Product Traceability and Uncertainty for the GRUAN RS92 radiosonde geopotential height product

Version 2.0

GAIA-CLIM
Gap Analysis for Integrated
Atmospheric ECV Climate Monitoring
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Work Package 2; Complied by David Medland, Paul Green & Tom Gardiner (NPL)

Table of Contents

Version history

Version	Principal updates	Owner	Date
1.0	First issue	NPL	26.07.2017
2.0	Issued as annex D to D2.6	NPL	30.11.2017

1 Product overview

Product name: In-situ radiosonde RS92 geopotential height
Product technique: Capacitive pressure sensor / GPS altitude
Product measurand: Pressure/Altitude
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: Site operators, see www.gruan.org
Instrument provider: 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.

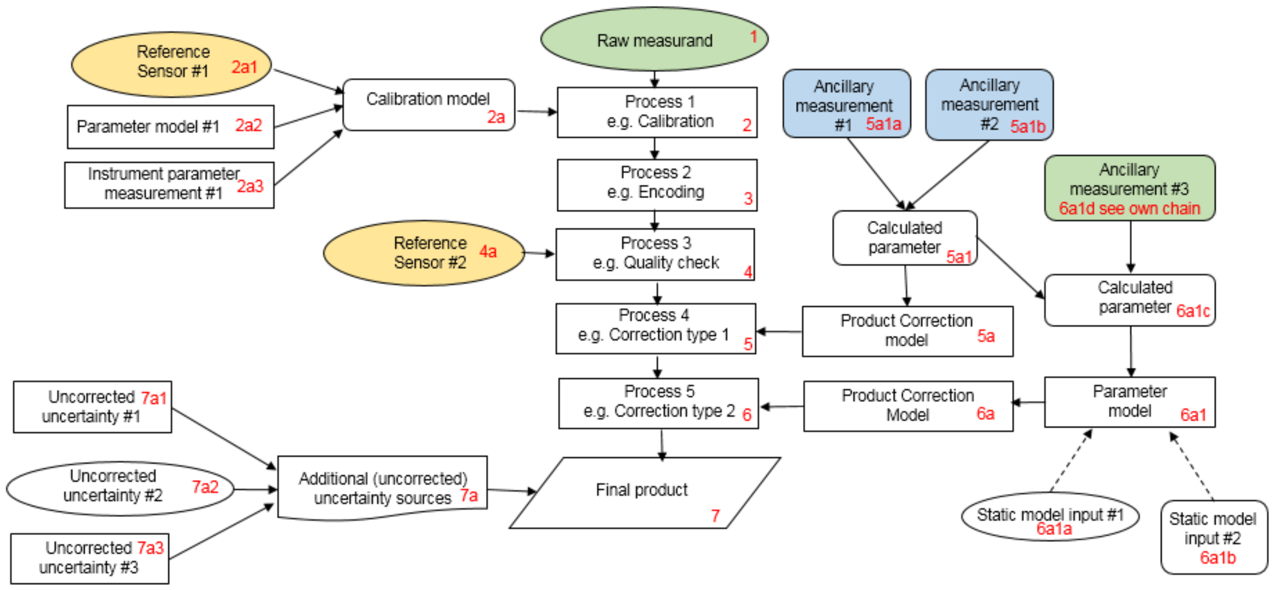


Figure 1. Example traceability chain. Green represents a key measurand or ancillary measurand recorded at the same time with the product raw measurand. Yellow represents a source of traceability. Blue represents a static ancillary measurement

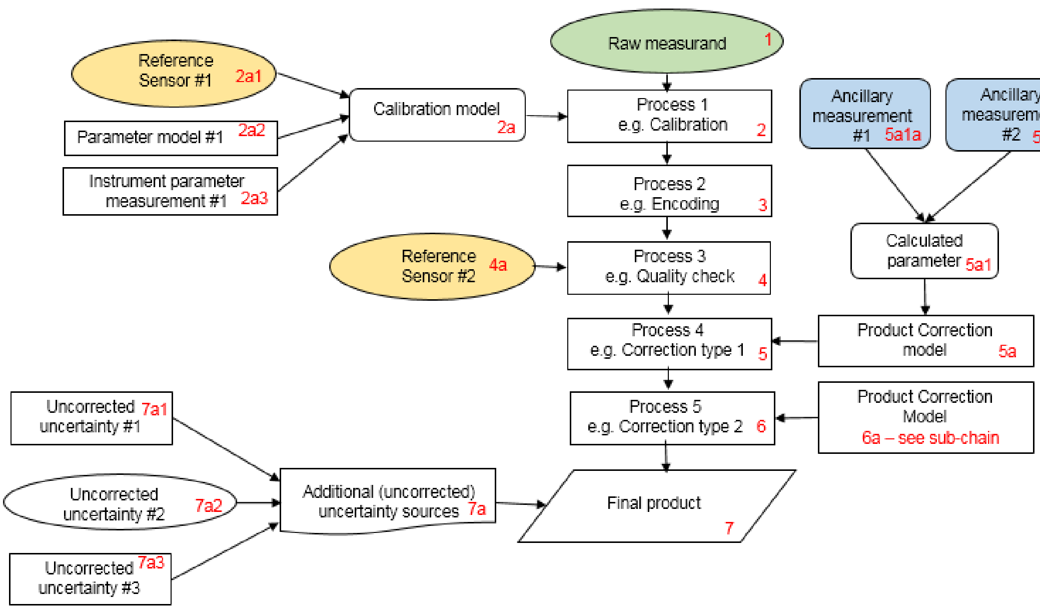


Figure 2. Example chain as sub-divided chain. Green represents a key measurand or ancillary measurand recorded at the same time with the product raw measurand. Yellow represents a source of traceability. Blue represents a static ancillary measurement

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.

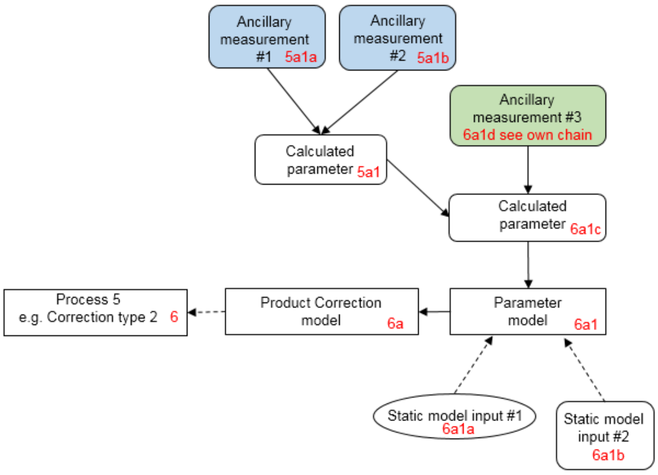


Figure 3. Example chain contribution 6a sub-chain. Green represents a key measurand or ancillary measurand recorded at the same time with the product raw measurand. Blue represents a static ancillary measurement

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.

