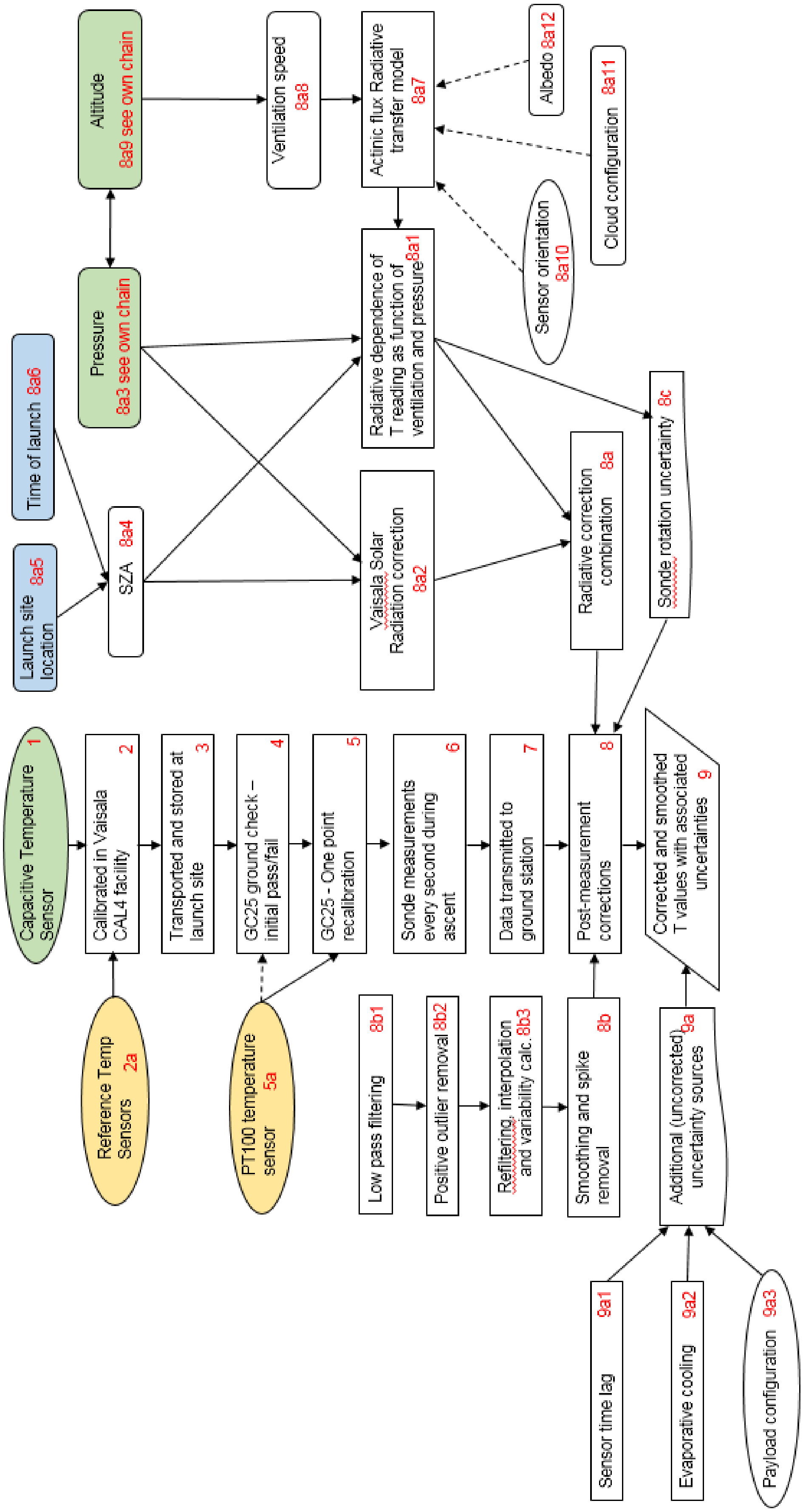
Corrections reduce errors in the temperature and humidity due to solar radiation, time-lag of the RH sensor, and sensor recalibration during the pre-flight ground check. Furthermore, corrections are applied for spurious noise like temperature spikes[4]. Most of these correction algorithms are proprietary and are not disclosed to the user. An overview of relevant modifications in the RS92 hardware and the processing software is available at the Vaisala data continuity website[5]. The RS92 has participated in a number of campaigns and inter-comparisons[6-11]. Campaigns have identified error sources for the RS92 such as radiation dry bias[12] sensor time-lag[13], and a temperature- dependent calibration error for the humidity sensors[12,14].

Figure 4. Photograph of the RS92 radiosonde showing the GPS antenna on the left and the sensor boom on the right. The inset shows the magnified tip of the sensor boom with the wire-shaped temperature sensor and one of the humidity sensors

The temperature sensor of the RS92 radiosonde consists of a temperature-dependent capacitive sensor (Thermocap)[15]. The sensor wire is covered with a reflective, hydrophobic coating to reduce solar heating and systematic errors from evaporative cooling by any water or ice collected during passage through clouds. With an operating range from −90 to +60 ˚C, Vaisala (2007)[4] quotes an accuracy of better than 0.5 K.

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[16]. 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 processing of RS92 routine soundings until 2010, when this was increased to 0.78 K[5]. 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[8]. A recent comparison between radiosoundings and space- borne GPS radio occultation measurements reports a 0.5–1 K warm bias at 17 hPa for Vaisala-corrected RS92 temperature profiles[17]. The stated accuracy of the satellite-retrieved temperature is approximately 0.2–0.3 K in the middle stratosphere[18,19].

4 Product Traceability Chain



5 Element contributions

5.1 Capacitive Temperature Sensor (1), $u_{u(T)}$

The temperature sensor of the RS92 radiosonde consists of a temperature-dependent capacitive sensor (Thermocap)[20]. The sensor wire is covered with a reflective, hydrophobic coating to reduce solar heating and systematic errors from evaporative cooling by any water or ice collected during passage through clouds. With an operating range from -90 to +60 ◦C, Vaisala[3] quote an accuracy of better than ±0.5 K.

The reported uncertainty associated with the sensor is its statistical uncertainty, defined from the standard deviation, reported in the datafile. Typical values are 0.1-0.15 K (1σ) in the troposphere, rising to 0.5 K (1σ) at 10 hPa.

