Met Office

Final Report on the WVSS-II Sensors fitted to the FAAM BAe 146

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Contents

Abstract

Results are presented from the twenty-six research flights of the FAAM BAe 146-301 aircraft comparing humidity data from two WVSS-II sensors (one with the standard, flush mounting inlet, henceforth denoted by the subscript $_{\_flu}$ and one fed from a Rosemount inlet, henceforth $_{\_ram}$) against General Eastern 1011B ('GE') and Buck CR2 ('Buck') chilled mirror hygrometers and the Total Water Content ('TWC') probe. The measurements were made during four field campaigns in 2011: the Combined Observations of the Atmospheric Boundary Layer to study the Evolution of StratoCumulus (COALESC), Fennec pilot, BOReal forest fires on Tropospheric oxidants over the Atlantic using Aircraft and Satellites (BORTAS) and AEGEAN Pollution: Gaseous and Aerosol airborne MEasurements (AEGEAN-GAME).

Within the limits of this study, the WVSS-II hygrometers agree well with the GE and the Buck in most situations. In very dry conditions, however, the WVSS$_{_flu}$ appears to over read substantially. Of the two, the WVSS$_{_ram}$ shows closer agreement overall, although it is slower to respond to rapid changes than WVSS$_{_flu}$ and can over read in the presence of liquid water. The speed of response of both WVSS-II is, however, reasonable under all conditions encountered, easily coping with transitions to which the chilled mirror devices cannot respond adequately but consistently lagging behind the TWC. No significant change in the performance of either WVSS-II sensor was evident during the test period.

The performance of the WVSS-II hygrometer appears to be good in all conditions encountered but significant shortcomings are evident in both the inlets used.

Nomenclature

The following system of abbreviations and subscripts shall be used throughout this report to denote the various quantities and the origins of the data.

Parameter	Abbreviation
pressure	P
impact pressure	q
temperature	T
water vapour mass mixing ratio	m
absolute humidity	d
dewpoint/frostpoint	T_d
relative humidity	RH

Qualifier/data origin	Subscript
WVSS-II with flush inlet	$_{\_flu}$
WVSS-II with Rosemount inlet	$_{\_ram}$
reference instrument	$_{\_ref}$
ambient/static/external	$_{s}$
within instrument	$_{c}$

Where data from multiple hygrometers are plotted, the following colour convention is followed. Where data from one instrument are subtracted from another, the colour shall follow the latter.

Instrument	Colour
WVSS-II with flush inlet	red
WVSS-II with Rosemount inlet	blue
General Eastern	pink
Buck CR2	green
Total Water Content	cyan

1. Test Flights

The data used in this study were collected on an opportunistic basis on twenty-six days spanning a 198 day period, totalling 135 flying hours, during four field experiments:

Experiment	Location	Dates	Flights	Hours
COALESC	England	23 Feb. - 19 March	12	65
Fennec pilot	Morocco	29 March - 9 April	4	21.5
BORTAS	E. Canada	31 July & 2 Aug.	2	9.5
Aegean-GAME	Crete	31 Aug. - 8 Sept.	8	39

In the course of these flights the aircraft encountered a range of conditions including ice and liquid cloud, drizzle, icing conditions, desert dust, anthropogenic pollution and biomass burning aerosol. The data presented here were recorded at altitudes ranging from 15 m to 10.7 km with temperatures ranging from 208-313 K, and absolute humidities from 0.001- 20 g/m^3 (*RH* with respect to liquid water from 1-123% - this level of supersaturation is well known in cirrus clouds).

2. Instruments and Installation

The FAAM aircraft was fitted with two chilled mirror hygrometers, a General Eastern 1011B (Ström et al. 1994, FAAM 2011a) and a Buck CR2 (FAAM 2011b). The former has been operated for many years on this aircraft and, previously, on the Met Office C-130 Hercules; the latter was first flown in 2008 on the FAAM aircraft. Chilled mirror hygrometers have the advantage that they provide an absolute measure of atmospheric water vapour content but suffer from slow response times, particularly at low temperatures and large dew point depressions; by contrast, optical absorption instruments do not provide an absolute measure but have a substantially faster response and the potential to perform well in very dry conditions. For some of the flights, the aircraft was also equipped with the Met Office-developed Total Water Content probe (Nicholls et al. 1990), a Lyman-α absorption instrument which can be regarded as a hygrometer in clear air. Calibration issues mean that the humidities derived from the TWC are not reliable in the absolute sense, but they are presented for comparison of the WVSS-II response to rapid transitions as its very short inlet and high flow rate result in almost instantaneous response.

The two WVSS-II instruments were installed on forward window blanks on the starboard side of the aircraft (plates 1 and 2). The inlets are angled down to match the local air flow and are located so as to minimise possible contamination from leakage of cabin air past the forward starboard door. The instruments are identical except that $WVSS_{\_ram}$ had an internal heater disconnected prior to its acquisition by the Met Office; this has remained disconnected for the duration of the study. The Rosemount inlet is mounted on a stand-off giving an overall separation of 12 cm between the inlet and the aircraft skin.

3. Calibration Drift and Bias

Figure 1 shows a time series (comprising all twenty-six flights) of the difference between the two WVSS-II sensors and the GE; figure 2 presents the differences between GE and Buck, similarly, for comparison; note that abscissae are temporally discontinuous. Data have been excluded where there are grounds to believe that the chilled mirror devices were unstable or where their slower response was preventing the tracking of atmospheric changes. Data were also excluded when other instrumentation indicated the presence of aerosol or cloud particles. The best fitting straight lines to these data show slight trends, amounting to +0.037 g/m^3 and -0.11 g/m^3 for $WVSS_{\_ram}$ and $WVSS_{\_flu}$ respectively over the course of the comparison period; the GE shows a drop of about 0.024 g/m^3 relative to the Buck over the same period. The 'campaign' nature of the flights make it difficult to establish from these data to what extent the apparent drift may, or may not, be due to the conditions encountered during each experiment.

4. Comparisons

Figures 3 to 6 show comparisons of the four hygrometers plotted as [instrument 1]-minus-[instrument 2] as a percentage of [instrument 2], versus [instrument 2]. In each case the heavy line indicates the mean of the difference between the instruments (calculated in equal-sized bins). For the comparisons of the WVSS-II against the GE, three plots are presented: firstly data for the two instruments using only stable, clear air data (as described above), secondly, data from $WVSS_{\_flu}$ in clear air (pale) overlaid with data where liquid water was detected (dark), and thirdly, a similar plot for $WVSS_{\_ram}$.

4.1 GE vs Buck: Figure 3 shows that in clear air and stable conditions, the two instruments agree to within one standard deviation throughout the range of humidities encountered although the GE generally reports lower *d* than the Buck; this is more pronounced in drier conditions, although the standard deviation also increases. It is plain from this plot that, despite attempts to use only stable data, some of the differences due to mirror temperature fluctuations remain.

4.2 WVSS-II vs GE: Figure 4 shows data from clear air. $WVSS_{\_ram}$ agrees with the GE (1σ) throughout the range of humidities encountered although it is clearly reads lower than the GE in dry conditions and higher at high humidities. $WVSS_{\_flu}$ reports significantly lower than the GE for most of the range and lower than $WVSS_{\_flu}$ above 0.2 g/m^3. Below 0.01 g/m^3, however, $WVSS_{\_flu}$ shows a very pronounced rise, suggesting that this sensor is unable to cope with very dry conditions.

Figures 5 and 6, for $WVSS_{\_flu}$ and $WVSS_{\_ram}$, respectively, present only the data where liquid water was detected by other instruments on the aircraft. There is no statistical difference (1σ) between the dry and wet means although the spread of data is greatly increased in the latter case, such that both WVSS-II agree with the GE.