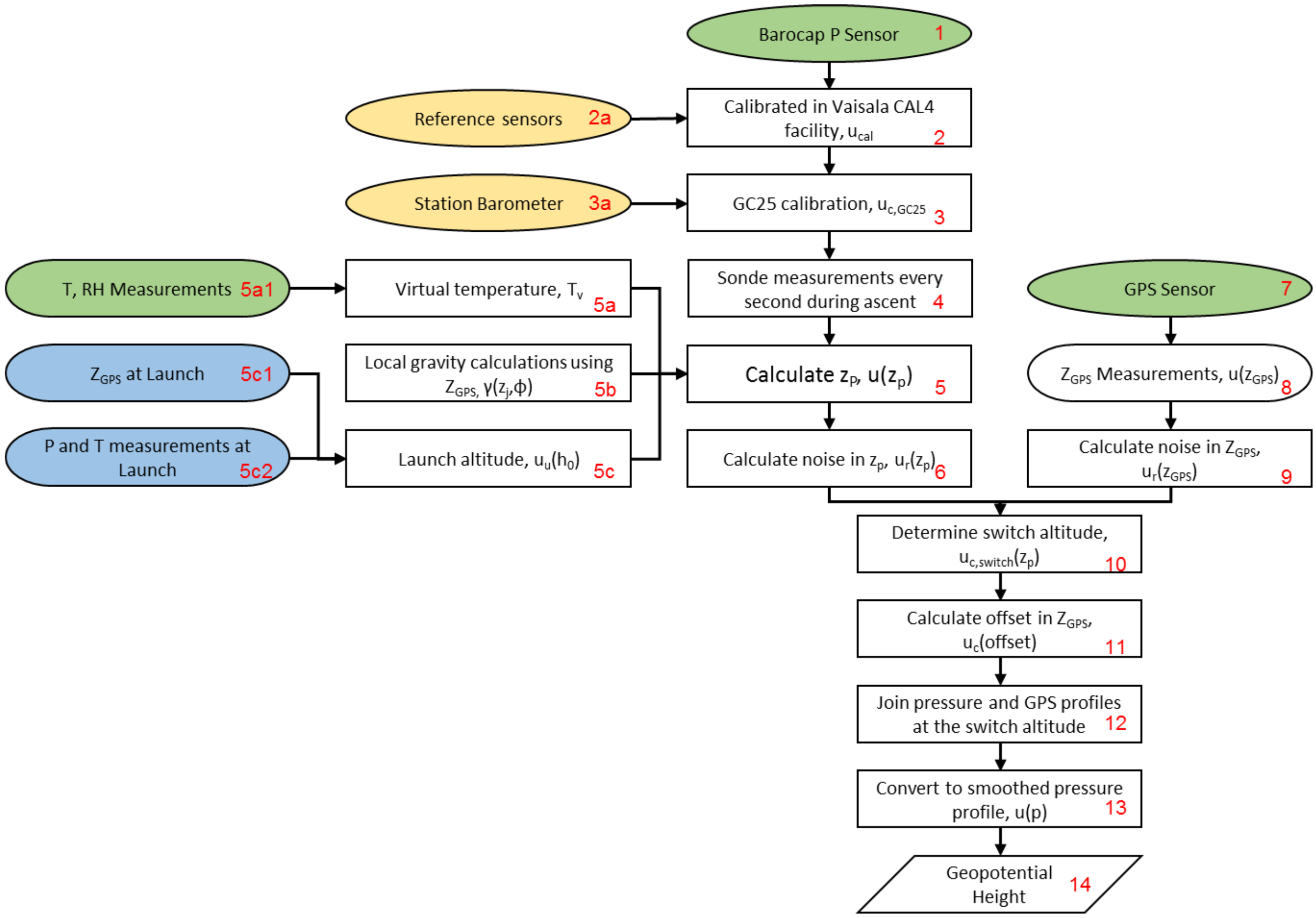
2 Introduction

This document describes the product traceability and uncertainty information for the GRUAN (GCOS (Global Climate Observing System) Reference Upper-Air Network) RS92 radiosonde geopotential height product. The derivation of the geopotential height uses the GRUAN RS92 radiosonde altitude product as well as the GRUAN RS92 radiosonde pressure product and so the traceability and uncertainty information of these data products is also contained within this document.

The RS92 Radiosonde is equipped with a Barocap, which determines pressure from the capacitance between an electrode on a silicon membrane separated from another electrode by a vacuum. Data is transmitted at 1 second intervals and stored by DigiCora ground station equipment. It is also equipped with a GPS receiver which collects xyz coordinates in WGS-84 (World Geodetic System 1984). These are converted to longitude, latitude and altitude by the DigiCora system using altitude derived from pressure measurements as a reference. Geopotential height is calculated using measurements collected from both of these instruments. The Barocap is calibrated by Vaisala using their CAL4 facility and is recalibrated during a pre-flight ground check using a GC25 unit.

The process through which the GRUAN geopotential height product is derived from raw pressure and altitude data, as well as the methods used at ground check to calibrate the instruments and determine the uncertainty of the data product are described in Dirksen et al[1]. 2014, which has been used for the creation of this document, and the methods and uncertainties detailed here are as they present. The data product was developed to meet the criteria for reference measurements, these include the collection of metadata, the use of well documented algorithms and estimates of the measurement uncertainty. Overall GRUAN uncertainty estimates are 0.6 hPa for pressure and 10-50 m for altitude and geopotential height.

3 Product Traceability Chain



4 Element Contributions

4.1 Barocap pressure sensor (1)

The RS92 radiosonde measures pressure using a Barocap. This has one electrode on a silicon base and another on a silicon membrane separated by a vacuum. As pressure changes so does the separation of the electrodes, varying the capacitance which is converted to a pressure measurement. The uncertainty expressed here is the standard deviation between twin soundings as determined by Vaisala, but is not used in the GRUAN processing.

Information / data	Type / value / equation	Notes / description
Name of effect	Barocap pressure sensor	Random noise of barocap pressure sensor and calibration uncertainty
Contribution identifier	1	
Measurement equation parameter(s) subject to effect	Geopotential height	
Contribution subject to effect (final product or sub-tree intermediate product)	Geometric pressure altitude, pressure readings with uncertainties	
Time correlation extent & form	none	
Other (non-time) correlation extent & form	none	
Uncertainty PDF shape	normal	
Uncertainty & units (2σ)	0.5 hPa > 100 hPa 0.3 hPa < 100 hPa	Variability between twin soundings. 2σ. From Vaisala RS92 technical data[2].
Sensitivity coefficient	1	Uncertainty not included in GRUAN processing
Correlation(s) between affected parameters	Launch height uncertainty.	
Element/step common for all sites/users?	yes	
Traceable to …	Vaisala	
Validation	N/A	

4.2 Calibrated in Vaisala CAL4 facility (2), u_{cal}

The uncertainty represented here is the repeatability in calibration which is carried out at Vaisala's CAL-4 facility. This tests the RS92 barocap in 4 chambers with constant temperature and pressure between 1080 and 2 hPa. Ten pressure levels are used to fit a calibration curve at +25 °C and the temperature dependence of the barocap determined by the deviation from this calibration curve.