Information / data	Type / value / equation	Notes / description
Name of effect	Capacitive temperature sensor	
Contribution identifier	1, statistical uncertainty $u_{u(T)}$	
Measurement equation parameter(s) subject to effect	Temperature	
Contribution subject to effect (final product or sub-tree intermediate product)	Temperature	
Time correlation extent & form	None	Random over ascent
Other (non-time) correlation extent & form	None	Random over ascent
Uncertainty PDF shape	Normal	
Uncertainty & units	±0.5 K (2σ) [accuracy] & 0.1-0.15 K (1σ) in the trop., rising to 0.5 K (1σ) at 10 hPa [statistical unc.]	
Sensitivity coefficient	1	
Correlation(s) between affected parameters	None	
Element/step common for all sites/users?	Yes	
Traceable to …	Accuracy to 2	Calibration in Vaisala CAL4 facility
Validation	Inter-comparison studies.	

5.2 Calibration in Vaisala CAL4 facility (2) $u_{c,\ cal(T)}$

Radiosonde sensor calibration curves determined in Vaisala CAL4 facility over a range of temperatures and pressures.

Information / data	Type / value / equation	Notes / description
Name of effect	Vaisala CAL4 facility calibration	
Contribution identifier	2, $u_{c,\ cal(T)}$	
Measurement equation parameter(s) subject to effect	Temperature	
Contribution subject to effect (final product or sub-tree intermediate product)	Temperature	
Time correlation extent & form	None	Assuming that each sensor is calibrated independently. If not then there may be correlation across batches.
Other (non-time) correlation extent & form	None	See above
Uncertainty PDF shape	Normal	Assumed
Uncertainty & units (1σ)	±0.15 K (1σ)	Repeatability of calibration
Sensitivity coefficient	1	
Correlation(s) between affected parameters	None	
Element/step common for all sites/users?	Yes	
Traceable to …	2a - reference T sensor	
Validation	Inter-comparison studies.	

5.3 Reference T Sensors (2a)

The CAL4 contains PTU reference sensors that are recalibrated at regular intervals against standards that are traceable to NIST (for pressure and temperature) and its Finnish equivalent, MIKES (for humidity). The respective operating ranges and accuracies of the PTU sensors are 3 (±0.6) to 1080 (±1) hPa,−90 (±0.5) to 60 (±0.5) ˚C, and 0 (±5) to 100 (±5) % RH, respectively[3].

Information / data	Type / value / equation	Notes / description
Name of effect	Reference T sensors	Reference sensors in Vaisala CAL4 facility
Contribution identifier	2a	
Measurement equation parameter(s) subject to effect	Temperature	
Contribution subject to effect (final product or sub-tree intermediate product)	CAL4 calibration	
Time correlation extent & form	Long-term	Correlated over period of reference sensor recalibration.
Other (non-time) correlation extent & form	None	
Uncertainty PDF shape	Normal	
Uncertainty & units (1σ)	<±0.1 K (2σ)	Assumed to be at least as good as GC25 reference sensor.
Sensitivity coefficient	1	
Correlation(s) between affected parameters	None	
Element/step common for all sites/users?	Yes	
Traceable to …	NIST	Temperature and pressure
Validation	Intercomparison studies	Indirect validation

5.4 Transported and stored at launch site (3)

Radiosondes are shipped from Vaisala to launch location and then stored on site. It is currently assumed that any changes to sensor performance during this period is corrected for by the Ground Check.

Information / data	Type / value / equation	Notes / description
Name of effect	Transportation and storage	
Contribution identifier	3	
Measurement equation parameter(s) subject to effect	Temperature	
Contribution subject to effect (final product or sub-tree intermediate product)	Temperature	

Time correlation extent & form	None	Assuming no batch dependence.
Other (non-time) correlation extent & form	None	Assuming no batch dependence.
Uncertainty PDF shape	N/A	
Uncertainty & units (1σ)	0	Assumes that effect corrected by Ground Check
Sensitivity coefficient	1	
Correlation(s) between affected parameters	None	
Element/step common for all sites/users?	Yes	
Traceable to …	N/A	
Validation	N/A	

5.5 GC25 ground check – initial pass/fail (4)

The manufacturer's operational procedure demands that prior to flight a ground check is performed. During this check the sensor boom is inserted into a calibration unit (GC25) and the sensors are heated to remove contaminants that introduce a dry bias in the humidity measurements ("reconditioning"). The initial quality control verifies that the readings of the PTU sensors during the ground check are within pre-defined limits before GRUAN corrections are applied. For the data to be processed, the corrections determined inthe GC25 must be less than 1K for T, 1.5 hPa for P, and less than 2% RH for U.

Information / data	Type / value / equation	Notes / description
Name of effect	GC25 Pass/Fail	
Contribution identifier	4	
Measurement equation parameter(s) subject to effect	Temperature	
Contribution subject to effect (final product or sub-tree intermediate product)	Temprerature	
Time correlation extent & form	None	
Other (non-time) correlation extent & form	None	
Uncertainty PDF shape	Rectangular	
Uncertainty & units (1σ)	<1K* Typically ±0.3 K (2σ)	Not a formal uncertainty value. Cut-off to ensure no sensors with >1K difference are flown.

Sensitivity coefficient	1	
Correlation(s) between affected parameters	None	
Element/step common for all sites/users?	Yes	
Traceable to …	GC25 T sensor	
Validation	N/A	

5.6 GC25 - One point recalibration (5) u_{GC25}

The manufacturer's operational procedure demands that prior to flight a ground check is performed. During this check the sensor boom is inserted into a calibration unit (GC25) and the sensors are heated to remove contaminants that introduce a dry bias in the humidity measurements ("reconditioning"). A one-point recalibration is applied to the PTU, based on comparing the temperature and pressure sensors to a PT100 temperature sensor and the station barometer, respectively, and recording the humidity sensor readings in a dry zone over a bed of desiccant.

The uncertainty components of GC25 temperature measurement are the calibration uncertainty, the long-term stability of the Pt-100, the reference resistor and the GC25 electronics uncertainty (A/D transformation etc.).

Combined uncertainty: ± 0,098°C 2-sigma (k=2) confidence level (95.5%). For long-term stability a maximum value of 0.05 °C is assumed.