When the dry data are plotted in terms of *m* (figure 7), although the $WVSS_{\_ram}$ still shows good agreement with the GE throughout the range, $WVSS_{\_flu}$ reports significantly (1σ) higher values than either the GE or $WVSS_{\_ram}$ below 0.3 gkg^{-1}, increasing sharply below 0.02 gkg^{-1}.

The difference between the *d* and *m* comparisons might suggest an issue in the conversion from one quantity to the other. Figure 8 shows the difference between P_{c_flu} and P_{c_ram} in flight as a function of P_s. As the Rosemount inlet is a ram device, P_{c_ram} will be dependent upon impact pressure; the data have, therefore, been restricted close to the modal value to limit any influence upon the comparison. A substantial discrepancy is clearly seen, with P_{c_flu} being significantly lower than P_{c_ram} at all P_s, increasing from around 5% near the surface to 25-30% at high level. It is believed that this difference in behaviours between the two instruments' pressure sensors contributes to the differences seen in the humidity comparisons. Figures 14 to 16 show some further evidence of a possible pressure related bias between the WVSS-II.

5. Case Studies

5.1 Ascent and Descent: Figures 9 and 10 show two examples of data, one climb and one descent from flight B592 on 7th April 2011 over Morocco. In the descent (figure 10), following rapid changes in humidity, the chilled mirrors exhibit the oscillations characteristic of this type of instrument, but it can also be seen that these oscillations encompass the WVSS-II data, which are in agreement with each other, except for the dry bias of $WVSS_{\_flu}$, giving some confidence that the WVSS-II are providing accurate data. In the climb (figure 9), the chilled mirrors fail to track all but the broadest features; again this is a characteristic of chilled mirror measurements. In both cases, $WVSS_{\_flu}$ responds noticeably more rapidly than $WVSS_{\_ram}$, although both lag behind the TWC, which benefits from a high flow rate and very short inlet. Figure 11 shows a section of the descent in figure 10 as a time series to further illustrate these lags. The examples presented here are representative of the profile comparisons during this period.

5.2 Liquid Water: Although, in general, both inlets perform well in humid conditions, anomalous behaviour has been seen; figure 12 shows one such occurrence from flight B584 (15^{th} March 2011 over the North Sea) involving two penetrations of liquid cloud. In addition to hygrometric data, time series of the aircraft pressure altitude, the concentration of droplets in the size range 2-50 µm from the cloud droplet probe (CDP, Lance et al., 2010), and liquid water content from the Johnson-Williams (JW, Neel 1973) and Nevzorov (Korolev et al., 1998) hot-wire sensors are shown along with mean size spectra from the CDP for the two penetrations.

The initial penetration takes place from clean air; the second occurs in the presence of aerosol (detected with other instruments, not shown). In both cases, there are clear signals from the JW, Nevzorov and CDP, but the responses of $WVSS_{\_ram}$ and $WVSS_{\_flu}$ are quite different. In the first penetration, $WVSS_{\_ram}$ can be seen to over read substantially, compared to the other three instruments, whilst in the second penetration the discrepancy is substantially less (~30% of previous). The CDP data show different droplet size spectra for the two penetrations and although this may well contribute to the discrepancy, the mechanism is not obvious.

Figure 13 shows the results of CFD calculations carried out for an instrument mounted in a similar location on the fuselage. The black spot is approximately 12 cm from the skin and the dots show a uniform distribution of cloud droplets, disturbed by the passage of the aircraft. The black dots represent 5 µm droplets and the blue dots, 20 µm droplets. Inset in the lower left is a similar plot illustrating that this shadowing effect increases with droplet size; here the orange dots represent droplets of 50 µm diameter with 5 µm droplets in black, again. These model data would appear to show that $WVSS_{\_ram}$ might be effected by droplets of 5 µm or smaller but that it should be immune to those of greater diameter, but the figure 12 shows that the droplets present during the first penetration had a modal value greater than 20 µm, whereas those in the second, less effected penetration, had a modal value less than 10 µm. The model calculations do not, however, take any account of droplets shattering on the aircraft and, clearly, further work is required to resolve this issue. $WVSS_{\_flu}$ appears to be influenced very little by the droplets but $WVSS_{\_ram}$ might be affected by fragments of shattered large drops. Current flying shall produce data in heavy liquid cloud and precipitation which will assist in this investigation.

Figure 14 shows time series from flight B574 on 24th February. At the start of the sequence the aircraft descends from clear air through a stratocumulus deck. The following series of straight and level runs, initially below and then in the stratocumulus, encounter varying amounts of drizzle, picked up by the 2DC. Although the mission scientist notes clear air at 9.8 hours, the CDP is clearly recording smaller droplets throughout these runs. At 1100, the aircraft climbs through the top of the stratocumulus into clear air. Although there are variations in the difference between the WVSS-II, these do not appear to correlate with the cloud physics data available. There is a small but noticeable reduction in the difference between the WVSS-II during this period. The reason for this is not known, although it may be related to differences between P_{c_flu} and P_{c_ram}.

5.3 Mineral Dust:

Figure 15 shows data from flight B592, 7th April 2011, out of Ouarzazate, Morocco, when no liquid water was encountered - the CDP data indicates the presence of mineral dust. The relative behaviour of the WVSS-II sensors is similar in that closer agreement is seen both between the WVSS-II, and between these and the GE in the more humid conditions than in the dry, agreeing with the bulk data presented in figure 4. There does, however, appear to be some correlation between the WVSS-II difference and the CDP concentration which, although small, should be investigated further.

5.4 Ice Clouds: Figure 16 shows a time series from flight B573 on 23rd February. This section starts with a straight and level run at 8.5 km, the aircraft then descends to 7.6 km to carry another straight and level run before recommencing the descent. Around 16.2 hours the aircraft passes through a clear patch, either side of which it is in cirrus with the 2DC reporting substantial numbers of large ice particles; the CDP can be seen recording the presence of smaller particles, but these data are compromised by the instrument's small sample volume. Again, there is a reduction in the WVSS-II during the period, possibly relating to pressure measurement. Again, too, although there are small, more rapid, changes in the difference, they do not show any obvious correlation to the cloud physics data.

5.6 Icing Conditions: Figure 17 shows a time series from the four hygrometers in drizzle, liquid cloud and icing conditions, from flight B576 on 1st March. At *A* the aircraft entered the cloud base as indicated by the CDP; some drizzle is noted. At *B* the turbulence probe is suspected of having iced up; this was confirmed at *C*, along with a note of icing on other instruments and pylons. The aircraft then descended, clearing the ice at *D*. At *E*, however, substantial icing is noted again on assorted instruments and pylons. As neither of the WVSS-II inlets are visible from onboard the aircraft there is no direct record of when or if icing occurred but it is known that unheated Rosemount inlets are susceptible to icing and during the periods when icing was occurring elsewhere on the aircraft, the previously small and stable difference between the WVSS-II can be seen to vary substantially. During the second ice-free period (following *D*) the difference between the two instruments is once again stable around 3%. There is very obvious disagreement between the two chilled mirrors during this period, preventing their use in assessing the WVSS-II and further work is required to assess properly their performance in these conditions. A comparison with the performance of the performance of other unheated inlets on the aircraft might yield useful information.

6. Conclusions and Further Work

Analysis of data from twenty-six research flights around the United Kingdom, north Africa, the Aegean and eastern Canada show that, within the limits of this study, the WVSS-II hygrometer agrees well with the GE and the Buck in most situations. In very dry conditions, however, $WVSS_{\_flu}$ appears to over read substantially. Of the two, $WVSS_{\_ram}$ shows closer agreement overall, although it is slower to respond to rapid changes than $WVSS_{\_flu}$. The speed of response of both WVSS-II is, however, reasonable under all conditions encountered, easily coping with transitions to which the chilled mirror devices cannot respond adequately but consistently lagging behind the TWC (see dry slots in figure 11). There was no significant degradation of the WVSS-II with time; although changes in bias can be seen over this period, it is not clear whether they are due to changes in the instruments or a result of differing performance of the two inlets during the four experiments; the latter seems more likely, on account of the substantially different aims and atmospheric conditions encountered during the campaigns.