Information / data	Type / value / equation	Notes / description

Name of effect	Calibrated in Vaisala CAL4 facility.	
Contribution identifier	2, u_{cal}	
Measurement equation parameter(s) subject to effect	Geopotential height	
Contribution subject to effect (final product or sub-tree intermediate product)	Geopotential height	
Time correlation extent & form	Long term	Between calibrations of the reference sensors.
Other (non-time) correlation extent & form	Over flight.	Used in calculating uncertainty in pressure.
Uncertainty PDF shape	normal	
Uncertainty & units (2σ)	0.4 hPa >100 hPa 0.3 hPa <100 hPa	Repeatability in calibration. k = 2. From Vaisala RS92 technical data[2].
Sensitivity coefficient	1	
Correlation(s) between affected parameters	Barocap pressure sensors	
Element/step common for all sites/users?	yes	
Traceable to …	Vaisala	
Validation	N/A	

4.3 Reference pressure sensors (2a)

The CAL4 contains PTU reference sensors that are recalibrated at regular intervals against standards that are traceable to NIST for pressure. The operating range and accuracy of the PTU sensors for pressure is 2 (±0.3) to 1080 (±0.3) hPa.

Information / data	Type / value / equation	Notes / description
Name of effect	Reference pressure sensors	
Contribution identifier	2a	
Measurement equation parameter(s) subject to effect	Geopotential height,	
Contribution subject to effect (final product or sub-tree intermediate product)	Calibrated in Vaisala CAL4 facility	
Time correlation extent & form	Long-term	Correlated over period of reference sensor recalibration, 6 months for digital barometers, 12 months for analogue pressure transmitters[3].

Other (non-time) correlation extent & form	none	
Uncertainty PDF shape	normal	
Uncertainty & units (2σ)	<0.3 hPa	K=2, From vaisala 2007 CAL4 technical note[3].
Sensitivity coefficient	1	
Correlation(s) between affected parameters	none	
Element/step common for all sites/users?	yes	
Traceable to …	NIST	
Validation	None	

4.4 GC25 Calibration (3), $u_{c,GC25}$

Determined from the calibration uncertainty of the pressure sensor and the difference between the station barometer and RS92 pressure sensor during ground check. This uses a Vaisala GC25 unit. For the ground check of the pressure sensor a separate reference measurement is used, in this case from the station barometer. This is entered into the GC25 which applies the correction factor, calculated as $c = p_{station}/p_{RS92,GC25}$, which is applied to the entire pressure profile. The GRUAN processing uses the recalibrated data. The uncertainty in the calibration is the geometric sum of the Vaisala calibration uncertainty and a contribution from the applied correction based on the difference in the radiosonde and station barometer pressure readings, this is usually around 0.5 hPa and any sondes with a difference greater than 1.5 hPa are rejected.

Information / data	Type / value / equation	Notes / description
Name of effect	GC25 Calibration	Pre-launch re-calibration with onsite barometer
Contribution identifier	3, $u_{c,GC25}$	
Measurement equation parameter(s) subject to effect	Geopotential height	
Contribution subject to effect (final product or sub-tree intermediate product)	Geopotential height	
Time correlation extent & form	Long term	Between recalibrations of the station barometer.
Other (non-time) correlation extent & form	Systematic over flight	Does not affect the uncertainty of geopotential height
Uncertainty PDF shape	rectangular	
Uncertainty & units (2σ)	$u_{c,GC25}(p) = \sqrt{u_{cal}^2 + (\frac{\Delta p_{GC25}}{3})^2}$ Using typical values of u_{cal}=0.4 hPa and Δp_{GC25}=0.5 hPa gives $u_{c,GC25}(p)$=0.43 hPa.	U_{cal} is the calibration uncertainty of the pressure sensor. Δp_{GC25} is pressure difference between the sonde and station barometer at

		ground check[1].
Sensitivity coefficient	1	
Correlation(s) between affected parameters	none	
Element/step common for all sites/users?	Yes	
Traceable to …	Barocap pressure sensor, station barometer	
Validation	N/A	

4.5 Station barometer (3a)

The station barometer is used in determining the launch altitude of the sonde and in re-calibrating the sondes pressure sensor.

Information / data	Type / value / equation	Notes / description
Name of effect	Station Barometer	
Contribution identifier	3a	
Measurement equation parameter(s) subject to effect	Geopotential height, Pressure	
Contribution subject to effect (final product or sub-tree intermediate product)	GC25 Calibration	
Time correlation extent & form	Long term systematic	Between re-calibrations of the station barometer
Other (non-time) correlation extent & form	none	
Uncertainty PDF shape	normal	
Uncertainty & units (2σ)	< 0.5 m <0.06 hPa	$U_{u,launch}(z_p)$ is included in $u_u(h_0)$ so has to be smaller. Converted to pressure using equation 22 in Dirksen et Al.
Sensitivity coefficient	1	
Correlation(s) between affected parameters	Launch altitude uncertainty	
Element/step common for all sites/users?	yes	
Traceable to …	Station specific	
Validation	N/A	

4.6 Sonde Measurements every second during ascent (4)

The pressure measurements are taken by the radiosonde using the barocap every second after launch during the ascent. The uncorrelated uncertainty associated with this step is calculated as part of step 6, calculate noise in z_p.

Information / data	Type / value / equation	Notes / description
Name of effect	Sonde measurements every second during ascent	
Contribution identifier	4	
Measurement equation parameter(s) subject to effect	Geopotential height, Pressure	
Contribution subject to effect (final product or sub-tree intermediate product)	Geopotential height	
Time correlation extent & form	none	
Other (non-time) correlation extent & form	none	
Uncertainty PDF shape	Normal	
Uncertainty & units (1σ)	0	Covered in element 6
Sensitivity coefficient	1	
Correlation(s) between affected parameters	Virtual temperature	
Element/step common for all sites/users?	yes	
Traceable to …	Vaisala	
Validation	N/A	

4.7 Calculate geometric pressure altitude (5), z_p

The change in geometric altitude between two measurements is calculated from pressure using:

$$\Delta H_{1,2} = \frac{R_d}{\gamma(z_j,\varphi)}\bar{T}_v ln(\frac{p_1}{p_2})$$