The uncertainty in this step would be a combination of the GC25 measurement uncertainty and the GC25 ground check difference, so typically $\sqrt{[((\pm 0.1\ K)^2 + ((\pm 0.4\ K)/3)^2]} = \pm 0.17$ K

Information / data	Type / value / equation	Notes / description
Name of effect	GC25 recalibration	Not known if shift or scale adjustment
Contribution identifier	5, u_{GC25}	
Measurement equation parameter(s) subject to effect	Temperature	
Contribution subject to effect (final product or sub-tree intermediate product)	Temperature	
Time correlation extent & form	Systematic over flight	
Other (non-time) correlation extent & form	Systematic over flight	
Uncertainty PDF shape	Rectangular	Difference during ground check
Uncertainty & units (2σ)	$\sqrt{u_c{}^2 + (\frac{\Delta T_{GC25}}{3})^2}$	Combined with Vaisala calibration uncertainty

	typically 0.17 K (2σ)	
Sensitivity coefficient	1	
Correlation(s) between affected parameters	None	
Element/step common for all sites/users?	Yes	
Traceable to …	PT100 (5a)	
Validation	Intercomparisons	Indirect

5.7 PT100 temperature sensor (5a)

Ground-check calibration unit (GC25) contains a PT100 Platinum Resistance Temperature Detector as the temperature reference.

Information / data	Type / value / equation	Notes / description
Name of effect	PT100 temperature sensor	
Contribution identifier	5a	
Measurement equation parameter(s) subject to effect	Temperature	
Contribution subject to effect (final product or sub-tree intermediate product)	GC25 recalibration	
Time correlation extent & form	Long-term systematic	Systematic between PT100 replacement
Other (non-time) correlation extent & form	None	
Uncertainty PDF shape	Normal	Assumed
Uncertainty & units (1σ)	±0.15 K	Assumes a Class A resistance tolerance: ±(0.15 + 0.002*t)°C or 100.00 ±0.06 O at 0ºC
Sensitivity coefficient	1	
Correlation(s) between affected parameters	None	
Element/step common for all sites/users?	Yes	
Traceable to …	PT100 specifications	Assuming the PT100 is not calibrated against a reference standard
Validation	N/A	

5.8 Sonde measurements every second during ascent (6)

A radiosonde temperature measurement is recorded every second during the sonde ascent. The uncorrelated uncertainty of these measurements (measurement noise) is assessed as part of the spike removal algorithm (Contribution 8b) within the post-measurement corrections (Contribution 8). It is assumed there are no other uncertainty sources within this step.

Information / data	Type / value / equation	Notes / description
Name of effect	Temperature measurments during sonde ascent	
Contribution identifier	6	
Measurement equation parameter(s) subject to effect	Temperature	
Contribution subject to effect (final product or sub-tree intermediate product)	Temperature	
Time correlation extent & form	None	
Other (non-time) correlation extent & form	None	
Uncertainty PDF shape	N/A	
Uncertainty & units (1σ)	None	Covered in spike removal algorithm (8b)
Sensitivity coefficient	1	
Correlation(s) between affected parameters	1	
Element/step common for all sites/users?	Yes	
Traceable to …	N/A	
Validation	Intercomparisons	

5.9 Data transmitted to ground station (7)

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 transmission	
Contribution identifier	7	
Measurement equation parameter(s) subject to effect	Temperature	

Contribution subject to effect (final product or sub-tree intermediate product)	Temperature	
Time correlation extent & form	None	
Other (non-time) correlation extent & form	None	
Uncertainty PDF shape	N/A	
Uncertainty & units (1σ)	0	
Sensitivity coefficient	1	
Correlation(s) between affected parameters	None	
Element/step common for all sites/users?	Yes	
Traceable to …	N/A	
Validation	N/A	

5.10 Post-measurement corrections (8)

The dominant systematic error is due to solar radiative heating (radiative correction (8a)). Smoothing & spike removal (8b) is the other post-measurment correction.

This contribution is the combined effect of all these corrections.

Information / data	Type / value / equation	Notes / description
Name of effect	Post-measurement correction	Combined 8a & 8b
Contribution identifier	8	
Measurement equation parameter(s) subject to effect	$T' = T - \Delta T$	
Contribution subject to effect (final product or sub-tree intermediate product)	Temperature	
Time correlation extent & form	None	
Other (non-time) correlation extent & form	None	
Uncertainty PDF shape	Normal	
Uncertainty & units (1σ)	±0.22 K (2σ) in trop. ±0.5 K (2σ) in strat.	Combination of branch 8 sub-elements.
Sensitivity coefficient	1	
Correlation(s) between affected parameters	None	

Element/step common for all sites/users?	Yes	
Traceable to …		
Validation		

5.11 **Radiative correction (8a)**

The mean of the GRUAN and Vaisala radiative corrections is used for the daytime measurements. Only the Vaisala correction is used for nighttime measurments.

The GRUAN radiation correction, relies on laboratory experiments and radiative transfer calculations to estimate the actinic flux on the sensor. Laboratory work has determined the relation between temperature error and actinic flux as a function of pressure and ventilation.
Other sources of error include temperature spikes[4] due to patches of warm air coming off the sensor housing and the balloon, evaporative cooling of the wetted sensor after exiting a cloud and sensor time-lag. The last two effects are not corrected because no appropriate correction algorithm is available for evaporative cooling, although affected data points should be flagged and the impact of time-lag is considered negligible.

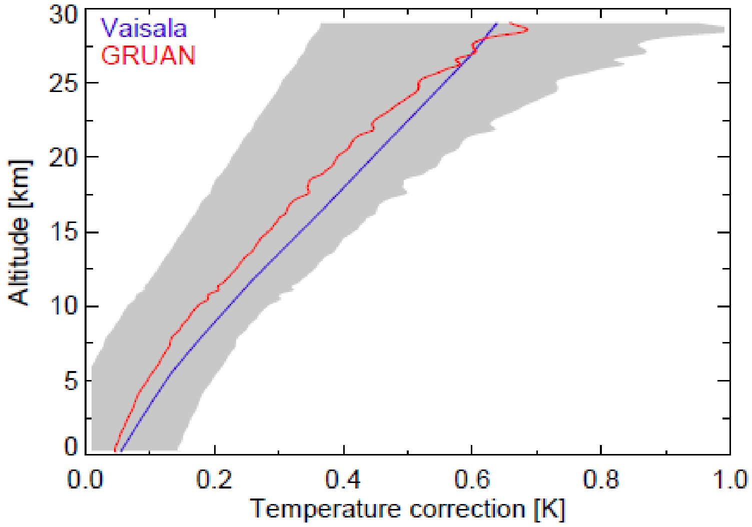


Figure 7. Comparison of the GRUAN and Vaisala correction models for the radiation temperature error. Blue trace: Vaisala correction profile (DigiCora version 3.64); red trace: GRUAN correction profile. The grey bar represents the uncertainty estimate of the GRUAN temperature correction. The correction profiles are evaluated for a sounding performed at Lindenberg on 17 September 2013 at 12:00 UTC; maximum solar zenith angle during the sounding: 36.5°.