Examples of data gathered in clear air, ice and liquid cloud, drizzle, icing conditions and mineral aerosol are presented. Although no significant bias relating to clear and cloudy conditions is evident in figures 5 and 6, figure 12 shows some evidence that $WVSS_{\_ram}$ is susceptible to liquid water under certain circumstances. There were very few encounters with ice cloud recorded during these flights, but those data that exist do not give any cause for concern. Performance in icing conditions is difficult to assess and at least one WVSS-II was significantly effected (figure 17).

There appears to be a pressure dependant discrepancy between the two WVSS-II instruments which is thought to relate to one of the sample cell pressure sensors rather than to the difference in the inlets. This requires further investigation and it should be remembered that $WVSS_{\_ram}$ has no sample heater, this having been disconnected prior to acquisition by the Met Office, but both WVSS-II have standard, heated inlet hoses. A comparison of the performance of the same two WVSS-II but with their inlets swapped could provide useful data.

In summary, the performance of the WVSS-II in these flights was very encouraging; the WVSS-II hygrometer appears to perform well in all conditions encountered, but there are significant shortcomings in the performance of both the inlets used. The standard, flush inlet appears unable to cope with very dry conditions and is likely to produce data with a serious wet bias in the upper tropopause/lower stratosphere (UTLS). There remains concern that the flush inlet may be susceptible to run-off in heavy rain. Flights are planned over the next month which should address this issue and confirm concerns about UTLS data. The Rosemount inlet, by contrast, appears to work well in very dry conditions but can be susceptible to liquid water under certain circumstances and, for operational use, $WVSS_{\_ram}$ data in the presence of liquid water should be removed. There are also some grounds to suspect a susceptibility to mineral aerosol but this requires further investigation. Investigation of an inlet capable of providing reliable data both in the presence of liquid water and in the UTLS should be carried out.

7. References

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8. Figures

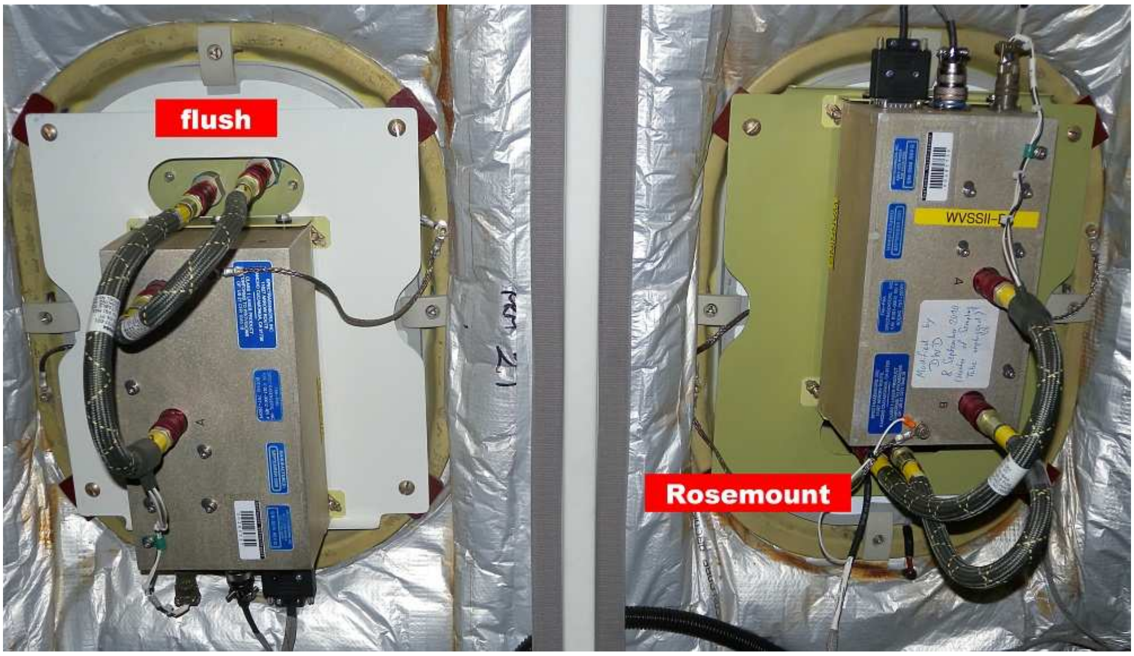

Plate 1. Installation of WVSS-II sensors on FAAM aircraft.

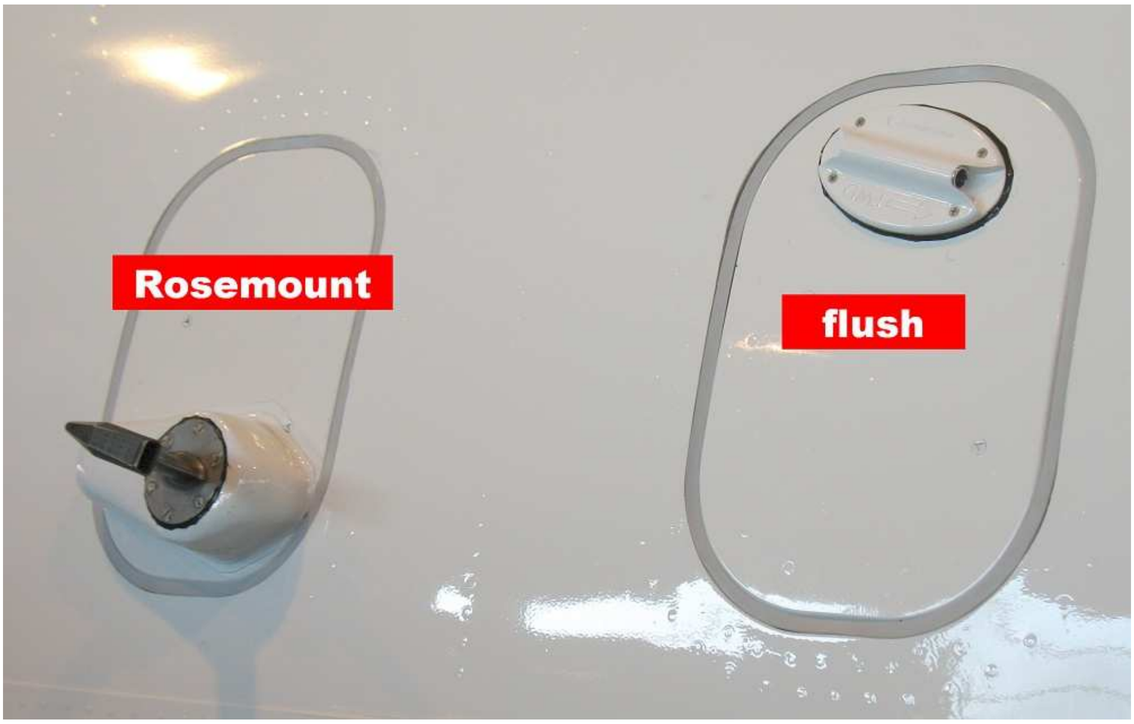

Plate 2. Outside view of installation of WVSS-II sensors on FAAM aircraft showing the two inlets angled down to match the local air flow in flight.

