TIME-LAG CORRECTION OF OPERATIONAL RS80-A RADIOSONDE HUMIDITY

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ABSTRACT

It is described the method and results of time-lag correction of Vaisala RS80 A-Humicap radiosonde humidity sensor correction. Specially developed numeric technique and free public software for its application is presented. Results of correction have been validated by comparison of humidity profiles, obtained during ascent, with descent ones, and, as well with FN-sonde data – a special research version of Vaisala RS90 radiosonde, with faster sensors.

Since January 2003 described lag correction procedure was in operational use at Meteorological Observatory Lindenberg, Germany – GUAN and GVaP reference upper-air station, until its transition to new Vaisala RS92 radiosonde in July 2004.

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1. Introduction

The work, presented here, was undertaken within the long-term activity of Meteorological Observatory Lindenberg (MOL), Germany, which is GUAN and GVaP reference upper-air station, to develop comprehensive correction of Vaisala RS80-A radiosonde humidity measurements /8/. The development of the correction was based on their regular weekly comparison with research humidity reference radiosondes using developed in Lindenberg so-called *Standardized Frequencies* (FN)-method (FN-sonde - a special research version of Vaisala RS90 radiosonde /5/).

As many of real world measurement, humidity measurements of A-HUMICAP sensor of RS80-A radiosonde suffer from sensor's inertia. As sensor requires time to reach equilibrium with ambient environment, variable in general case time delay, or lag, appears between the variations of ambient humidity and sensor's output, expressed in the units of relative humidity. Exposure the sensor from dry to moister environment results in too low measurements (and vice verse – from moist to drier conditions – in too high ones) before the sensor gets the equilibrium (if environment is stable). Corresponding error component is referred to as lag error.

Comparison of RS80-A with FN-sonde /5/ humidity has shown that lag error has rather deterministic nature and noticeable magnitude to be worth to be corrected.

2. Background

Basis for correction is that sensor response follows well-established equation, assuming that rate of change of sensor's output is proportional to the difference between ambient humidity and sensor's output

$$\lambda \cdot \frac{dU}{d\tau} = U^{true} - U \qquad (1)$$

or, in canonic form

$$\lambda \cdot \frac{dU}{d\tau} + U - U^{true} = 0 \qquad (2)$$

where

U^{true} – ambient humidity, %RH

U – measured sensor's output in relative humidity units, %RH

τ – time, seconds

λ – time constant, seconds, defined as time required to sensor to reach 63% of input signal variation after its instantaneous change.

More strictly notation for time constant should be $\lambda\{t(\tau)\}$, where t is the ambient temperature as A-HUMICAP response is strongly temperature dependent (see Equation (9)), but for the sake of clarity we will use hereinafter $\lambda(t)$.

Equation (2) is the 1st order ordinary linear differential equation with general solution in form

$$U = \exp\left(\int -\frac{d\tau}{\lambda(t)}\right) \cdot \left(C + \int U^{true} \cdot \exp\left(\int \frac{d\tau}{\lambda(t)}\right) \frac{d\tau}{\lambda(t)}\right) \qquad (3)$$

where $C=(U^{true})_0$.

An important property of solution (3) is that it is linear regarding U^{true}.

Important partial case is when input parameter varies with constant rate

$$U^{true} = u_0 + u_\tau \cdot \tau$$

Solution 3 in that case looks like

$$U=U_0\cdot\exp(-\frac{\Delta\tau}{\lambda(t)})+u_0\cdot(1-\exp(-\frac{\Delta\tau}{\lambda(t)}))+u_\tau\cdot\tau-u_\tau\cdot\lambda\cdot(1-\exp(-\frac{\Delta\tau}{\lambda(t)})) \qquad (4)$$

In steady state, i.e. when $\Delta\tau\rightarrow\infty$, we have from Equation (4)

$$U = u_0 + u_\tau\cdot\tau - u_\tau\cdot\lambda$$

or

$$U = U^{true} - u_\tau\cdot\lambda \qquad (5)$$

From Equation (5) it follows that within layers with constant humidity gradients in steady state (after termination of transition processes) measured humidity has the same gradient as true humidity, and time delay between actual and measured humidity is equal to time constant regardless of gradient value itself:

$$U(\tau) = U^{true}(\tau - \lambda) \qquad (6)$$

In presentation of radiosonde ascents pressure or height is used as abscissa instead of time. As well, for the analysis of ascent-descent flights (see later in section 3.2) only presentation in height or pressure domain is reasonable. For this, expressing time differential $d\tau$ as $s\cdot dH$, where s is vertical (ascent or descent) velocity and H is height, we receive from Equation (1)

$$\lambda s\cdot\frac{dU}{dH} = U^{true} - U \qquad (7)$$

In principle, we can also come to pressure domain using hydrostatic equation to relate height and pressure differentials but it has no practical sense. Again, for the s stricter notation should be $s(H)$.