Figure 5. Dirksen et al[1] figure 7, showing typical corrections for the solar radiation effects on temperature.

Information / data	Type / value / equation	Notes / description
Name of effect	Radiative correction	Combined of GRUAN and Vaisala corrections
Contribution identifier	8	
Measurement equation parameter(s) subject to effect	$T' = T + (\Delta T_G + \Delta T_V)/2$	During daytime. $T' = T + \Delta T_V$, at night.
Contribution subject to effect (final product or sub-tree intermediate product)	Temperature	
Time correlation extent & form	None	
Other (non-time) correlation extent & form	None	
Uncertainty PDF shape	Normal	
Uncertainty & units (1σ)	<0.36 K (2σ)	Combination of the 8a sub-elements
Sensitivity coefficient	1	
Correlation(s) between affected parameters	none	
Element/step common for all sites/users?	yes	
Traceable to …		
Validation		

5.12 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[22] 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 nightime the Vaisala correction of 0.04 K at 5 hPa is used.

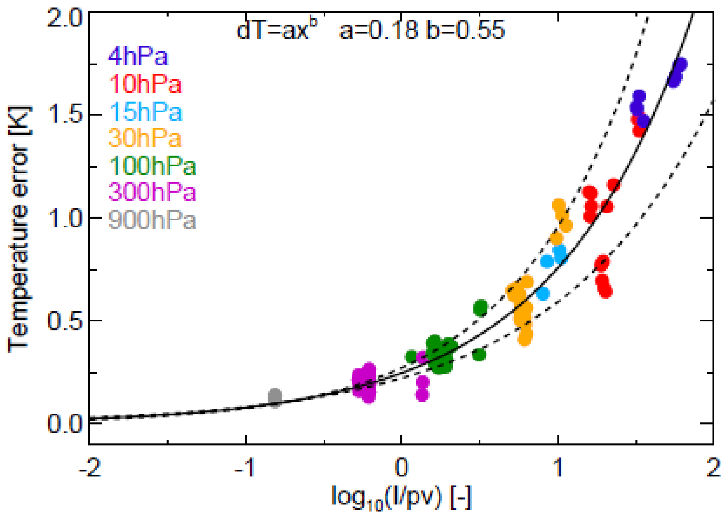


Figure 6. Dirksen et al[1] figure 4

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	$T' = T - \Delta T,$ $where\ \Delta T = a.\left(\frac{I_a}{p.v}\right)^b$	
Contribution subject to effect (final product or sub-tree intermediate product)	Radiation correction	
Time correlation extent & form	None	Point to point correction
Other (non-time) correlation extent & form	N/A	
Uncertainty PDF shape	Normal	
Uncertainty & units (1σ)		
Sensitivity coefficient	1	
Correlation(s) between affected parameters	None	
Element/step common for all sites/users?	Yes	
Traceable to …		
Validation		

5.13 Vaisala radiation correction (8a2)

The Vaisala correction for the radiation temperature error is available as a table for various pressures and solar elevation angles[23]. 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 7. DigiCora radiation correction table[24]

Information / data	Type / value / equation	Notes / description
Name of effect	Vaisala radiation correction	
Contribution identifier	8a2	
Measurement equation parameter(s) subject to effect	$T' = T - \Delta T$	
Contribution subject to effect (final product or sub-tree intermediate product)	Temperturature	
Time correlation extent & form	None	
Other (non-time) correlation extent & form	None	
Uncertainty PDF shape	Normal	
Uncertainty & units (1σ)	0.1 K in the troposphere, up to 0.4 K in the stratosphere.	Derived from validation experiments but not included in overall uncertainty assessment.
Sensitivity coefficient	1	

Correlation(s) between affected parameters	None	
Element/step common for all sites/users?	Yes	
Traceable to …		
Validation	Vaisala validation experiments	

5.14 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)	Solar radiation 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	±0.2 hPa (1σ), typically <0.001 K (1σ) in the troposphere, rising to ±0.03 K (1σ) in the strat.	For the GRUAN solar radiation correction.
Sensitivity coefficient	1	
Correlation(s) between affected parameters	Altitude	
Element/step common for all sites/users?	Yes	
Traceable to …		

Validation		

5.15 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		

5.16 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		

5.17 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		

5.18 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[16]. 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 processing of RS92 routine soundings until 2010, when this was increased to 0.78 K[5].

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[8].

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[17]. The reported accuracy of the satellite-retrieved temperature is approximately 0.2–0.3K in the middle stratosphere[18,19].

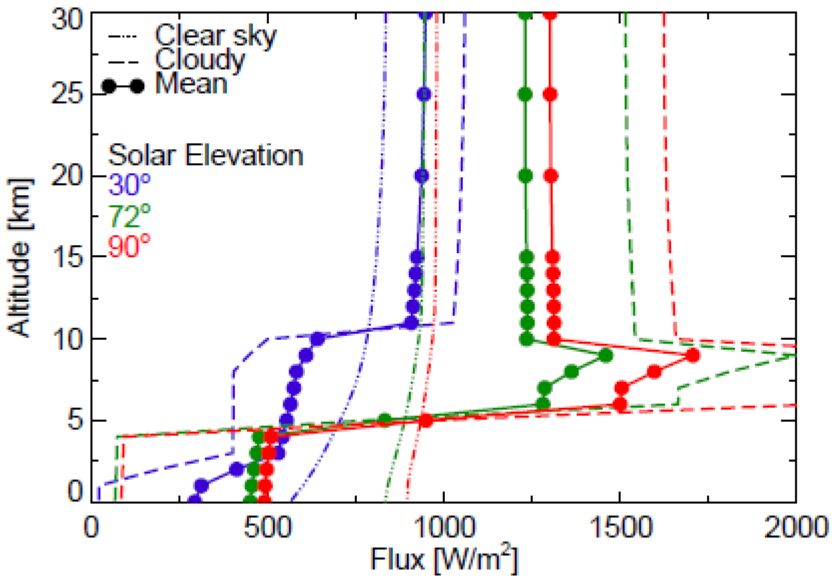


Figure 8. Dirksen figure 5

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 (1σ)	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		

5.19 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 9.