Where $\bar{T}_v$ is the average virtual temperature between pressure levels p_1 and p_2, discussed in section 3.8, and $\gamma\left(z_j,\varphi\right)$ is the local gravity, discussed in section 3.10. The geometric altitude is then calculated as:

$$z_p = h_0 + \sum \Delta H$$

Where h_0 is the launch altitude. The uncertainty in geometric pressure altitude is calculated as the geometric sum of the random ($u_r(z_p)$, see section 3.14) and correlated uncertainty and the uncertainty in launch height ($u_u(h_0)$, see section 3.11). This uncertainty is dominated by correlated uncertainty which is calculated from the bias of the pressure sensor ΔP:

$$\Delta p = p\,[\exp\left(\frac{\gamma \Delta z}{R_d T}\right) - 1]$$

Where $\Delta z = z_p - z_{GPS}$. The correlated uncertainty $u_c(z_p)$ is then:

$$u_c(z_p) = 0.5 \times (z(p + \Delta p) - z(p - \Delta p))$$

Information / data	Type / value / equation	Notes / description
Name of effect	Geometric pressure altitude	
Contribution identifier	5, z_p	
Measurement equation parameter(s) subject to effect	Geopotential height	
Contribution subject to effect (final product or sub-tree intermediate product)	Geopotential height	
Time correlation extent & form	none	
Other (non-time) correlation extent & form	Sounding, throughout flight	Influences uncertainty in geometric GPS altitude
Uncertainty PDF shape	normal	
Uncertainty & units (2σ)	$u(z_p) = \sqrt{u_u(h_0)^2 + u_r(z_p)^2 + u_c(z_p)^2}$	Usually starts at 0.5 m and increases with altitude up to between 10-50 m. the uncorrelated uncertainty is usually <2 m[1].
Sensitivity coefficient	1	
Correlation(s) between affected parameters	none	
Element/step common for all sites/users?	yes	
Traceable to …	Launch altitude uncertainty, bias of pressure sensor	
Validation	Altitude from GPS	

4.8 Virtual temperature (5a), T_v

Virtual temperature of a moist air parcel is equal to the temperature that a dry air parcel of the same pressure and density would have. It is used in calculating geometric altitude from pressure, or pressure from geometric altitude, which depends on the average virtual temperature between two pressure levels $\overline{T_v}$ where:

$$\overline{T_v} = \frac{\overline{T}}{1 - 0.01 \cdot RH(1 - 0.622)p_s/\overline{p}}$$ [1]

Here p_s is the saturation pressure for water vapour at $\overline{T}$ calculated according to the formulation of Hyland and Wexler 1983[4]. 0.622 is the ratio of the molar masses of water vapour and dry air, RH is the relative humidity. $\bar{T} = \frac{T_1+T_2}{2}$ and $\bar{p} = \sqrt{p_1 p_2}$. The uncertainty in virtual temperature would have an effect on the final uncertainty in geopotential height but it is assumed small and not accounted for.

Information / data	Type / value / equation	Notes / description
Name of effect	Virtual Temperature	
Contribution identifier	5a, T_v	
Measurement equation parameter(s) subject to effect	Geopotential height	
Contribution subject to effect (final product or sub-tree intermediate product)	Geometric pressure altitude	
Time correlation extent & form	none	
Other (non-time) correlation extent & form	none	
Uncertainty PDF shape	N/A	
Uncertainty & units (1σ)	$u(\bar{T_v}) \approx u(T)$	Based on sensitivity tests using ΔT = u_temp and Δrh = u_rh.
Sensitivity coefficient	1	Uncertainty not included in GRUAN processing
Correlation(s) between affected parameters	Smoothed pressure profile, geopotential height	
Element/step common for all sites/users?	yes	
Traceable to …	Sonde T and RH measurements, p measurements, geopotential height, saturation pressure calculations.	
Validation	N/A	

4.9 Sonde T and RH readings (5a1)

The radiosonde carries a thin film capacitor humidity sensor and a capacitive wire temperature sensor. These are used in calculating mean virtual temperature and the bias of the pressure sensor, but the uncertainties they contribute are assumed small and not accounted for in the final geopotential height uncertainty. The assessment of the uncertainty in the GRUAN temperature or relative humidity product can be found in the relevant PTU documents.

Information / data	Type / value / equation	Notes / description
Name of effect	Sonde T and RH readings	
Contribution identifier	5a1	
Measurement equation	Geopotential height	

parameter(s) subject to effect		
Contribution subject to effect (final product or sub-tree intermediate product)	Virtual temperature	
Time correlation extent & form	none	
Other (non-time) correlation extent & form	none	
Uncertainty PDF shape	normal	
Uncertainty & units (1σ)	Change in ΔH: 0.05 % with change in T, throughout profile. 0.02 % with change in RH, throughout profile. Change in z_p: 5 m at 15 km with change in T. <0.7 m at 15 km with change in RH.	Using sensitivity tests with ΔT=u_cor_temp and ΔRH = u_cor_rh. Correlated uncertainty was used as z is calculated from a sum of many individual steps and it would be expected that the statistical errors in each step cancel out.
Sensitivity coefficient	1	Uncertainty not included in GRUAN processing
Correlation(s) between affected parameters	Also used in bias of the pressure sensor, launch altitude	
Element/step common for all sites/users?	yes	
Traceable to …	GRUAN T and RH measurements.	See temperature and relative humidity traceability documents.
Validation	N/A	

4.10 Local Gravity Calculations (5b)

Local gravity is used in calculating geometric altitude from pressure and the bias of the pressure sensor. It can be found using:

$$\gamma(z_j, \varphi) = 9.780318 \cdot \left(1 + 5.3024 \cdot 10^{-3} sin^2(\varphi) - 5.8 \cdot 10^{-6} sin^2(2\varphi)\right) - 3.085 \cdot 10^{-5} z_j$$ [5]

Where z_{GPS} is used for z_j to avoid recursive calculation.

Information / data	Type / value / equation	Notes / description
Name of effect	Local Gravity Calculations	
Contribution identifier	5b, $\gamma(z_j, \varphi)$	
Measurement equation parameter(s) subject to effect	Geopotential height	

Contribution subject to effect (final product or sub-tree intermediate product)	Geometric pressure altitude	
Time correlation extent & form	none	
Other (non-time) correlation extent & form	none	
Uncertainty PDF shape	N/A	
Uncertainty & units (1σ)	Change in ΔH: 7×10^{-4} % with change in z_{GPS}, throughout profile. 4×10^{-4} % with change in φ, throughout profile. Change in z_p: 0.06 m at 15km with change in z_{GPS} 0.1 m at 15 km with change in φ	Based on sensitivity tests using Δz_{GPS} = 20 m and Δφ = 0.001°.
Sensitivity coefficient	1	Uncertainty not included in GRUAN processing
Correlation(s) between affected parameters	Smoothed pressure profile	
Element/step common for all sites/users?	yes	
Traceable to …	GPS altitude measurements	
Validation	N/A	

4.11 Launch altitude (5c), $u_u(h_0)$

The launch altitude is calculated from the first sonde pressure reading after launch and the station barometer using the hydrostatic equation and the station barometers altitude. The total uncertainty in launch altitude is determined from the uncertainty of the station barometer, including the uncertainty in the station barometers altitude, and from the random noise of the pressure sensor at launch. ρ_0 is calculated from the sonde pressure and temperature readings at launch and $\gamma(h_{station},\varphi_{station})$ is the local gravity.