Correspondingly, for the layers with constant vertical gradient of measured humidity Equation (6) is transformed under condition of constant (more-less) vertical velocity to

$$U(H) = U^{true}\cdot(H - \lambda s) \qquad (8)$$

that easily characterizes vertical height shift between measured and actual profile.

3. RS80 A-HUMICAP time constant model

3.1. Literature data

Determination of time constant for humidity sensors is quite complicated and challenging technical task. So, it's not surprising that little information is available on this matter. Actually, these are early report of Vaisala RS80 introduction /2/, results of ordered by Vaisala the NIST measurements /4/, several measurements @ 20 and –20 °C, made during the 1st Phase of WMO Radiosonde Humidity Sensor Intercomparison /3/ and more recent /7/. Results are more less consistent and indicate strong dependency of time constant from the temperature which is expressed according to /4/ as

$$\lambda = \lambda_0 \cdot e^{\lambda_t \cdot t} \qquad (9)$$

where

λ is time constant in seconds

t is temperature, °C

λ_0=1.7, λ_t= -0.06916966 (from the Figure 3 in /7/ there were derived values λ_0=1.0 and λ_t-0.0743).

It is really tremendous relationship - enough to say that time constant increases almost twofold ($\ln 2$=0.69314718) from the temperature decrease by 10 °C.

As well, /4/ indicates that response of sensor follows exponential law and the 90% response time is 2.3 times as longer as the 63% response time, or time constant. It is to some extent confirmed by results of /3 /. This allows application of model from Equation (1). Also, results of the Figure 1 from unpublished report of the Phase-I Laboratory Test of WMO Radiosonde Humidity Sensor Intercomparison prove us in adequacy of Equation (1).

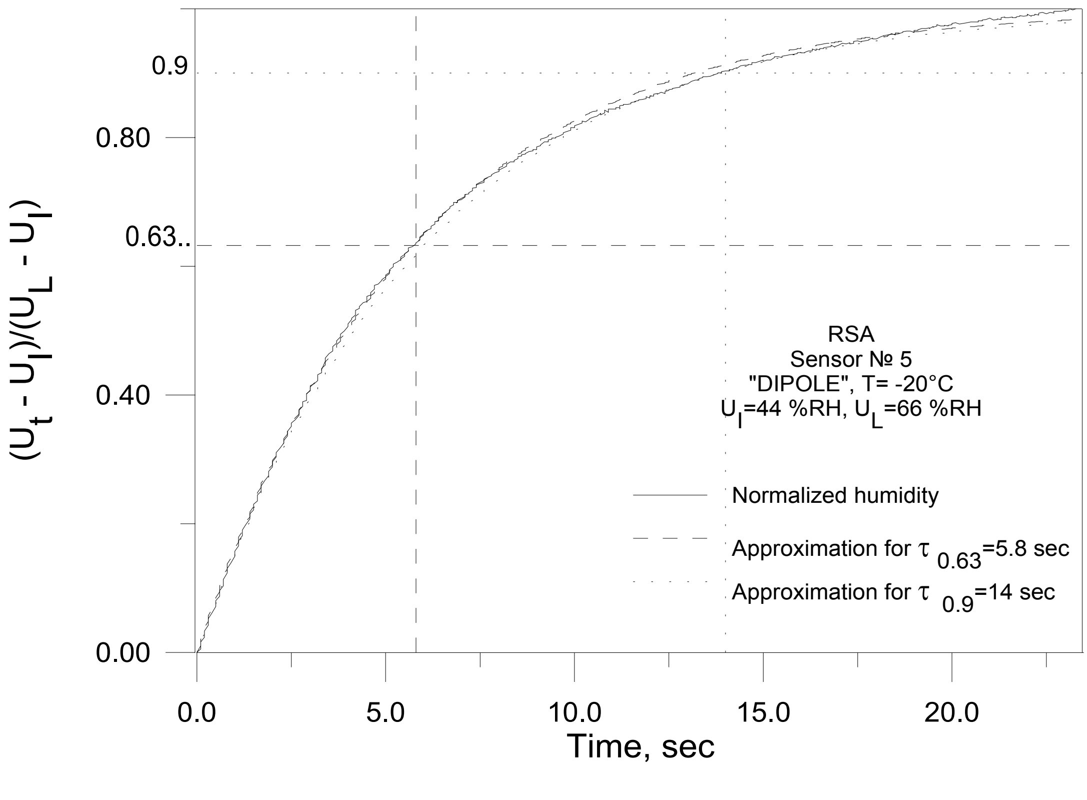

Figure 1: An example of RS80-A time constant examination from WMO Radiosonde Humidity Sensor Intercomparison (see /3/). It is shown variation of normalized relative humidity with time after step-wise change of humidity (U_I – initial, U_L – final and U_t – intermediate humidity) from U_I to U_L.