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.

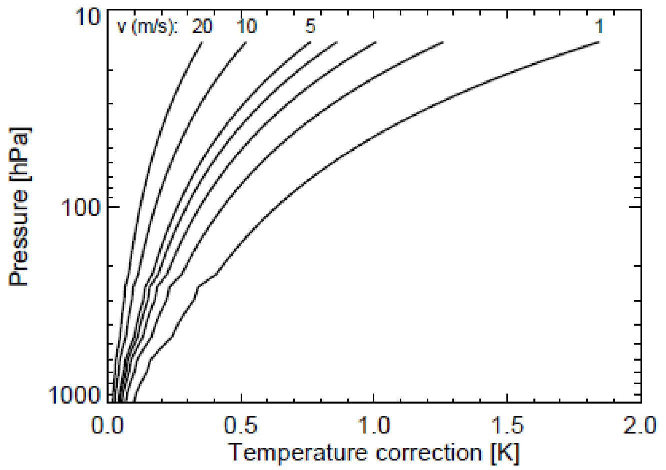


Figure 6. Profiles of the GRUAN radiation temperature correction for ventilation speeds between 1 and 20 $\mathrm{m\,s^{-1}}$. The correction was calculated for a radiosounding performed in Lindenberg on 17 September 2013 at 12:00 UTC. The kinks in the profiles between 900 and 200 hPa result from the 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 9. 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 equivilant to 0.01 K in the troposphere, rising upto 0.3 K in the stratosphere (2σ).

Information / data	Type / value / equation	Notes / description
Name of effect	Ventilation speed correction	
Contribution identifier	8a4, u_v & $u_{vent(\Delta T)}$	
Measurement equation parameter(s) subject to effect	Temperature	
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 $m.s^{-1}$ ± 1$m.s^{-1}$ suggesting a defined limit uncertainty.

Uncertainty & units (1σ)	u(v) = ±1m/s (2σ), with the temperature dependence given by $\Delta T \cdot u(v)/v$ Equivilant to 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		

5.20 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	8a5	
Measurement equation parameter(s) subject to effect	-	
Contribution subject to effect (final product or sub-tree intermediate product)	Ventialtion speed	
Time correlation extent & form	None	
Other (non-time) correlation extent & form	None	
Uncertainty PDF shape	Normal	
Uncertainty & units (1σ)	0	
Sensitivity coefficient	1	
Correlation(s) between affected parameters	None	
Element/step common for all sites/users?	Yes	
Traceable to …	No	

Validation	Ventilation speed validation experiments.	

5.21 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		

5.22 Cloud configuration (8a11)

No separate contribution – the uncertainty is effectively included as part of the radiative model fit uncertainity (8a2).

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		

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

$$\Delta T \cdot u_c(I_a)/I_a$$

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	8a9	
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	Typical values are 0.2-0.5x ΔT in the trop. and 0.03-0.2x ΔT in the strat., so <0.05 K (2σ) throughout the ascent.	60-250 W/m^2 in the troposphere, 30-200 W/m^2 in the stratosphere dependant on 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		

5.24 **Smoothing and spike removal (8b)**

The smoothing and spike removal is covered by a series of three sub-processes: a low-pass filtering step (8b1), a positive outlier removal step (8b2) and a refiltering, interpolation and variability calculation (8b3). The uncertainty and correlation effects are covered in the sub-process sections.

Information / data	Type / value / equation	Notes / description
Name of effect	Smoothing and spike removal	
Contribution identifier	8b	
Measurement equation parameter(s) subject to effect	$T' = f(T),$	
Contribution subject to effect (final product or sub-tree intermediate product)	Temperature	
Time correlation extent & form	Filter width, 10s	
Other (non-time) correlation extent & form	None	
Uncertainty PDF shape	Quasi-rectangular	
Uncertainty & units (1σ)	±0.05K (2σ)	
Sensitivity coefficient	1	

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

5.25 Low pass filtering (8b1)

Low-pass filtering is applied over a 10 sec running average, reducing the vertical resolution to 50 m, although data is reported at 1 second intervals.

No uncertainty associated with this process is considered.

Information / data	Type / value / equation	Notes / description
Name of effect	Low pass filtering	
Contribution identifier	8b1	
Measurement equation parameter(s) subject to effect	$T' = f(T)$	
Contribution subject to effect (final product or sub-tree intermediate product)	Tempertaure	
Time correlation extent & form	Over filter width (10 sec)	
Other (non-time) correlation extent & form	None	
Uncertainty PDF shape	Normal	
Uncertainty & units (1σ)	0 K	
Sensitivity coefficient	1	
Correlation(s) between affected parameters	8b2	
Element/step common for all sites/users?	Yes	
Traceable to …	No	
Validation	No	

5.26 Positive outlier removal (8b2)

Spikes in the daytime temperature profile may result from air being heated by the radiosonde package, and possibly from passing through the warm wake of the balloon due to the pendulum motion of the payload[25,4].

Reduces the mean temperature, by removing positive outliers.

Information / data	Type / value / equation	Notes / description
Name of effect	Outlier correction	
Contribution identifier	8b2	
Measurement equation parameter(s) subject to effect	Temperature	
Contribution subject to effect (final product or sub-tree intermediate product)	Radiation correction (8)	
Time correlation extent & form	Correlated over smoothing kernel, 10sec	
Other (non-time) correlation extent & form	Correlated over smoothing kernel, 10sec	
Uncertainty PDF shape	Rectangular	
Uncertainty & units (1σ)	0.05K	
Sensitivity coefficient	1	
Correlation(s) between affected parameters		
Element/step common for all sites/users?	Yes	
Traceable to …	None	
Validation		

5.27 Refiltering, interpolation and variability calc. (8b3)

No uncertainty associated with the refiltering, interpolation & variability processing is considered.