Information / data	Type / value / equation	Notes / description
Name of effect	Launch altitude uncertainty	
Contribution identifier	5c, $u_u(h_0)$	
Measurement equation parameter(s) subject to effect	Geopotential height, pressure readings with uncertainties.	
Contribution subject to effect (final product or sub-tree intermediate product)	Geometric pressure altitude	

Time correlation extent & form	Between recalibrations of the station barometer and measurements of the station barometer altitude.	
Other (non-time) correlation extent & form	Throughout sounding	
Uncertainty PDF shape	normal	
Uncertainty & units (2σ)	$u_u(h_0) = \sqrt{u_{u,launch}^2(z_p) + (100 \cdot \frac{u_r(p_1)}{\rho_o \gamma(h_{station}, \emptyset_{station})})^2}$ Typical value < 0.5 m	Geometric sum of uncertainty of station barometer and random noise[1]. $U_u(h_0)$ is included in $u(z_p)$. Assuming p is measured in hectopascals, the factor of 100 scales the measurements to pascals.
Sensitivity coefficient	1	
Correlation(s) between affected parameters	none	
Element/step common for all sites/users?	yes	
Traceable to …	Pre-launch pressure readings, station barometer, local gravity calculations, sonde temperature readings.	
Validation	N/A	

4.12 GPS altitude at launch (5c1)

Used in calculating the station local gravity for the uncertainty in launch altitude.

Information / data	Type / value / equation	Notes / description
Name of effect	GPS altitude at launch	
Contribution identifier	5c1	
Measurement equation parameter(s) subject to effect	Geopotential height	
Contribution subject to effect (final product or sub-tree intermediate product)	Launch altitude	
Time correlation extent & form	none	
Other (non-time) correlation extent & form	none	
Uncertainty PDF shape	normal	

Uncertainty & units (2σ)	20 m[5]	Vertical position uncertainty according to Vaisala RS92 datasheet[6] Used in calculating local gravity, but the uncertainty is not propagated.
Sensitivity coefficient	1	Uncertainty is not used in GRUAN processing.
Correlation(s) between affected parameters	none	
Element/step common for all sites/users?	yes	
Traceable to …	GPS sensor	
Validation	N/A	

4.13 Pre-launch pressure readings (5c2)

The statistical noise is determined from 100 pressure readings taken around the time of launch. Used in determining the uncertainty in the launch altitude.

Information / data	Type / value / equation	Notes / description
Name of effect	Pre-launch pressure readings	Statistical noise of 100 readings taken around launch time
Contribution identifier	5c2	
Measurement equation parameter(s) subject to effect	Geopotential height	
Contribution subject to effect (final product or sub-tree intermediate product)	Launch height uncertainty	
Time correlation extent & form	none	
Other (non-time) correlation extent & form	none	
Uncertainty PDF shape	normal	
Uncertainty & units (2σ)	0.06 hPa	Calculated using typical values of 0.5 m uncertainty, 1.225 kgm^{-3} air density and 9.8 ms^{-2} local gravity.
Sensitivity coefficient	$100/(\rho_0\gamma(h_{station},\varphi_{station}))$	Factor of 100 scales the pressure uncertainty from hectopascals to pascals.
Correlation(s) between affected parameters	none	
Element/step common for all sites/users?	yes	

Traceable to …	Barocap pressure sensor	
Validation	N/A	

4.14 Calculate noise in z_p (6), $u_r(z_p)$

The noise in z_p is calculated using a 100-point wide window so it can be compared to the noise in z_{GPS} to determine the switch altitude. The statistical uncertainty at a point s_i is calculated using[7] (equation A5 in Dirksen et al.):

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

Where $N' = (\sum_{j=-M}^{M} c_j^2)^{-1}$ is the effective sample size and c_j normalizes the kernel, so that $\sum c_j = 1$ and $c_{-j} = c_j$.

Information / data	Type / value / equation	Notes / description
Name of effect	Calculate noise in z_p	
Contribution identifier	6, $u_r(z_p)$	
Measurement equation parameter(s) subject to effect	Geopotential height	
Contribution subject to effect (final product or sub-tree intermediate product)	Switch altitude	
Time correlation extent & form	100 measurement points.	
Other (non-time) correlation extent & form	normal	
Uncertainty PDF shape	normal	
Uncertainty & units (2σ)	About 0.25 m below z_{switch} but rapidly increases above 15 km altitude to 1.5 m - 2 m	Based on Dirksen et al. 2014 figure 19 – see figure 1.
Sensitivity coefficient	1	
Correlation(s) between affected parameters	none	
Element/step common for all sites/users?	yes	
Traceable to …	Geometric altitude	
Validation	N/A	

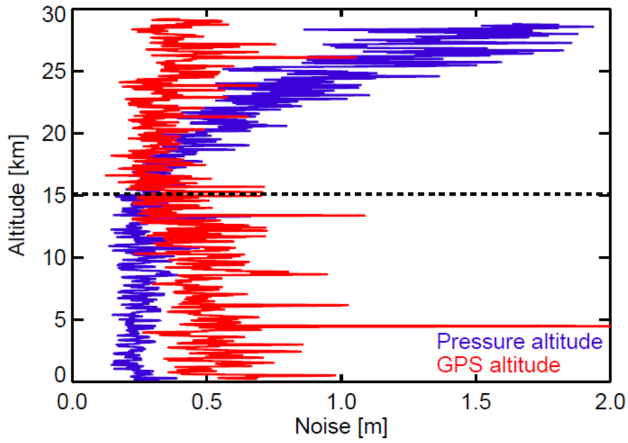


Figure 19. Noise of the geometric altitude derived from the pressure sensor (blue) and the GPS sensor (red). The standard deviation is calculated using Eq. (A5) for a low-pass filter with a cut-off frequency of 0.067 Hz (corresponding to a period of 15 s). The dashed black line indicates the altitude (15.1 km) where the switch from pressure-based to GPS-based altitude occurs. The sounding was performed at Lindenberg on 17 September 2013 at 12:00 UTC.

Figure 4 Dirksen et al. figure 19

4.15 GPS sensor (7)

The RS92-SGP radiosonde uses a code-correlating GPS sensor. Because of accuracy problems in the first few kilometres the geopotential height is only calculated using the GPS measurements for higher altitudes.

Information / data	Type / value / equation	Notes / description
Name of effect	GPS Sensor	
Contribution identifier	7	
Measurement equation parameter(s) subject to effect	Geopotential height	
Contribution subject to effect (final product or sub-tree intermediate product)	Geopotential height	
Time correlation extent & form	none	
Other (non-time) correlation extent & form	none	
Uncertainty PDF shape	normal	
Uncertainty & units (2σ)	20 m	Vertical position uncertainty, from Vaisala RS92 data sheet[6].
Sensitivity coefficient	1	Uncertainty is not used in GRUAN processing.

Correlation(s) between affected parameters	Z_{GPS} at launch	
Element/step common for all sites/users?	yes	
Traceable to …	Vaisala	
Validation	N/A	

4.16 GPS altitude measurements (8)

The RS92 GPS takes vertical and horizontal position measurements every second after launch using WGS-84 xyz coordinates. Standard Vaisala processing uses a station GPS antenna as a reference but GRUAN processing uses z_p, calculated from the station barometer, to convert these to altitude. The total uncertainty in the GPS altitude measurements is the geometric sum of the statistical noise of z_{GPS}, the correlated uncertainty at the switch altitude (see section 3.5) and the uncertainty of the offset, which is the statistical uncertainty of z_p-z_{GPS} at the switch altitude.