However, some measurements, made by authors of /3/ in addition to official program demonstrate that response of sensor itself, without protective cap, rather faster than usual configuration. That means possible presence of the second-order term or transport delay in more accurate than Equation (1) model.

Also /4/ declares that to curtain (although not quantified) extent time constant depends from direction of humidity variation. Other parameters, that remained beyond the scope of investigation of A-HUMICAP response and potentially could affect it, are pressure, ventilation, humidity itself and last but not least production variability.

So, present state-of-the-art knowledge of A-HUMICAP response do provide necessary background to the development of lag compensation algorithm but could not serve as solid fundament therefore empiric should be involved to reach plausible results.

3.2. Comparison of ascent and descent profiles

To make qualitative validation of available information on RS80-A Humicap time constant under different temperatures it was decided to analyze data of flights with radiosonde ascent followed by descent. Typically ascent data are shifted towards upper levels relative to ones of descent. Assuming that radiosonde penetrate the same air mass on both stage of the flight apparent, a vertical displacement of ascent and descent profiles results from lag error and therefore carries out information about time constant.

It's evident that comparative analysis of ascent and descent data should be made in height domain. And using Equation (11) for the layers with constant vertical gradient of humidity gives reasonable background for rough analysis as it doesn't require calculation of derivatives and gives in this case clear interpretation of vertical height displacement of ascent and descent profiles

$$\Delta H_{asc\text{-}desc} = \lambda_{\uparrow} s_{\uparrow} + \lambda_{\downarrow} s_{\downarrow} \qquad (10)$$

or, assuming $\lambda_{\uparrow} = \lambda_{\downarrow}$, just as

$$\Delta H_{asc\text{-}desc} = \lambda (s_{\uparrow} + s_{\downarrow}) \qquad (11)$$

In MOL there were specially organized 13 RS80 flights with descent data recording. In addition to routine procedure all of the flights were made with parachute although usually reflector alone is considered to be enough to provide low drop velocity nearby the surface. As PC-CORA do not provide descent data processing, PC-CORA raw data files were used as the source for analysis[1]. They contain conventional unedited (except in terms of plausible engineering quantities) PTU data from each telemetry cycle instead of standard edited (i.e. controlled and smoothed) 10-seconds data along with elapsed time since switching on power of receiving system. As well, release time is provided according as detected by Vaisala data processing software from variation of pressure. Unfortunately, resolution of humidity readings again is 1%RH that introduces

[1] Comparison of raw and edited data revealed one interesting typical but prominent peculiarity. The point is that routine data processing software in addition to rounding “truncates” to 1%RH all humidity below this value. In many cases this seemed unimportant feature introduce noticeable distortion into derivative resulting in symptomatic artifact in humidity profile just in place where it comes to 1%RH. In one flight the minimal raw reported humidity was –3%RH so visible bend in profile curvature in edited data brought attention and allowed to understand the reason of artifact observed. Although that ascent was an extreme case of negative reported humidity in many other flights raw data humidity minimum was <0%RH that brings an assumption about presence of slight negative dry-end bias in A-HUMICAP measurements at low temperatures.

additional unnecessary uncertainty into results. And is more pity that time resolution in output files of 1 sec is insufficient in comparison with potential capability of radiosonde (telemetry cycle is about 1.5 sec) and receiver, that makes it difficult e.g. to compare the data with FN-sondes and investigate the influence of editing and smoothing on to final 10-s output, proper calculation of vertical velocity etc.

Some experience of the processing may be of general interest itself. As it was shown earlier we need to consider humidity data versus height coordinate in comparison with ascent and descent velocity to enable evaluation of time constant. Conventional geopotential calculations were based on hydrostatic equation. And it was pressure that was used to match ascent and descent part of measured profiles. From the uppermost part of ascent with sufficient data quality it was taken on of the latest pressure level and its height was assigned to corresponding matching pressure level of descent. Lower levels' heights were calculated again from hydrostatic equation. Examinations of relative displacement of characteristic peculiarities (prominent features or variations) of ascent and descent vertical profiles proved that accuracy of relative overlay of ascent and descent profiles against height was of order about 10-20 m.