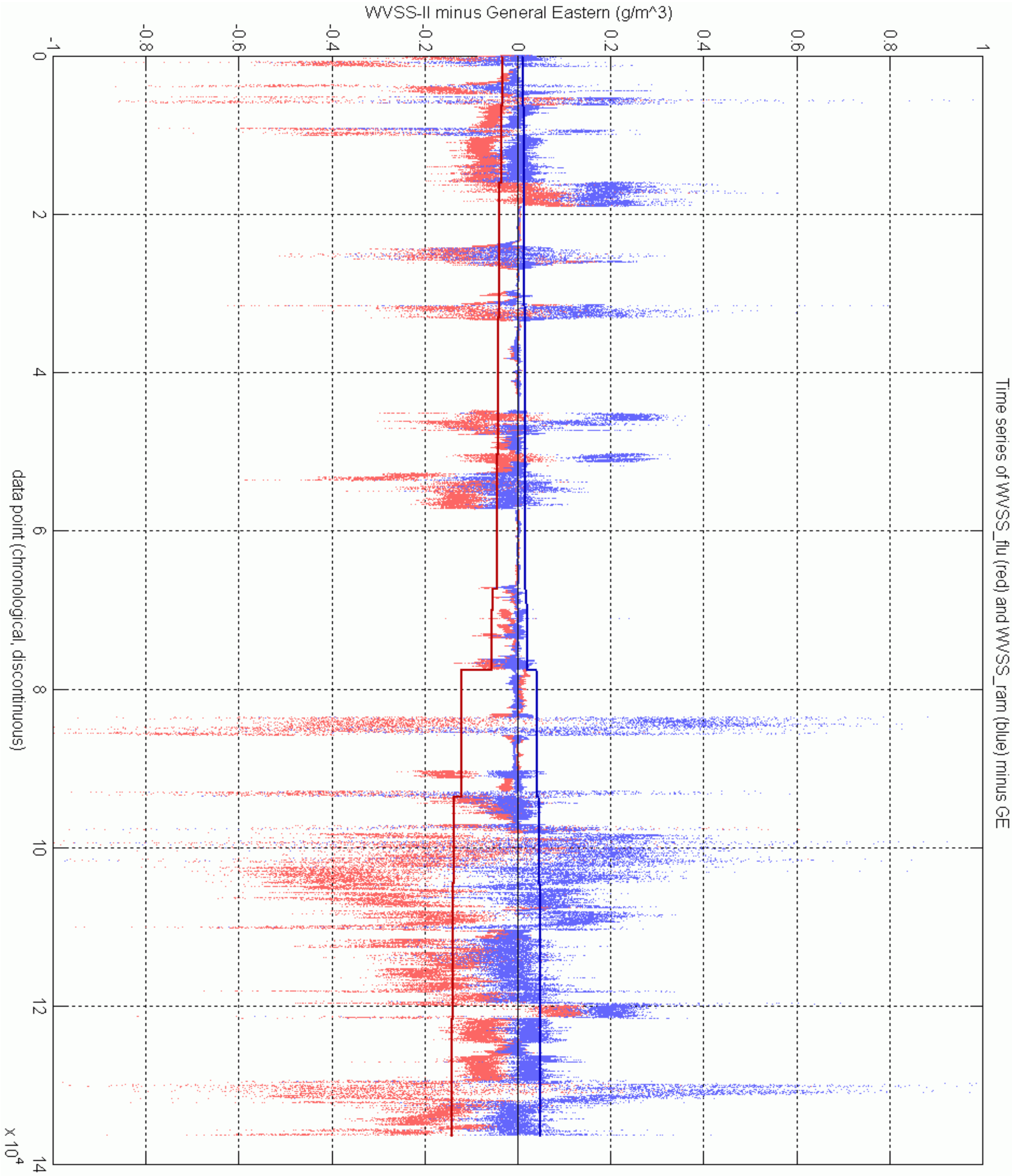

Figure 1. Assessment of calibration drift between WVSS-II and GE.

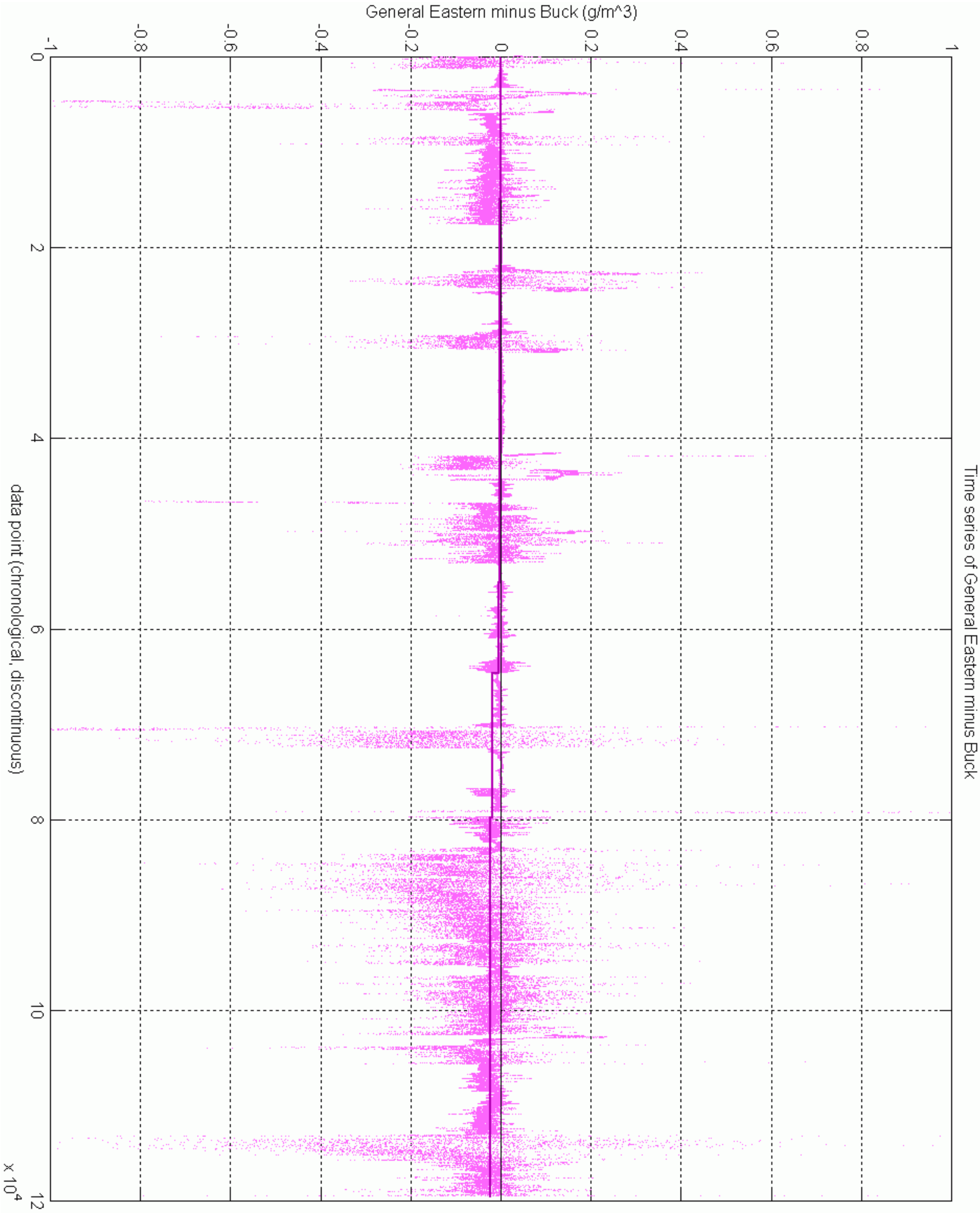

Figure 2. Assessment of calibration drift between GE and Buck.