Information / data	Type / value / equation	Notes / description
Name of effect	GPS measurements	
Contribution identifier	8, z_{GPS}	
Measurement equation parameter(s) subject to effect	Geopotential height,	
Contribution subject to effect (final product or sub-tree intermediate product)	Geometric GPS altitude	
Time correlation extent & form	none	
Other (non-time) correlation extent & form	none	
Uncertainty PDF shape	normal	
Uncertainty & units (2σ)	$u(z_{GPS}) = \sqrt{u_r(z_{GPS})^2 + u_c(offset)^2 + u_{c,switch}(z_p)^2}$ Is fairly constant and usually between 10-50 m	This is dominated by the correlated uncertainty[1].
Sensitivity coefficient	1	
Correlation(s) between affected parameters	Local gravity calculations	
Element/step common for all sites/users?	yes	
Traceable to …	GPS sensor, switch altitude, offset calculation	
Validation	Altitude from pressure.	

4.17 Calculate Noise in Z_{GPS} (9), $u_r(Z_{GPS})$

The statistical noise in z_{GPS} calculated over a 100 point window using the same method described in section 4.12

Information / data	Type / value / equation	Notes / description
Name of effect	Calculate noise in z_{GPS}	
Contribution identifier	9, $u_r(z_{GPS})$	
Measurement equation parameter(s) subject to effect	Geopotential height	
Contribution subject to effect (final product or sub-tree intermediate product)	Switch altitude	
Time correlation extent & form	none	
Other (non-time) correlation extent & form	100 measurement points.	
Uncertainty PDF shape	normal	
Uncertainty & units (2σ)	0.4 m	Based on Dirksen et al. 2014 figure 19, see Figure 1.
Sensitivity coefficient	1	
Correlation(s) between affected parameters	none	
Element/step common for all sites/users?	none	
Traceable to …	z_{GPS}	
Validation	N/A	

4.18 Switch altitude (10), z_{switch}

The switch altitude is the altitude at which geometric pressure altitude stops being used and geometric GPS altitude starts being used instead. This is determined as the first level above 3km where the statistical noise in z_{GPS} exceeds the statistical noise in z_p by less than 20%. Usually lies between 9km and 17km. See Figure 1 for example.

Information / data	Type / value / equation	Notes / description
Name of effect	Switch altitude	
Contribution identifier	10, z_{switch}	
Measurement equation parameter(s) subject to effect	Geopotential height, pressure readings with uncertainties	
Contribution subject to effect (final product or sub-tree intermediate product)	Geometric GPS altitude	

Time correlation extent & form	none	
Other (non-time) correlation extent & form	Sounding above switch altitude	
Uncertainty PDF shape	normal	
Uncertainty & units (2σ)	$U_{c,switch}(z_p)$, <10-50 m	The correlated uncertainty of the geometric pressure altitude at the switch altitude. Is included in $u(z_{GPS})$ so has to be smaller[1].
Sensitivity coefficient	1	
Correlation(s) between affected parameters	none	
Element/step common for all sites/users?	yes	
Traceable to …	Z_p, z_{GPS}	Depends on the noise in z_p and in z_{GPS}.
Validation	N/A	

4.19 Geometric altitude offset (11), z_{offset}

The offset is the difference between the geometric pressure altitude and the GPS altitude measurement at the switch altitude. Typically has a value of about 50m. The uncertainty of the offset is the statistical uncertainty of z_p-z_{GPS} at the switch altitude, z_{switch}.

Information / data	Type / value / equation	Notes / description
Name of effect	Geometric altitude offset	
Contribution identifier	11, z_{offset}	
Measurement equation parameter(s) subject to effect	Geopotential height, pressure readings with uncertainties.	
Contribution subject to effect (final product or sub-tree intermediate product)	Geometric GPS altitude.	
Time correlation extent & form	None.	
Other (non-time) correlation extent & form	Sounding above switch altitude.	
Uncertainty PDF shape	Normal.	
Uncertainty & units (1σ)	< 10-50 m	Since u_c(offset) is included in $u(z_{GPS})$ the value has to be smaller than the total uncertainty.
Sensitivity coefficient	1	
Correlation(s) between affected	none	

parameters		
Element/step common for all sites/users?	yes	
Traceable to …	Z_p, z_{GPS},	
Validation	N/A	

4.20 Join Pressure and GPS profiles at the switch altitude (12), z

Joining pressure and GPS altitude profiles produces the geophysical altitude. The geophysical altitude is then z_p below the switch altitude and $z_{GPS}+z_{offset}$ above.

Information / data	Type / value / equation	Notes / description
Name of effect	Join z_p and z_{GPS} at the switch altitude	
Contribution identifier	12, z	
Measurement equation parameter(s) subject to effect	Geopotential height	
Contribution subject to effect (final product or sub-tree intermediate product)	Geopotential height	
Time correlation extent & form	none	
Other (non-time) correlation extent & form	none	
Uncertainty PDF shape	normal	
Uncertainty & units (2σ)	$U(z_p)$ below z_{switch} $U(z_{GPS})$ above z_{switch} 10-50 m (<35 usually)	For example values see Figure 2. 10-50 m range based on Dirksen et al. Data files show u_alt usually below 35 m. Both are dominated by correlated uncertainty.
Sensitivity coefficient	1	
Correlation(s) between affected parameters	none	
Element/step common for all sites/users?	yes	
Traceable to …	Z_p,z_{GPS},z_{switch},z_{offset}	
Validation	N/A	