To ensure preservation of the same atmospheric situation during the whole flight, minimal time and horizontal displacement are required. Ascents with following descents usually took as long as ~9000 sec. It was found that even in cases of moderate winds with distances of drop of order about 50 km temporal and spatial variability of humidity field in mid- and lower troposphere is too large to allow evaluation of time constant. Therefore, downfall trajectory was predicted based on profile of preceding ascent (in MOL soundings are performed with 6-h intervals). When predicted maximal distance didn't exceed 25 km upper-air station staff was requested to attach a parachute to an ascent rig and record descent data. For a few ascents it was also requested registration of radar tracking data. Unfortunately, it was available only as printout, not in machine-readable form. Therefore, use of these data was limited only to general verification of calculated geopotential height and comparison of predicted and actual descent rates and radiosonde horizontal coordinates.

Unclear issue was dependence of time constant from ventilation. Laboratory experience tell us that lower than 5 m/s ventilation really deteriorate sensor performance but it's unclear is essentially higher ventilation improves sensor's response. Even with usage of parachute descent rate was about 15 m/s at 14 km and 7-8 m/s near surface with in even higher values in flights with FN-sonde participation.

Qualitative estimates of time constant (under assumption of their independence from the ventilation) could be obtained from observing vertical displacement of profiles from ascent and descent of radiosonde given the horizontal displacement and time variations are not so big. There were processed 13 such flights. Typical example is shown on the figure 2. Analysis of vertical shift, based of Equation (11), has shown that reasonable analysis could be done only at temperatures below –45°C. At lower levels both time constant is too small and space and temporal variability are too large to make any estimates. But below –45…–50 °C graphical estimation reveals for the time constant more-less reasonable agreement with model of Equation (9) that is rather satisfactory for all shortcoming of this method.

Rough evaluation of ascent-descent flights was encouraging enough to open the way for the following development of lag compensation procedure. But after the first satisfaction with compatible results intention appeared to receive more quantitative results as accuracy of such graphical estimates is quite low to get quantitative estimates for the parameters of Equation (9). Taking into account the relatively large time constant at low temperatures it is required quite a long matching fragment of ascent and descent with constant gradient. And, temperature in such layers should not undergo noticeable variations as they strongly affect time constant. So, it was decided to undertake "inverse approach" – use these data later in more productive way for verification of developed lag compensation procedure by checking if corrected ascent and descent will match.

3.3. Empirical estimation

Unless more reliable experimental information on λ approximation is available the values λ_0=1 and λ_t=-0.06916966 (close to information of /7/) were estimated subjectively from the analysis of results of described below correction scheme (section 5) using following considerations:

- Corrected humidity profiles made during ascent and descent in the same flights should match each other
- Underestimation of time constant is safer than overestimation because using too high value leads to implausible spurious variation in corrected data
- Corrected RS80-A humidity profiles should be close to FN-sonde.

Parameters of RS80-A time constant approximation may require circumstantiation for the temperatures below -65°C.

4. Obstacles to lag correction

Having deal with mathematical abstractions it looks natural frontal solution of problem – direct use of Equation (1) to obtain immediately lag correction. However, in real world when we have a deal with discrete signal of finite accuracy and resolution accurate numeric differentiation is practically impossible. Differentiation operator is known to amplify errors of input signal. And the problem is that the more significant lag errors the more sensitive lag correction to errors in derivative calculation as their amplification is proportional to time constant.

Alternative inverse solution of Equation (3) in fact suffers from the same problems because of presence measurements, quantization and sampling errors in measured humidity. Both definition of problem are ill-posed ones. As measuring system inevitably looses information there are a priory no means to separate contribution of measurement errors and smaller scale humidity variation.

As the first guess to problem's solution it was decided to concentrate on head-on approach, i.e. use of numeric differentiation and Equation (1).

4.1. Particular problems of A-HUMICAP humidity lag compensation

Physical definition of relative humidity and requirements of presentation in upper-air messages impose domain constrains onto range of allowable values 1[2]-100.

One sort of uncertainty is that all known experiments on determination of time constant dealt with humidity variations under constant pressure and temperature and more or less stable ventilation while during ascent we have combined influence of variation of these factors in time to sensor output, inevitably resulting in hysteresis-like memory effects. That is, in terms of theory of system the problem is not stationary. At least, according to information of /6/ thermal time constant of system humidity sensor – sensor boom is about 15 seconds. Transition process is a combination of establishing water vapor and temperature equilibrium.