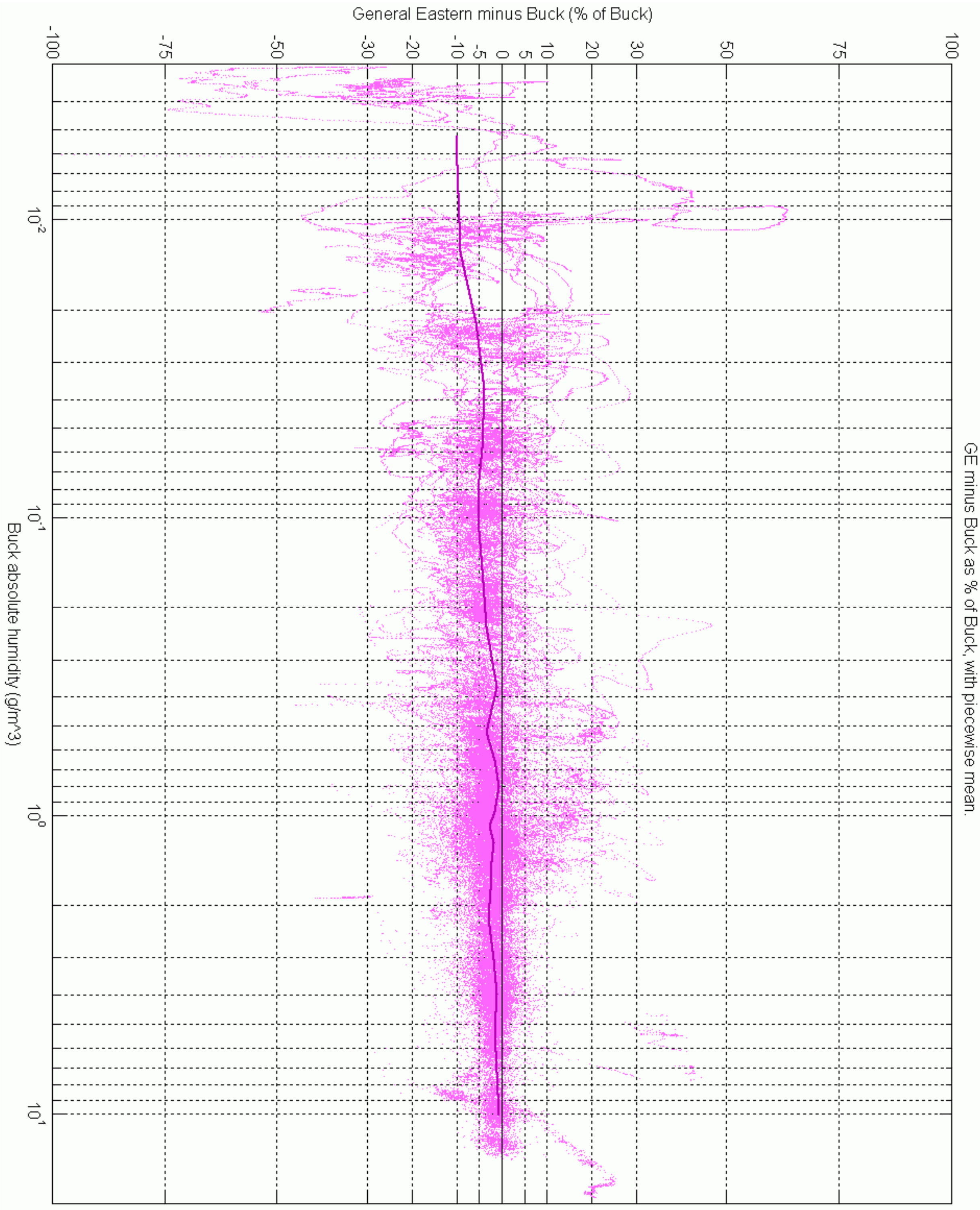

Figure 3. Comparison of GE and Buck in clear air.

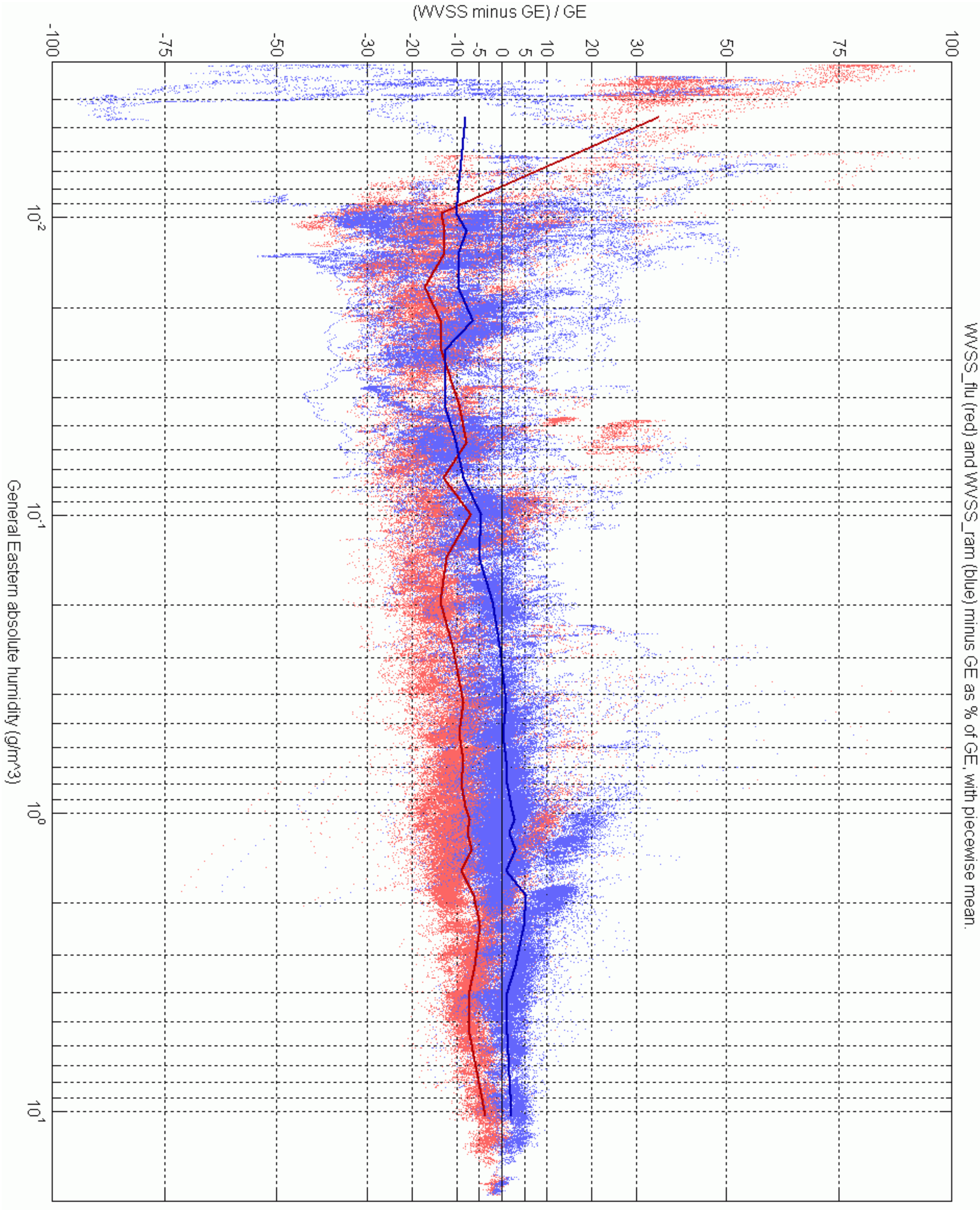

Figure 4. Comparison of $WVSS_{\_flu}$ and $WVSS_{\_ram}$ to GE in clear air.