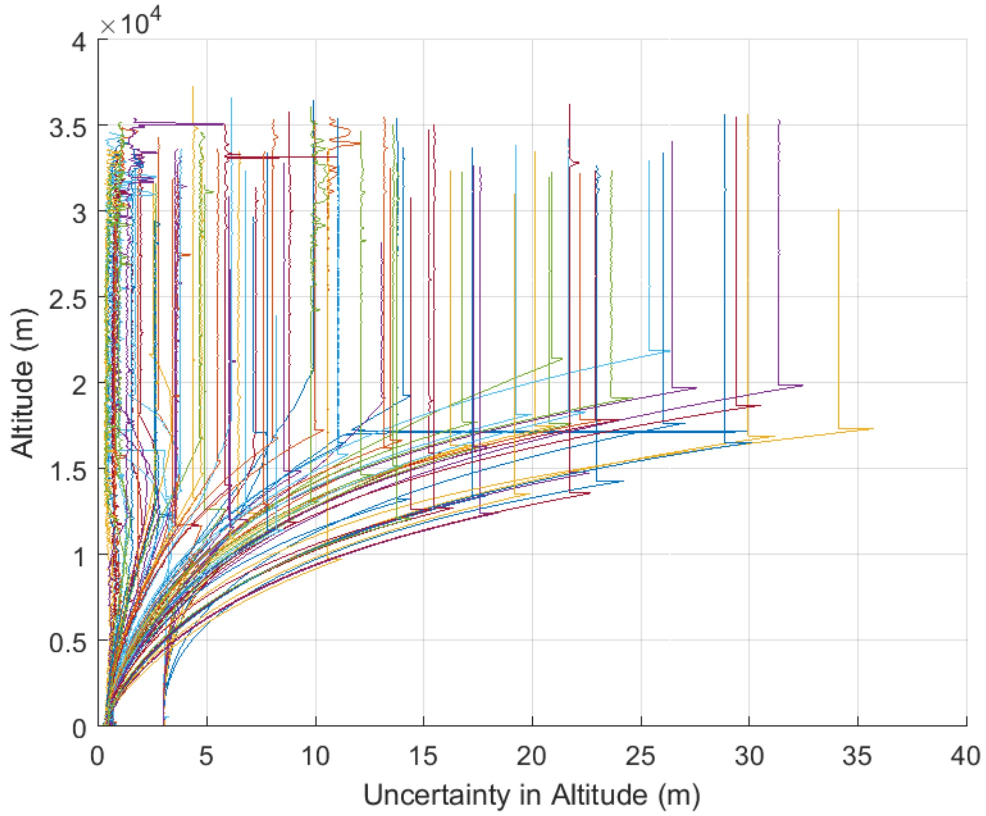


Figure 5. typical examples of uncertainty in altitude, u_alt, with altitude, taken from a sample of RS92 radiosondes launched at Lindenberg between 2012 and 2017.

4.21 Smoothed pressure profile (13), p

Geometric altitude is converted into a smoothed pressure profile before being converted into geopotential height. The pressure difference between two altitude levels is calculated using:

$$\Delta p_{j-1,j} = p_j[\exp\left(\frac{\gamma(z_j,\varphi)\cdot\Delta z_{j,j-1}}{R_d\cdot\bar{T}_{v,j}}\right)-1]$$

The uncertainty in p is then determined using u(z), where z is z_p below the switch altitude and z_{GPS} above it.

Information / data	Type / value / equation	Notes / description
Name of effect	Conversion to smoothed pressure profile	
Contribution identifier	13, p	
Measurement equation parameter(s) subject to effect	Geopotential height	
Contribution subject to effect (final product or sub-tree intermediate product)	Geopotential height	

Time correlation extent & form	none	
Other (non-time) correlation extent & form	Degree of smoothing	
Uncertainty PDF shape	normal	
Uncertainty & units (2σ)	$u(p) = \sqrt{(u_{c,GC25}(p))^2 + (\frac{\gamma_{45} \cdot p}{R_d \cdot T} \cdot \exp\left(-\frac{\gamma_{45} \cdot dz}{R_d \cdot T}\right) \cdot u(z))^2}$ < 0.6 hPa	For values see figure 3.
Sensitivity coefficient	1	
Correlation(s) between affected parameters	none	
Element/step common for all sites/users?	Yes	
Traceable to …	Geophysical altitude, GC25 calibration	
Validation	N/A	

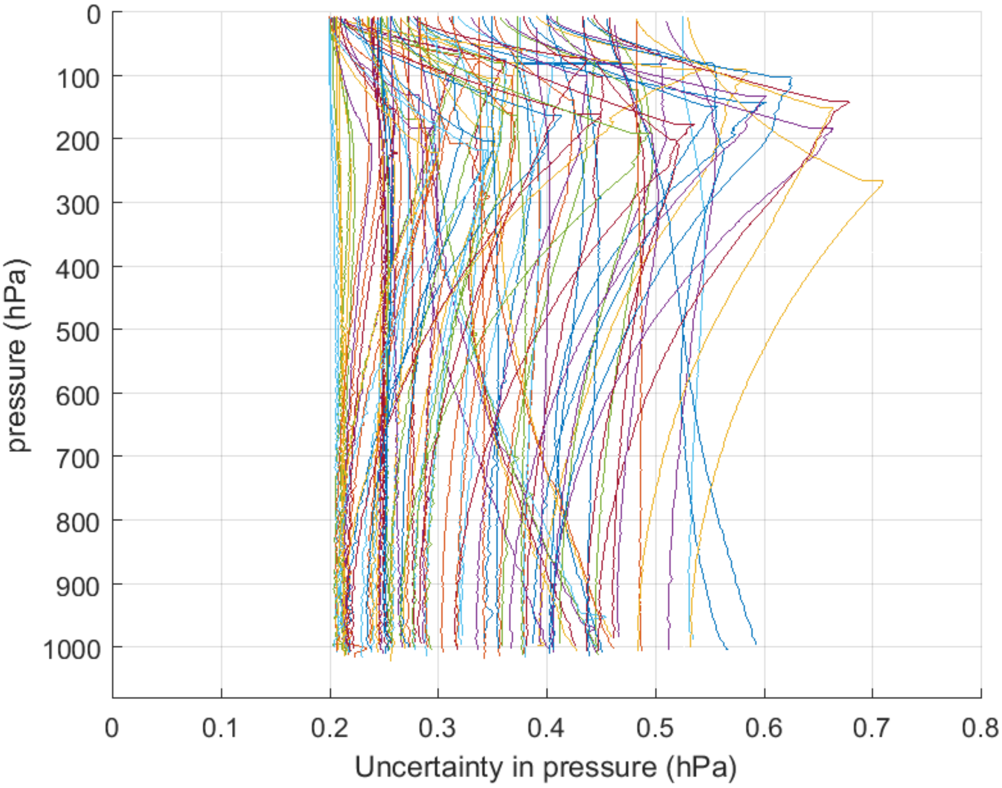


Figure 6, typical examples of uncertainty in pressure, u_press, taken from a sample of RS92 radiosondes launched at Lindenberg between 2012 and 2017.

4.22 Geopotential height (14) H

The geopotential height is calculated from the smoothed pressure profile using:

$$\Delta H_{1,2} = \frac{R_d}{\gamma_{45}} \overline{T_v} ln(\frac{p_1}{p_2})$$ [8]

Where R_d is the gas constant of dry air, γ_{45} the normal gravity at 45.542° latitude, and $\overline{T_v}$ the average virtual temperature between the levels p_1 and p_2.

Information / data	Type / value / equation	Notes / description
Name of effect	Geopotential height	
Contribution identifier	14, H	
Measurement equation parameter(s) subject to effect	none	End product
Contribution subject to effect (final product or sub-tree intermediate product)	none	
Time correlation extent & form	none	
Other (non-time) correlation extent & form	Degree of smoothing	
Uncertainty PDF shape	normal	
Uncertainty & units (2σ)	$u(z_p)$ for $z < z_{switch}$ $u(z_{GPS})$ for $z > z_{switch}$ 10-50 m (<35 usually)	The uncertainty in geopotential height is stated to be identical to the uncertainty in geometric altitude
Sensitivity coefficient	1	
Correlation(s) between affected parameters	none	
Element/step common for all sites/users?	yes	
Traceable to …	Geometric altitude from pressure and GPS measurements.	
Validation	N/A	