Information / data	Type / value / equation	Notes / description
Name of effect	Refiltering & interpolation	
Contribution identifier	8b3	
Measurement equation parameter(s) subject to effect	$T' = f(T)$	
Contribution subject to effect (final product or sub-tree intermediate product)	Temperature	
Time correlation extent & form	Over filter width (10 sec)	

Other (non-time) correlation extent & form	None	
Uncertainty PDF shape	Normal	
Uncertainty & units (1σ)	0 K	
Sensitivity coefficient	1	
Correlation(s) between affected parameters	8b2	
Element/step common for all sites/users?	Yes	
Traceable to …	No	
Validation	No	

5.28 Sensor rotation (8c) $u_{u,\, rot(\Delta T)}$

Due to spinning of the radiosonde in flight, the solar irradiance on the sensor wire cycles between 0 and maximum. In case of rapid spinning – i.e. more than, say, 10 revolutions per minute – the temperature rise due to the orientation should average out and should not introduce a mean bias in the temperature profile. Not knowing the instantaneous rotational rate leads to an increased uncertainty around the mean radiation bias. However, if the radiosonde rotates slowly, the orientation of the temperature sensor with respect to the Sun no longer averages out.
The orientation uncertainty and the associated temperature uncertainty only apply to the direct solar irradiance is because the temperature error from the diffuse (omnidirectional) background remains largely the same regardless of sensor orientation. proportional to radiation correction calculated in 8a1.

Figure 10 shows the typical magnitude of the sensor rotation (orientation) uncertainty compared to the other major sources of uncertainty.

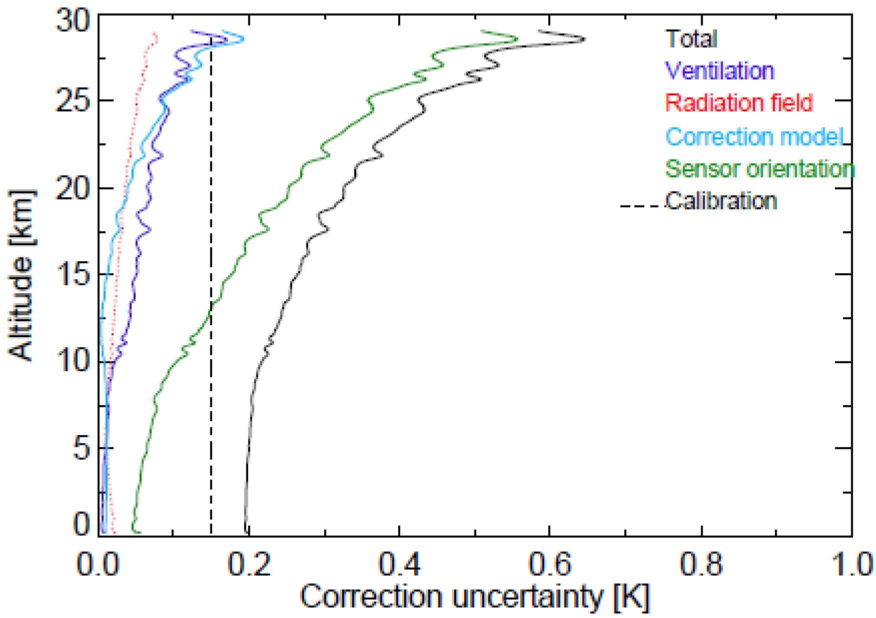


Figure 9. Contributions of the various uncertainty terms to the total uncertainty estimate of the GRUAN temperature correction for a sounding performed in Lindenberg on 17 September 2013 at 12:00 UTC; maximum solar zenith angle during the sounding: 36.5°. The radiation field represents the uncertainty due to the unknown albedo of the cloudy/cloud-free scene.

Figure 10. Dirksen et al[1] figure 9.

Information / data	Type / value / equation	Notes / description
Name of effect	Sonde rotation	
Contribution identifier	8c, $u_{u,\ rot(\Delta T)}$	
Measurement equation parameter(s) subject to effect	$u_{u,rot(\Delta T)} = 2.\frac{\Delta T}{\sqrt{3}}$	Where ΔT is the radiation correction.
Contribution subject to effect (final product or sub-tree intermediate product)	Temperature	
Time correlation extent & form	Corrected point by point.	
Other (non-time) correlation extent & form	Pressure & ventilation speed.	
Uncertainty PDF shape	Rectangular	As ΔT (8a2) is rectangular
Uncertainty & units (1σ)	±0.1 K (2σ) in trop. ±0.4 K (2σ) in strat. as a function of altitude & ventilation speed.	$u_{rot} = 2.\frac{\Delta T}{\sqrt{3}}$ Highest for low ventilation speed & high altitude.
Sensitivity coefficient	1	
Correlation(s) between affected parameters	Actinic flux inceratinty.	

Element/step common for all sites/users?	Yes	
Traceable to …		
Validation		

5.29 Uncorrected uncertainty sources (9)

The combination of the additional uncorrected uncertainty sources, sensor time lag (9a), evaporative cooling (9b) and payload configuration (9c), which are combined in the following way:

$$u_{uncor} = \sqrt{(u_{tlag}{}^2 + u_{evap}{}^2 + u_{payload}{}^2)}$$

Information / data	Type / value / equation	Notes / description
Name of effect	Uncorrected uncertainty sources	
Contribution identifier	9	
Measurement equation parameter(s) subject to effect	$T' = T$	Additional uncertainty alone
Contribution subject to effect (final product or sub-tree intermediate product)	Temperature	
Time correlation extent & form	None	
Other (non-time) correlation extent & form	None	
Uncertainty PDF shape	Systematic	
Uncertainty & units (1σ)	0 K	
Sensitivity coefficient	1	
Correlation(s) between affected parameters	8a5 & 8b	
Element/step common for all sites/users?	Yes	
Traceable to …	No	
Validation	No	

5.30 Sensor time lag (9a)

The RS92 temperature sensors respond to changes in the ambient temperature, with typical time constants of 1.7 s at 3 hPa, 1.3 s at 10 hPa, and < 0:5 s below 100 hPa[3]. Sensors made prior to 2007 were slightly thinner and responded with time constants approximately 60% smaller (e.g. 1 s at 3 hPa). The response of the temperature sensor converges exponentially to changes in ambient temperature, and the time constant is the time needed to register 63% of a step change in temperature. These response times are fast enough to keep the temperature error due to sensor time-lag below 0.1 K. Therefore, no correction for time-lag of the temperature sensor is applied in the GRUAN product.