Conventional output of Vaisala ground station provides data with 10 s resolution, i.e. Nyquist frequency is 0.05 Hz, or in terms of period 20 s. Therefore, at negative temperatures time constant is of order or larger than the Nyquist period.

Resolution of output humidity readings in 1%RH is quite insufficient in comparison with dynamic range of 1-100 %RH. This is a pity bearing in mind potential internal capabilities of radiosonde transducer and receiving system resolution of order 0.05%. That's, due to just rounding error we can have fictitious gradient 0.1%RH/sec (or, the same, error in determination of

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[2] Depending from minimal allowable resolution in humidity presentation

gradient) that is directly proportional by factor of time constant to superimposed error in lag correction.

4.2. Temperature correction versus lag compensation. Order of corrections

As lag compensation was developed for inclusion in RS80-A Humidity correction procedure, implemented in MOL, it is important do determine an order of application of different corrections. Mathematically, both time-lag correction and temperature dependant, or static, one are linear transformations. Therefore the final results in ideal are independent from the order of their application. This assumption was checked by applying of both corrections in different order. Results from both way of applying correction have shown good consistency with each other. However, as mentioned earlier, resulting values from both stages have to be rounded to 1%RH. So, to avoid possible bad influence of accumulation of rounding error onto calculation of derivatives, lag correction should be performed first.

5. Correction procedure

Mathematical sense of correction procedure is quite unpretentious and comprises numeric inversion of Equation (1) using temperature profile for estimation of time constant according (9). But to avoid severe errors in calculation of derivative, coming from finite sampling 10-s rate and 1%RH resolution, correction scheme consists in several subsequent numeric transformations of input data (only for levels with λ greater of 5 s that is half of 10-s sampling rate):

- Removing round-off humidity error using 5-points **l**ocal **p**olynomials least-square-fit **a**pproximation (following to idea of Savitzky-Golay smoothing filters /1/ but in application to non-evenly[3] spaced data). Approximation is adaptive, i.e. initial order of approximation polynomials is 3 and it increases up to 5 unless approximation error is greater of 1%RH. However, if its absolute value is greater of 0.8%RH original value is shifted only by 0.5%RH towards approximated one.

- Filtering implausible and sub-scale humidity variations (including coming from the previous stage) by means of time-constant dependent smoothing using **G**auss **k**ernel **s**moothing

$$Y_i = \sum_{j=1}^{N} X_i \cdot K\left(\frac{\tau_i - \tau_j}{B}\right) / \sum_{j=1}^{N} K\left(\frac{\tau_i - \tau_j}{B}\right) \qquad (12)$$

where kernel function is

$$K(x) = \frac{1}{\sqrt{2\cdot\pi}\cdot(0.37)} \cdot \exp\left(-\frac{x^2}{2\cdot 0.37^2}\right) \qquad (13)$$

[3] That is missing levels are allowable.

and variable time-constant dependent bandwidth is

$$B_i = B^0 + B^1 \cdot \lambda(t_i) + B^2 \cdot \lambda^2(t_i) \qquad (14)$$

where

B^0=10, B^1=0.5, B^2=0.0015

X_i – original RH at i-th level

Y_i – smoothed RH at i-th level

t_i – temperature at i-th level

τ_i – time of i-th level.

- Differentiation of filtered data using coefficients of 5-points 3[rd] order local approximating polynomials.
- Calculation of lag correction as $\Delta U_i = \lambda_{t_i} \cdot \frac{dU_i}{d\tau}$.
- Calculation of corrected value at levels, where time constant is larger then 5 seconds, as

$$U^{cor}_i = 0.6 \cdot U^{LPA}_i + 0.4 \cdot U^{GKS}_i + \Delta U_i \qquad (15)$$

where

U^{LPA}_i, U^{GKS}_i – values at particular level from steps 1 and 2.

- Due to limitations of existing DWD data processing scheme[4] results are rounded to 1%RH.

Parameters of correction procedure (including parameterization of (9)) were adjusted by comparison of corrected RS80-profiles with FN-sonde having sensors with faster response. Since June of 1999 in MOL are performed regular weekly ascents of FN-sonde with time constant at least 2.5 times faster of RS80-A /7/. The basis of investigation was the use of program SPLTau (see section 7). RS80-A–FN ascents were both *simultaneous* and *parallel* (i.e. with sondes attached to the *same* and the *different* balloons). In latter case comparison was done against height.