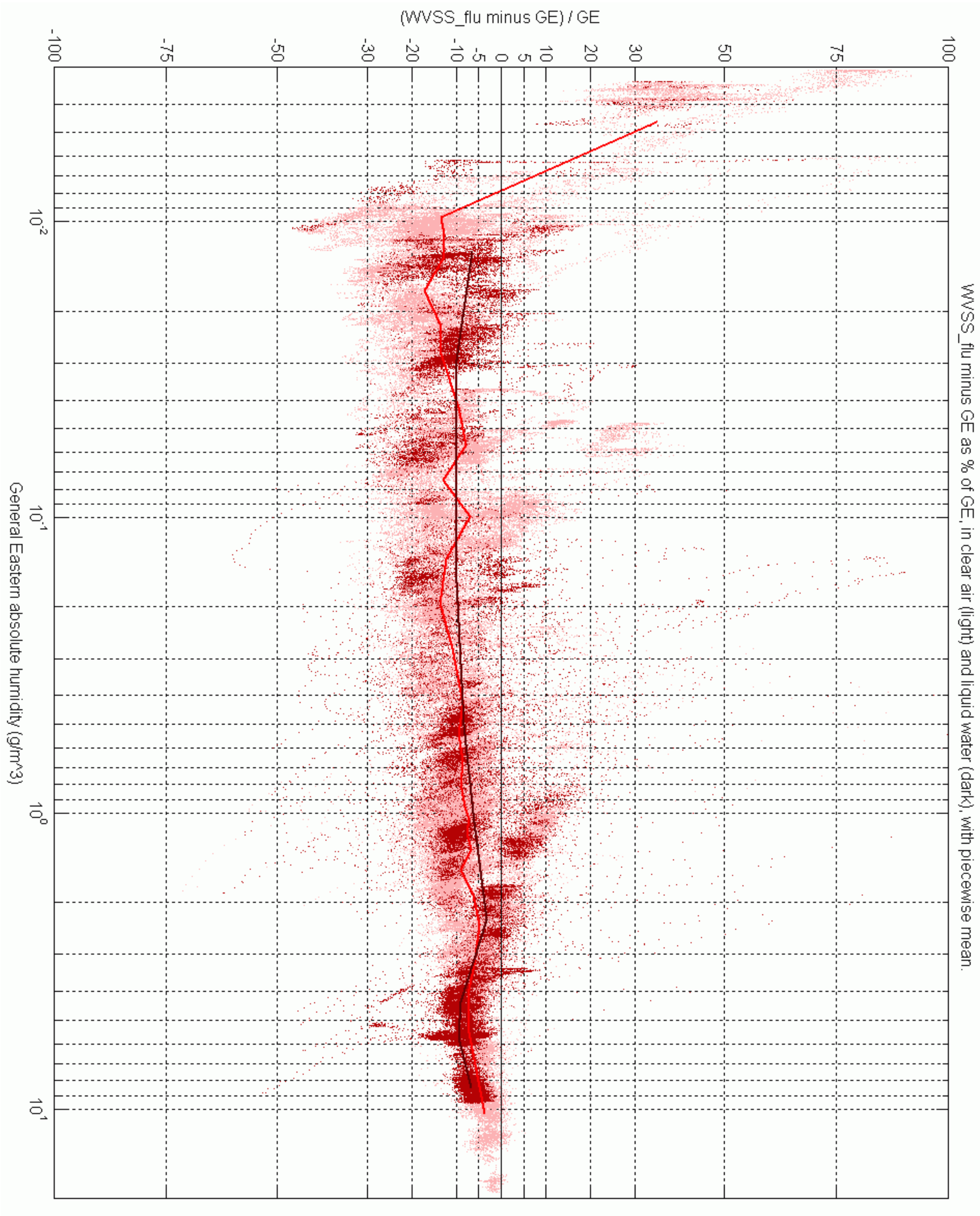

Figure 5. Comparison of $WVSS_{\_flu}$ to GE in clear air (light) and in the presence of liquid water (dark).

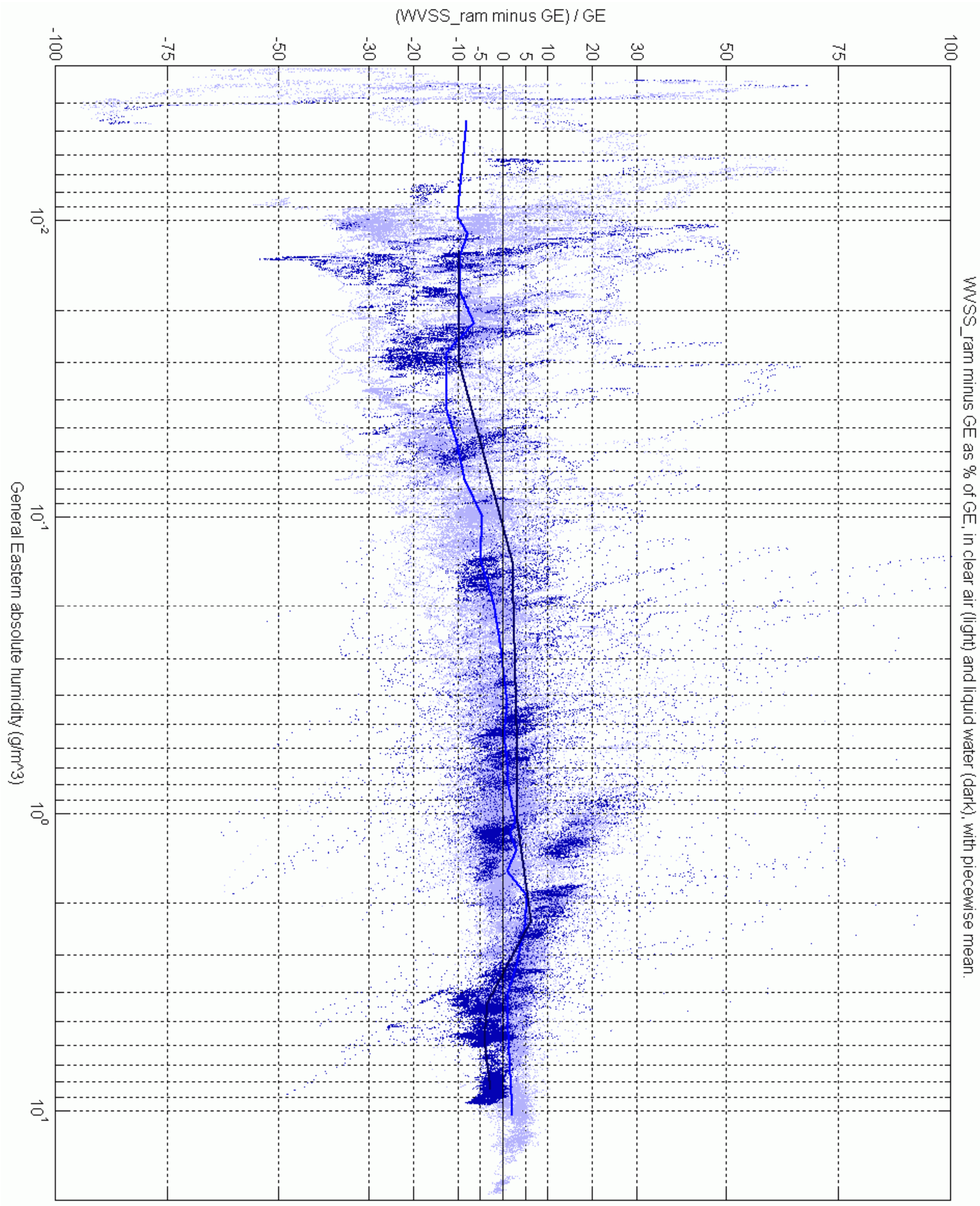

Figure 6. Comparison of $WVSS_{\_ram}$ to GE in clear air (light) and in the presence of liquid water (dark).