Information / data	Type / value / equation	Notes / description
Name of effect	Sensor time lag	
Contribution identifier	9a	
Measurement equation parameter(s) subject to effect	$T' = T$	Additional uncertainty alone
Contribution subject to effect (final product or sub-tree intermediate product)	Temperature	
Time correlation extent & form	None	
Other (non-time) correlation extent & form	None	
Uncertainty PDF shape	Quasi-systematic	
Uncertainty & units (1σ)	0 K	
Sensitivity coefficient	1	
Correlation(s) between affected parameters	None	
Element/step common for all sites/users?	Yes	
Traceable to …	No	
Validation	No	

5.31 Evaporative cooling (9b)

When the radiosonde flies through a cloud, the temperature sensor will inevitably be coated with water or ice, which may introduce errors in the temperature measurements above the cloud due to evaporative cooling. In extreme cases this effect can cause the occurrence of apparent superadiabatic lapse rates (SLRs) in radiosonde profiles near cloud tops[25]. Inside the cloud, the condensate on the temperature sensor is close to equilibrium with the surrounding air, so it is unlikely to affect the temperature measurement. However, after exiting the cloud, condensate starts to evaporate, leading to evaporative cooling of the sensor until all water or ice has evaporated. The magnitude and vertical extent of the error due to evaporative cooling are difficult to quantify as they depend on the unknown amount and phase of the condensate deposited on the sensor, and on the temperature and humidity of the ambient air above the cloud. Vaisala uses a special hydrophobic coating for the temperature sensor and the sensor boom to make the RS92 less prone to evaporative cooling. Currently, the GRUAN processing does not correct for this effect. In the next version of the data processing, evaporative cooling will be detected by superadiabatic lapse rates that coincide with a rapid decrease of humidity away from (near) saturation. The uncertainty budget will be adjusted where these SLRs occur.

Information / data	Type / value / equation	Notes / description
Name of effect	Evaporative cooling	
Contribution identifier	9b	
Measurement equation parameter(s) subject to effect	$T' = T$	Additional uncertainty alone
Contribution subject to effect (final product or sub-tree intermediate product)	Temperature	
Time correlation extent & form	None	
Other (non-time) correlation extent & form	None	
Uncertainty PDF shape	Quasi-systematic	
Uncertainty & units (1σ)	0 K	
Sensitivity coefficient	1	
Correlation(s) between affected parameters	None	
Element/step common for all sites/users?	Yes	
Traceable to …	No	
Validation	No	

5.32 Payload configuration (9c)

The payload configuration may introduce an additional error source. If a radiosonde is attached to a white Styrofoam ozone sonde box, this can act as a scattering surface and enhance the actinic flux on the temperature sensor in the same manner as clouds. A large object close to the radiosonde may also obstruct the proper ventilation of the temperature sensor. The GRUAN product does not employ a correction algorithm for the radiation and ventilation errors related to payload configuration. These errors are hard to quantify, and systematic experimental data to create such a correction is lacking. Therefore, in addition to the recommendations on the exposure of the temperature sensor given in chapter 12 of WMO (2008)[27], proper separation between neighbouring instruments within a payload should be considered, not only to ensure proper ventilation but also to minimize the additional radiation error.

Another effect of large payloads is the change of the rotation frequency of the rig, which changes the size and shape of the temperature spikes. The GRUAN spike algorithm removes all temperature spikes that exceed the threshold, provided the spike duration is short enough to be detected by the low-pass filter.

Information / data	Type / value / equation	Notes / description
Name of effect	Payload configuration	
Contribution identifier	9c	
Measurement equation parameter(s) subject to effect	$T' = T$	Additional uncertainty alone
Contribution subject to effect (final product or sub-tree intermediate product)	Temperature	
Time correlation extent & form	None	
Other (non-time) correlation extent & form	None	
Uncertainty PDF shape	Systematic (over ascent)	
Uncertainty & units (1σ)	0 K	
Sensitivity coefficient	1	
Correlation(s) between affected parameters	Ventilation speed 8a5 & spike removal 8b	
Element/step common for all sites/users?	Yes	
Traceable to …	No	
Validation	No	

6 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? (Use element identifier)
1	**Capacitive sensor**	**Accuracy** **statistical uncertainty** $\sigma(T)/\sqrt{N'}$	**±0.5 K (2σ)** **±0.1 K (1σ) in the trop. 0.2-0.5 K (1σ) in strat.**	**H** **H**	**Systematic (over ascent)** **random**	**none**
2	**Vaisala CAL4 calibration repeatability**	**constant**	**±0.15K (2σ)**	**H**	**random**	**none**
2a	Reference T sensor accuracy	constant	<±0.1 K (2σ)	H	systematic	none
3	**Transport & storage**	**constant**	**0 K**	**L**	**systematic**	**none**
4	**GC25 ground check pass/fail**	**Rectangular**	**0 K**	**M**	**systematic**	**2a**
5	**GC25 one point re-calibration**	**constant**	**±0.16 K (1σ)**	**H**	**systematic**	**2 & 5a**
5a	GC25 PT100 T sensor accuracy	constant	±0.15 K (1σ)	H	systematic	none
6	**Measurement time frame**	**N/A**	**0 K**	**H**	**random**	**none**
7	**Data transmitted to station**	**N/A**	**0 K**	**H**	**random**	**none**
8	**Post-measurement corrections**	**Primarily α ΔT (solar radiation correction)**	**±0.22 K (2σ) in trop. ±0.5 K (2σ) in strat.**	**M**	**quasi-systematic**	**none**
8a	Radiation correction	constant	<0.36 K (2σ)	M	systematic	none
8a1	Solar radiation temperature model	constant	<0.2 K (2σ)	M	systematic	none
8a2	Vaisala radiation correction	constant	0 K	M	quasi-systematic	8a1
8a3	Pressure	$\Delta T(I_a, p, v) = a \cdot x^b$ $\text{with } x = \frac{I_a}{p \cdot v}$	<0.001 K (1σ) in the trop., rising to ±0.03 K (1σ) in the strat.	M	random	Pressure product & 8a10
8a4	Solar Zenith Angle	constant	0 K	M	Systematic (over ascent)	
8a5	Launch site location	constant	0 K	H	Systematic	