For verification it was used comparison of ascent and descent corrected profiles. After compensation prominent features of humidity profile of ascent should shift toward the surface while ones of descent should shift towards the upper levels. Results were quite encouraging. In most ascents reconstructed profiles matched each other and only in one (06/05/2002-12UTC) the difference between corrected ascent and descent was larger (and of opposite sign) than between uncorrected data, and ascent and descent were more likely took place in different atmospheric conditions.

It's fair to say that suggested procedure is highly sensitive to case of sensor's icing and at upper levels may bring to useless results without automatic /8/ or manual icing recognition.

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4 In the program SplTau (section 7) this step is optional.

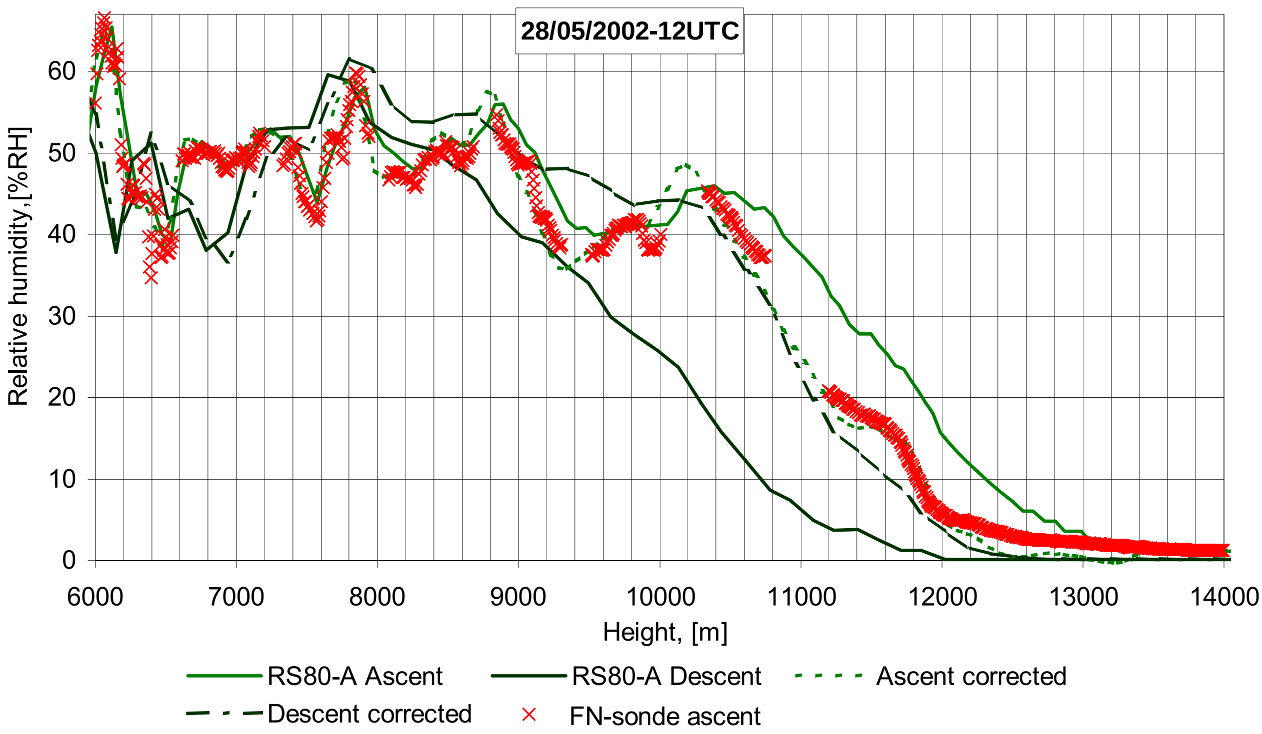

Figure 2: An example of ascent and descent humidity correction.

6. Statistical evaluation

For evaluation of overall impact made by proposed lag compensation algorithm, a new data set, called hereinafter RS80-A_{LC}, was prepared for the period between June 1999 and November 2001 from RS80-A data (with temperature-dependent and ground-check corrections applied) by application of the lag correction procedure.

Statistics of *parallel* differences (for details see /8/) between RS80-A_{LC} and RS80-A data, i.e. one reflecting lag correction, is presented on Figure 3. It is apparent presence of noticeable systematic components in differences between data sets at levels between 300 and 100 hPa, i.e. somewhere in between 9 and 16 km. These deviations look as climatological ones as they result from sensors' response to transition from moist in average tropospheric conditions to dry stratospheric ones accompanied by drastic increase of time constant due to mean temperature decrease towards tropopause. And magnitude of correction is compatible with root mean square deviation that tells about high variability of lag errors.