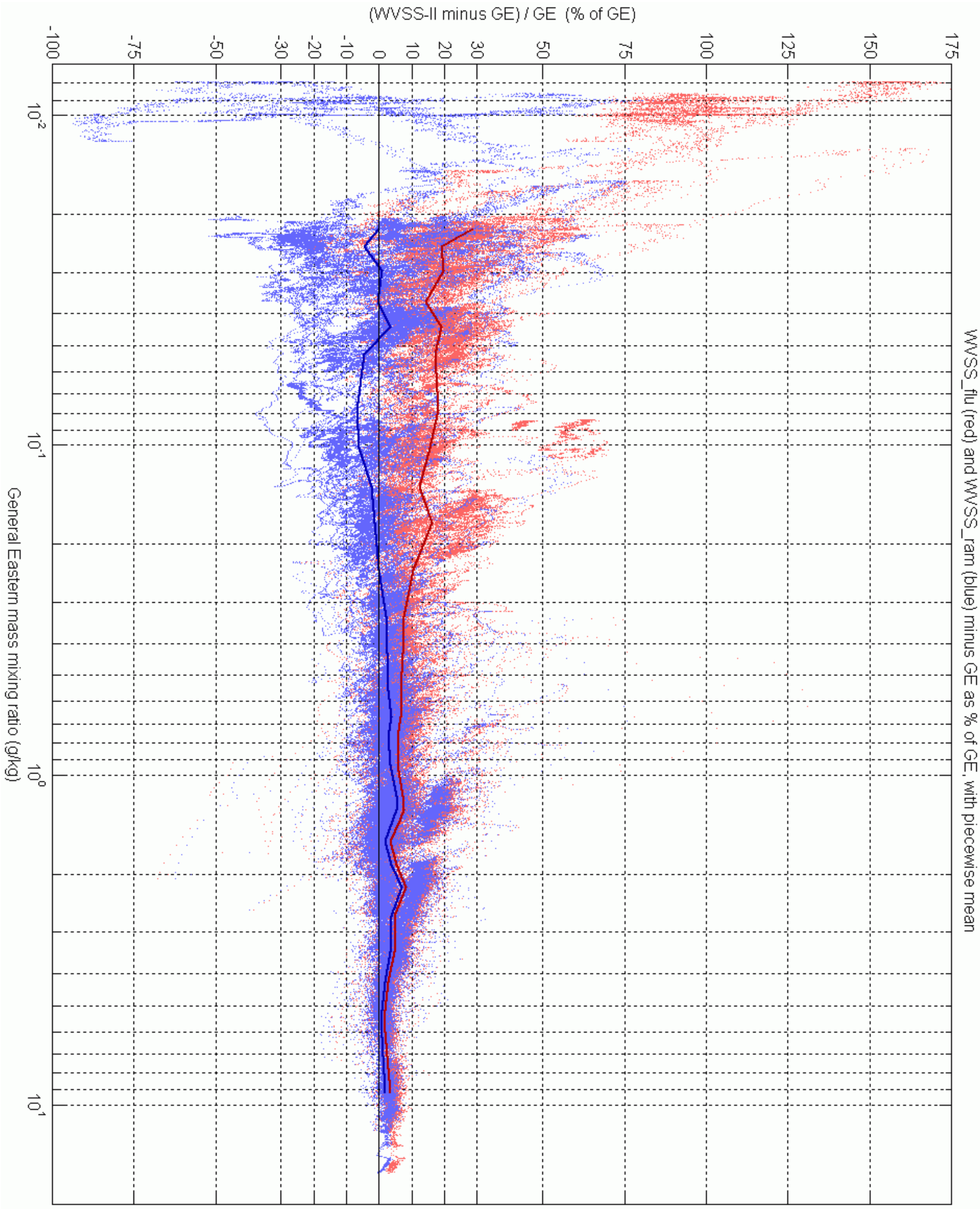

Figure 7. Comparison of $WVSS_{\_flu}$ and $WVSS_{\_ram}$ to GE in clear air.

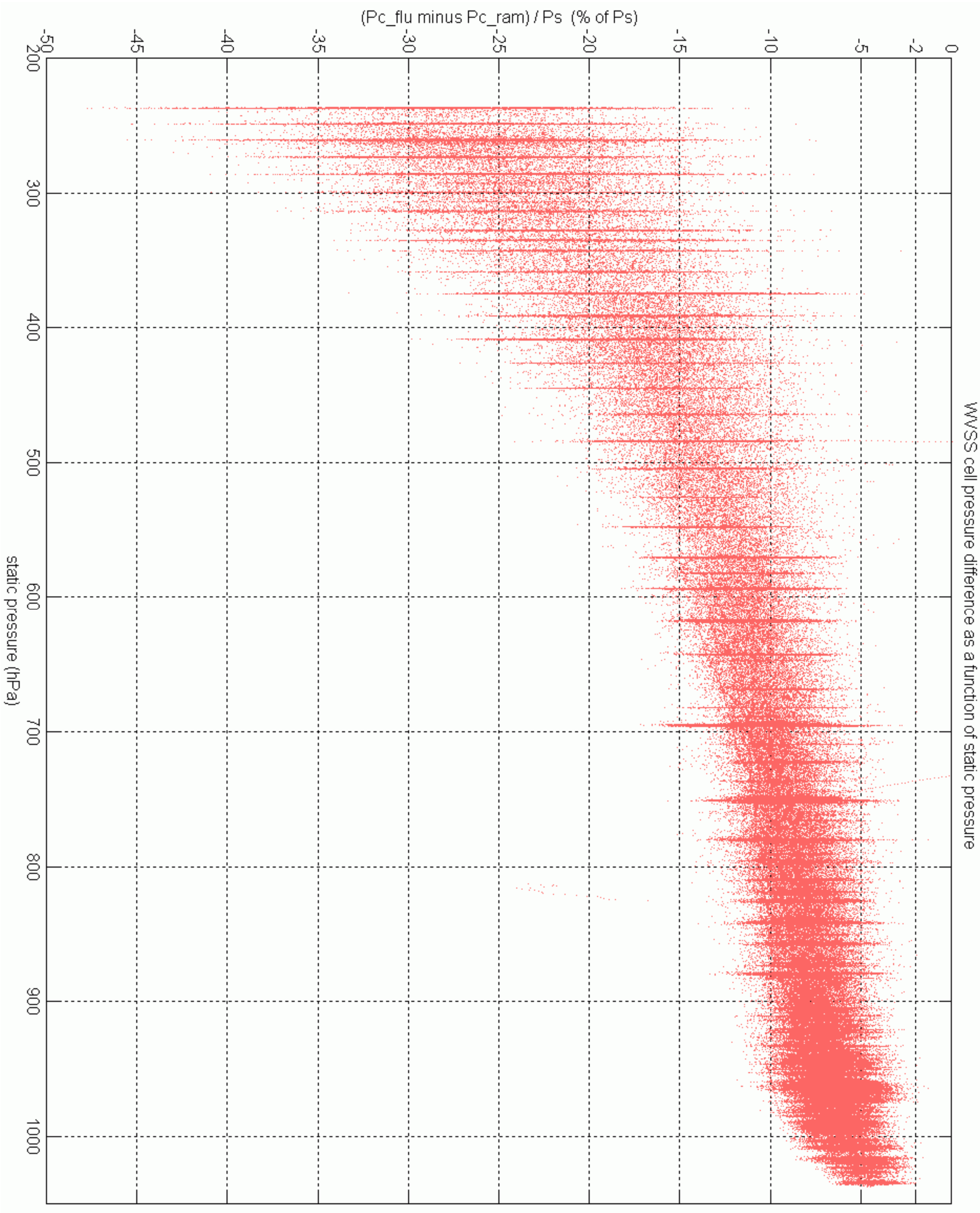

Figure 8. Comparison of WVSS cell pressure sensors in flight.