8a6	Time of launch	constant	0 K	H	Systematic (over ascent)	
8a7	Actrinic flux model	constant	0 K	M	quasi-systematic	none
8a8	Ventilation speed	constant	±0.01 K (2σ) in the trop. up to ±0.3 K (2σ) in the strat.	M	quasi-systematic	Altitude product
8a9	Altitude	constant	0 K	M	quasi-systematic	Altitude product
8a10	Sensor orientation	constant	0 K	M	systematic	8a1
8a11	Cloud configuration	constant	0 K	L	Systematic	
8a12	Albedo	$\Delta T \cdot u_c(I_a)/I_a$ where ΔT is the solar radiation correction term from 8a1 and $U_c(I_a) = \frac{1}{2\cdot\sqrt{3}}\lvert I_a^{\text{clear sky}} - I_a^{\text{cloudy}}\rvert$	<0.05K (2σ)	M	Systematic (over ascent)	none
8b	Smoothing & spike removal	constant	±0.05K (2σ)	M	quasi-systematic	2
8b1	Low pass filtering	constant	0 K	M	quasi-systematic	2
8b2	Positive outlier removal	constant	±0.05K (2σ)	M	quasi-systematic	2
8b3	Refiltering, interpolation & variability	constant	0 K	M	quasi-systematic	2
8c	Rotating sonde	$2 \cdot \Delta T/\sqrt{3}$ where ΔT is the solar radiation corr.	±0.1 K (2σ) in trop. ±0.4 K (2σ) in strat.	M	quasi-systematic	
9	**Additional uncorrected sources**	**constant**	**<0.2K (2σ)**	**M**	**Systematic (over ascent)**	**8a5 & 8b**
9a	Sensor time lag	constant	< 0.03K (2σ)	M	quasi-systematic	none
9b	Evaporative cooling	constant	<0.2K (2σ)	M	Systematic (over ascent)	none
9c	Payload configuration	constant	0 K	L	Systematic	8a5 & 8b

Table 2. Overview of the sources contributing to the temperature uncertainty budget; values are given for 2σ ($k=2$). The items involving ΔT relate to the radiation temperature correction.

Parameter	Value	(Un)correlated	Data field in product
Repeatability of calibration of the T sensor $u_c(\mathrm{cal})$	0.15 K	correlated	
Absolute uncertainty of T sensor calibration $u_{c,\,\mathrm{cal}}(T)$	$\sqrt{u_c(\mathrm{cal})^2 + (\Delta T_{GC25}/3)^2}$	correlated	u_cor_temp*
Uncertainty in T due to spike removal	0.05 K	correlated	
Uncertainty in T due to sensor time-lag	< 0.03 K	correlated	
$\sigma(T)$	Statistical standard deviation	uncorrelated	u_std_temp*
Random uncertainty of temperature $u_u(T)$	Statistical uncertainty $\sigma(T)/\sqrt{N'}$	uncorrelated	
Uncertainty of ΔT due to rotating radiosonde $u_{u,\,\mathrm{rot}}(\Delta T)$	$2 \cdot \Delta T/\sqrt{3}$	uncorrelated	
Uncertainty of I_a due to albedo $u_c(I_a)$	$\frac{1}{2\cdot\sqrt{3}}\lvert I_a^{\mathrm{clear\ sky}} - I_a^{\mathrm{cloudy}}\rvert$	correlated	u_swrad*
Uncertainty in ΔT due to uncertainty in albedo $u_{c,I_a}(\Delta T)$	$\Delta T \cdot u_c(I_a)/I_a$	correlated	
Uncertainty in ventilation velocity $u(v)$	$1\ \mathrm{m\,s^{-1}}$	uncorrelated	
Uncertainty in ΔT due to ventilation uncertainty $u_{u,\,\mathrm{vent}}(\Delta T)$	$\Delta T \cdot u(v)/v$	uncorrelated	
Uncertainty in ΔT due to uncertainty in parameters a and b $u_{c,RC}(\Delta T)$	< 0.2 K	correlated	
Total uncertainty	$[u_{c,\,\mathrm{cal}}(T)^2 + u_u(T)^2 + u_{u,\,\mathrm{rot}}(\Delta T)^2 + u_{c,I_a}(\Delta T)^2 + u_{u,\,\mathrm{vent}}(\Delta T)^2 + u_{c,RC}(\Delta T)^2]^{1/2}$	–	u_temp*

* In the product file for processing version 2 the uncertainty is stored as $k=1$.

Figure 11. Uncertainty summary table from Dirksen et al[1].

The contribution of the major uncertainty sources is summarised in Figure 11. The altitude dependence of these is shown in Figure 10.

The combination of uncertainties is given by

$$[u_{c,cal}(T)^2 + u_u(T)^2 + u_{u,rot}(T)^2 + u_{c,I_a}(T)^2 + u_{u,vent}(T)^2 + u_{c,RC}(T)^2]^{1/2}$$

Where

$$U_{c,\,cal(T)} = \sqrt{u_c(\mathrm{cal})^2 + (\Delta T_{GC25}/3)^2}$$

giving typical daytime uncertainties of ±0.62 K (2σ) in the troposphere and ±0.92 K (2σ) in the stratosphere.

7 Traceability uncertainty analysis

Traceability level definition is given in Table 2.

Table 2. 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 3, should be considered further to improve the overall uncertainty of the GRUAN temperature product. The entires are given in an estimated priority order.

Table 3. 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? (Use element identifier)
8a2	Vaisala radiation correction	constant	0 K	M	quasi-systematic	8a1
8c	Rotating sonde	$2 \cdot \Delta T/\sqrt{3}$ where ΔT is the solar radiation corr.	±0.1 K (2σ) in trop. ±0.4 K (2σ) in strat.	M	quasi-systematic	
8a8	Ventilation speed	constant	±0.01 K (2σ) in the trop. up to ±0.3 K (2σ) in the strat.	M	quasi-systematic	Altitude product
8a9	Altitude	constant	0 K	M	quasi-systematic	Altitude product
3	Transport & storage	constant	0 K	L	systematic	none
4	GC25 ground check pass/fail	Rectangular	0 K	M	systematic	2a
8a4	Solar Zenith Angle	constant	0 K	M	Systematic (over ascent)	
8a5	Launch site location	constant	0 K	H	Systematic	
8a6	Time of launch	constant	0 K	H	Systematic (over ascent)	
8a7	Actrinic flux model	constant	0 K	M	quasi-systematic	none

8a10	Sensor orientation	constant	0 K	M	systematic	8a1
8a11	Cloud configuration	constant	0 K	L	Systematic	
8b1	Low pass filtering	constant	0 K	M	quasi-systematic	2
8b3	Refiltering, interpolation & variability	constant	0 K	M	quasi-systematic	2

7.1 Recommendations

An assessment of the uncertainty of the Vaisala solar heating correction term (8a2) should be evaluated.

Rotating sonde (8c) and Ventiation speed (8a8) are major contributors to the stratospheric tempertaure uncertainty which, with further investigation, could potentially be improved.

There are 11 contributions that do not have an assigned uncertainty. Some analysis to determine the magnitude of these potential contributions1 would better constrain the uncertainty budget.

8 Conclusion

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

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