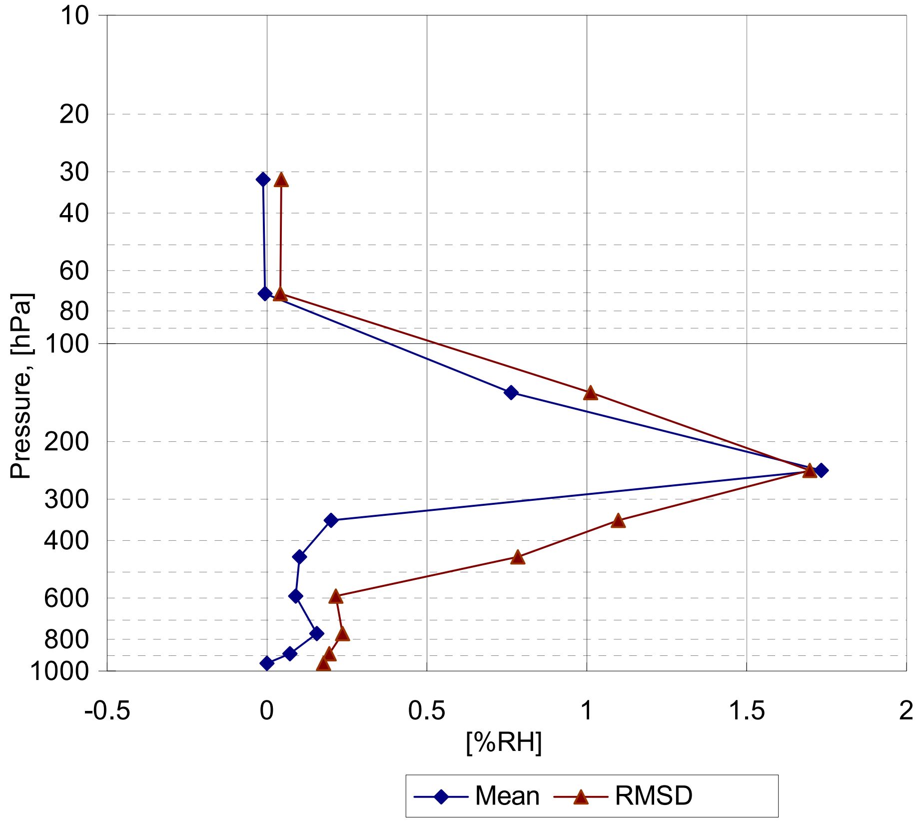

Figure 3: Statistics of "parallel" differences between original and corrected RS80-A humidity.

As well, for the same period it was calculated statistics of *parallel* differences between RS80-A_{LC} and FN-sonde humidity. Results, in comparison with ones for the RS80-A data set, are presented on Figure 4 a) - d).