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	Barocap pressure sensor, u_{cal}	Statistical uncertainty	0.5 hPa > 100 hPa, 0.3 < 100 hPa	H	random	none
2	Calibrated in Vaisal CAL4 facility	constant	0.4 hPa > 100 hPa, 0.3 < 100 hPa	H	Systematic	4
2a	Reference pressure sensors	constant	0.3 hPa	H	systematic	2,4
3	GC25 Calibration, $U_{c,GC25}(p)$	$\sqrt{u_{cal}^2 + (\frac{\Delta p_{GC25}}{3})^2}$	0.43 hPa	H	Quasi-systematic	12
3a	Station barometer, $u_{u,launch}(z_p)$	constant	<0.5 m	H	systematic	5c
4	Pressure measurements	Statistical uncertainty	1 hPa > 100 hPa, 0.6 < 100 hPa	H	random	5a
5	Calculate geometric altitude, $u(z_p)$	$\sqrt{u_u(h_0)^2 + u_r(z_p)^2 + u_c(z_p)^2}$	0.5 at launch up to $u(z_{GPS})$ at z_{switch}.	M	Structured-random	9,10,11
5a	Virtual Temperature	constant	0 m	L	random	12,13
5a1	Sonde T and RH readings	constant	0 m	L	random	5c
5b	Local Gravity Calculations	constant	0 m	L	random	12
5c	Launch altitude, $u_u(h_0)$	$\sqrt{u_{u,launch}^2(z_p) + (100 \cdot \frac{u_r(p_1)}{\rho_o \gamma(h_{station}, \emptyset_{station})})^2}$	<0.5 m	M	Structured-random	none
5c1	GPS altitude at launch	constant	0 m	L	random	none
5c2	Pre-launch pressure readings	Statistical uncertainty	0.5 hPa	H	random	none
6	Calculate noise in z_p	Statistical uncertainty	0.25 m	M	random	none
7	GPS sensor	constant	20 m	H	random	5c1
8	GPS altitude measurements, $u(z_{GPS})$	$\sqrt{u_r(z_{GPS})^2 + u_c(offset)^2 + u_{c,switch}(z_p)^2}$	10-50 m	M	Structured random	5b
9	Calculate noise in z_{GPS}	Statistical uncertainty	0.5 m	M	random	none
10	Switch altitude, $u_{c,switch}(z_p)$	Correlated uncertainty in z_p at z_{switch}	<10-50 m	M	Quasi-systematic	none
11	Geometric altitude offset, $u_c(offset)$	Statistical uncertainty of z_p-z_{GPS} at z_{switch}	<10-50 m	M	Quasi-systematic	none
12	Join z_p and z_{GPS} at the switch altitude, $u(z)$	$U(z_p)$ below switch altitude $U(z_{GPS})$ above switch altitude	10-50 m	M	Structured random	none

13	Smoothed pressure profile, u(p)	$\sqrt{(u_{c,GC25}(p))^2 + (\frac{\gamma_{45}\cdot p}{R_d\cdot T}\cdot \exp\left(-\frac{\gamma_{45}\cdot dz}{R_d\cdot T}\right)\cdot u(z))^2}$	0.6 hPa	M	Structured random	none
14	Geopotential height	$U(z_p)$ below switch altitude $U(z_{GPS})$ above switch altitude	10-50 m	M	Structured random	none

How the uncertainty in Geopotential height and altitude is calculated depends on whether it is above or below the switch altitude, z_{switch}. Below z_{switch} the uncertainty is the sum in quadrature of the uncertainty in launch height altitude and from the bias of the pressure sensor, as well as the noise in pressure measurements. Above z_{switch} the uncertainty is the sum in quadrature of the uncertainties in the switch altitude and the offset between altitude from pressure measurements and altitude from GPS, with random noise in GPS altitude measurements.

$$U(H) = \begin{cases} \sqrt{u_u(h_0)^2 + u_r(z_p)^2 + u_c(z_p)^2}, z < z_{switch} \\ \sqrt{u_r(z_{GPS})^2 + u_c(offset)^2 + u_{c,switch}(z_p)^2}, z > z_{switch} \end{cases}$$

The uncertainty in pressure is the sum in quadrature of the uncertainty from the calibration during ground check and an uncertainty contribution determined from the uncertainty in altitude as shown below.

$$U(p) = \sqrt{(u_{c,GC25}(p))^2 + (\frac{\gamma_{45}\cdot p}{R_d\cdot T}\cdot \exp\left(-\frac{\gamma_{45}\cdot dz}{R_d\cdot T}\right)\cdot u(z))^2}$$

The uncertainty in geometric altitude usually starts at launch around 0.5 m and increases with altitude up to the switch altitude, usually between 10 and 50 m. Most of this uncertainty is the correlated uncertainty resulting from the bias of the pressure sensor. Together random noise and launch height uncertainty contribute less than 20% of the total uncertainty. Above the switch altitude the uncertainty remains fairly constant, with some change as a result of random noise so the uncertainty here is between 10 and 50 m. Less than 5% of this is the uncertainty due to random noise while the rest is correlated uncertainty from the bias of the pressure sensor at the switch altitude and the uncertainty in the offset. The uncertainty in geopotential height is the same as in geometric altitude, starting at about 0.5 m rising up to between 10 to 50 m and then staying fairly constant. The uncertainty in pressure depends on the uncertainty in altitude and increases up to the switch altitude. Above the switch altitude the uncertainty in pressure decreases. The maximum uncertainty in pressure is usually below 0.6 hPa. Depending on altitude between 30% and 90% of the uncertainty is correlated uncertainty from the ground check and long term systematic uncertainty from the Vaisala calibration. The remaining uncertainty is broken down into correlated and uncorrelated uncertainty the same as $u(z_p)$ below z_{switch} and $u(z_{GPS})$ above z_{switch}.

6 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 2, should be considered further to improve the overall uncertainty of the GRUAN temperature product. The entries 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?
3	GC25 Calibration, $U_{c,GC25}(p)$	$\sqrt{u_{cal}^2 + (\frac{\Delta p_{GC25}}{3})^2}$	0.43 hPa	H	Quasi-systematic	12
7	GPS sensor	constant	20 m	H	random	5c1
5c1	GPS altitude at launch	constant	0 m	L	random	none
5a	Virtual Temperature	constant	0 m	L	random	12,13
5b	Local Gravity Calculations	constant	0 m	L	random	12

6.1 Recommendations

Calculating altitude from pressure uses virtual temperature which is calculated from temperature and relative humidity measurements, however no attempt is made to incorporate the uncertainty of these inputs into the uncertainty of the end product, and although sensitivity tests indicate that both would only have a small change on each calculated ΔZ, the number of steps means the uncertainty in z_p could be significant near the switch altitude.

There are also points in Dirksen et al. where the methods used are not fully clear or justified, particularly relating to the correlated uncertainty of the pressure sensor, where it is not obvious how the difference in ground check readings can be used as a contributor to uncertainty in the way it has been, and how the bias of the pressure sensor is interpolated linearly to it when it is apparently based on calculations of z_p-z_{GPS} throughout the entire profile.

The application of z_{offset} to all readings above the switch altitude introduces a correlated uncertainty to all high altitude readings. An alternative method that combines z_p and z_{GPS} in the switch region, with z_p used below and z_{GPS} used above, would goive improved uncertainties at higher altitudes.

It would also be useful if some of the data used to calculate the different uncertainties, such as at the ground check and switch altitude, were made available.

There are 4 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.

7 Conclusion

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

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