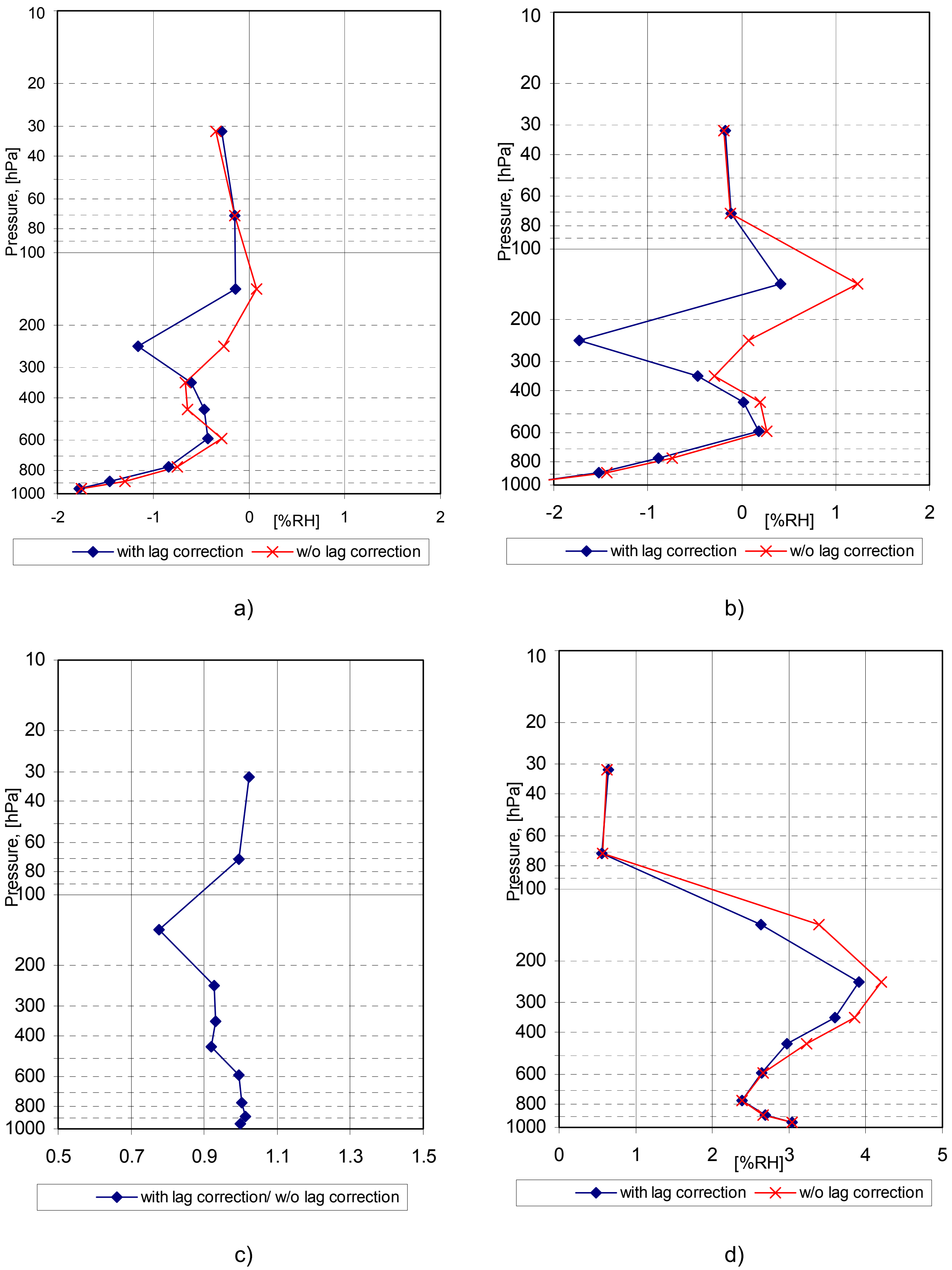

Figure 4: Statistics of RS80-A_{LC} (with lag correction) and RS80-A (without lag correction) minus FN humidity *parallel* differences:
a) mean differences; b) median of differences; c) standard, or root mean square, deviation;
d) ratio of standard deviations of RS80-A_{LC} − FN to RS80-A − FN differences.

It looks that introduction of lag correction removes positive bias at 200-100 hPa, that is just in average above tropopause where RS80-A apparently overestimates humidity and temperature-dependent correction is not so essential as humidity values are comparatively low. At lower layer, 300-200 hPa introduction of lag compensation results in negative bias as it was expected from statistics of Figure 3. It's likely, that MOL temperature dependent RS80-A correction component /8/ already contains climatological component of lag error compensation somewhere in temperature region -40…-55 °C. Therefore, in joint application of both correction procedure temperature dependent correction may require some adjustment in that temperature region. The source of this correction could be comparison RS80-A humidity data with and without lag correction in dependence from temperature. The reduction in variability of differences between corrected RS80-A and RS90FN data, characterized by standard deviation, is not so noticeable but apparent.

7. Software

For the application of lag correction there were developed two programs: TRAGKORR - DOS command-line utility for use in batch files within framework of routine DWD RS80-A data processing technology and SPLTau – standalone Windows menu-driven program for carrying out and presentation in time and height domain the results of lag compensation. SPLTau was developed as a versatile tool for the comprehensive investigation of influence of different variation in lag compensation algorithm on results of correction, their sensitivity to approximation of time constant from the temperature and as well for their validation by comparison with simultaneous or parallel RS90FN radiosonde. Last version of SPLTau includes now also a possibility to apply MOL ground-check and temperature dependant correction /8/ as well as correction according to /4/.

SPLTau version, able to handle RS80-A fine structure and edited data ASCII-files, produced by standard Vaisala sounding equipment family, is available from the authors for the public use.

8. Conclusions

It was developed an empiric algorithm for correction of lag in RS80-A humidity measurements as a part of overall humidity correction procedure /8/ including as well temperature-dependent and ground-check and recognition of icing. Applicability and parameters of algorithm were verified using RS80-A research flight with ascent followed by descent and by comparison with FN-sonde data. It was developed software for routine and research mode of application lag compensation to RS80-A data in MOL databank format and (research version) in standard Vaisala text data files.

Since January 2003 described lag correction procedure was in operational use at Meteorological Observatory Lindenberg, until its transition to new Vaisala RS92 radiosonde in July 2004.

9. References

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