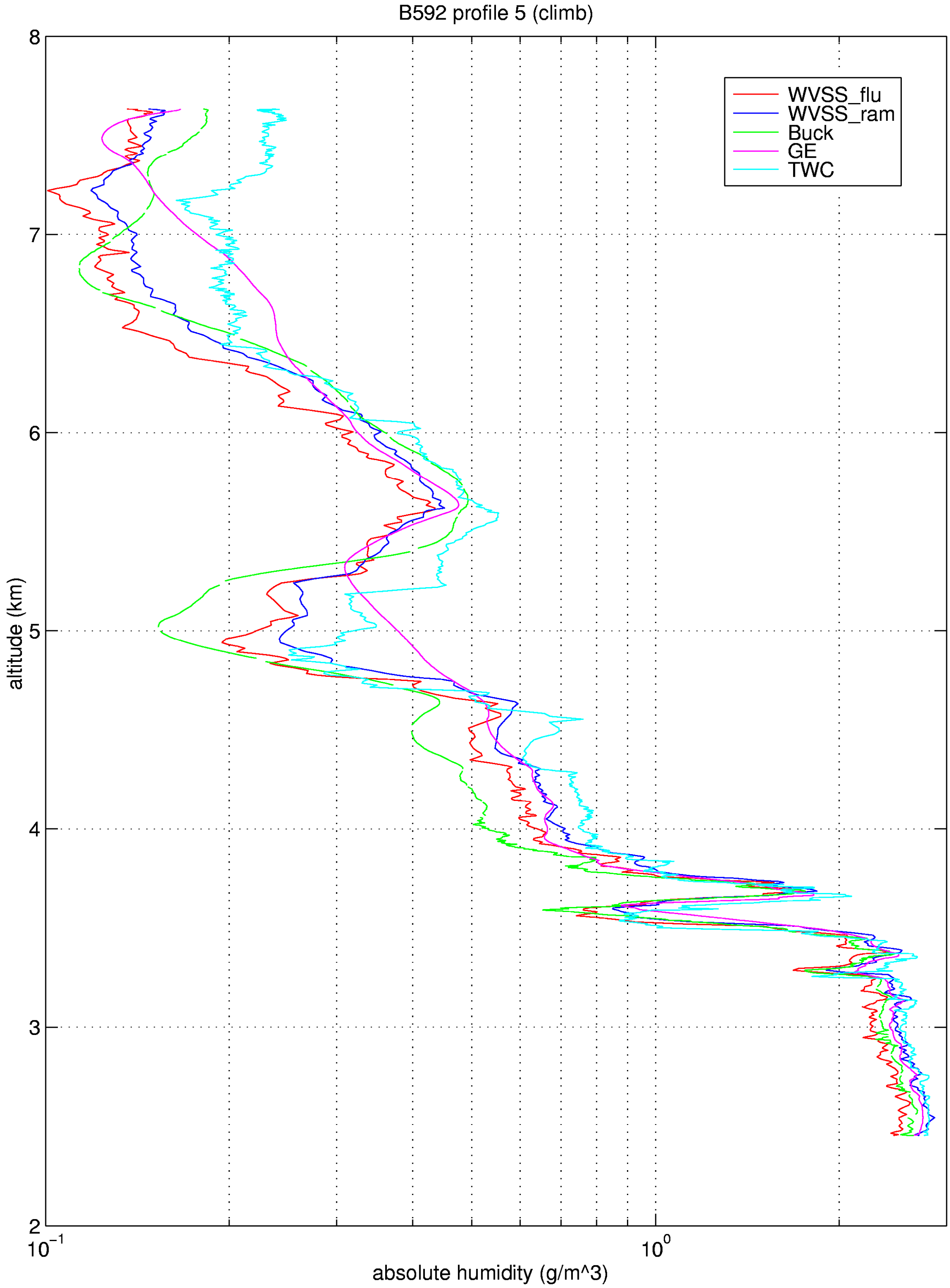

Figure 9. Data from the four hygrometers during a climb on 7th April over Morocco

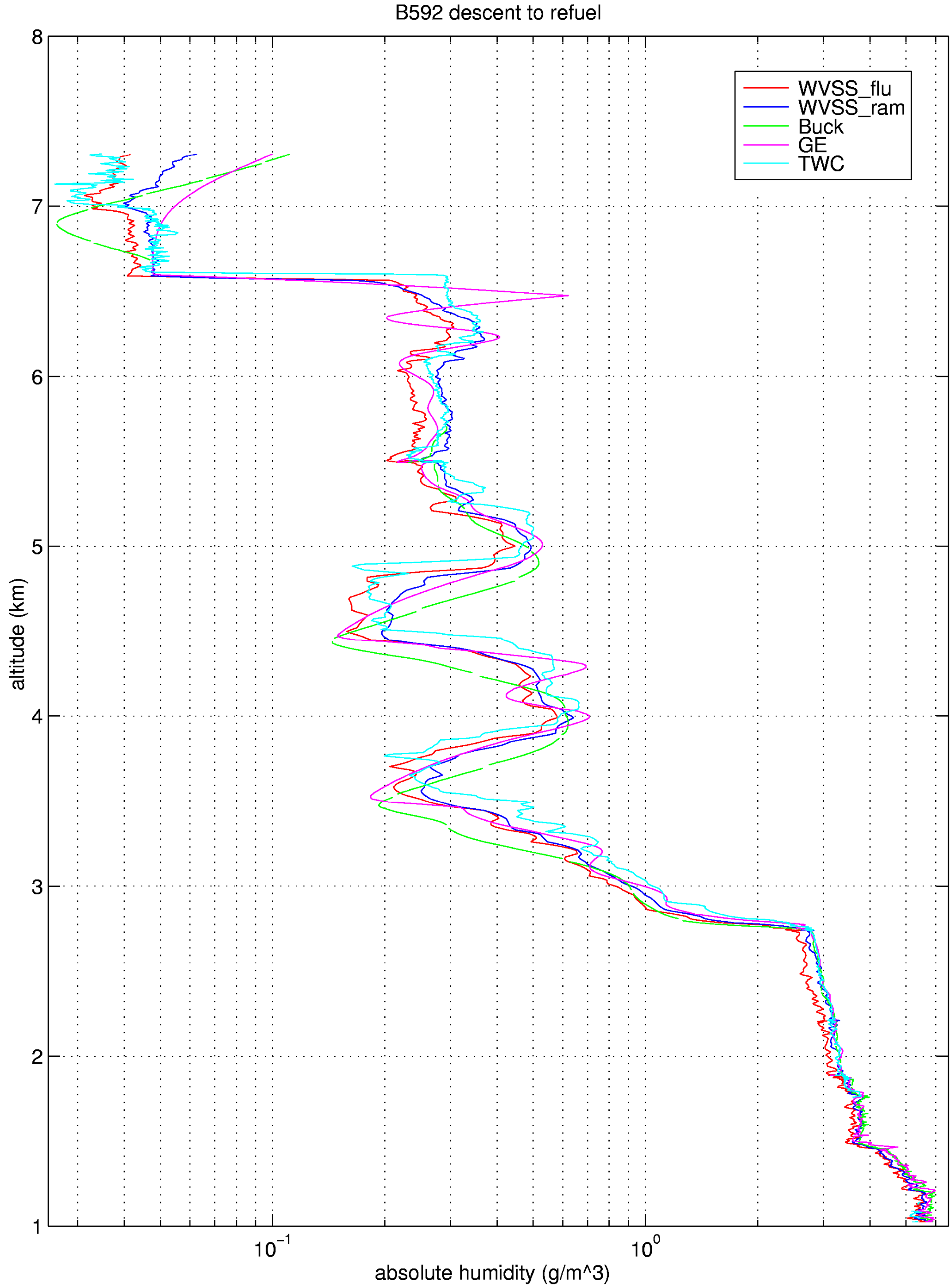

Figure 10. Data from the four hygrometers during a descent on 7th April over Morocco.

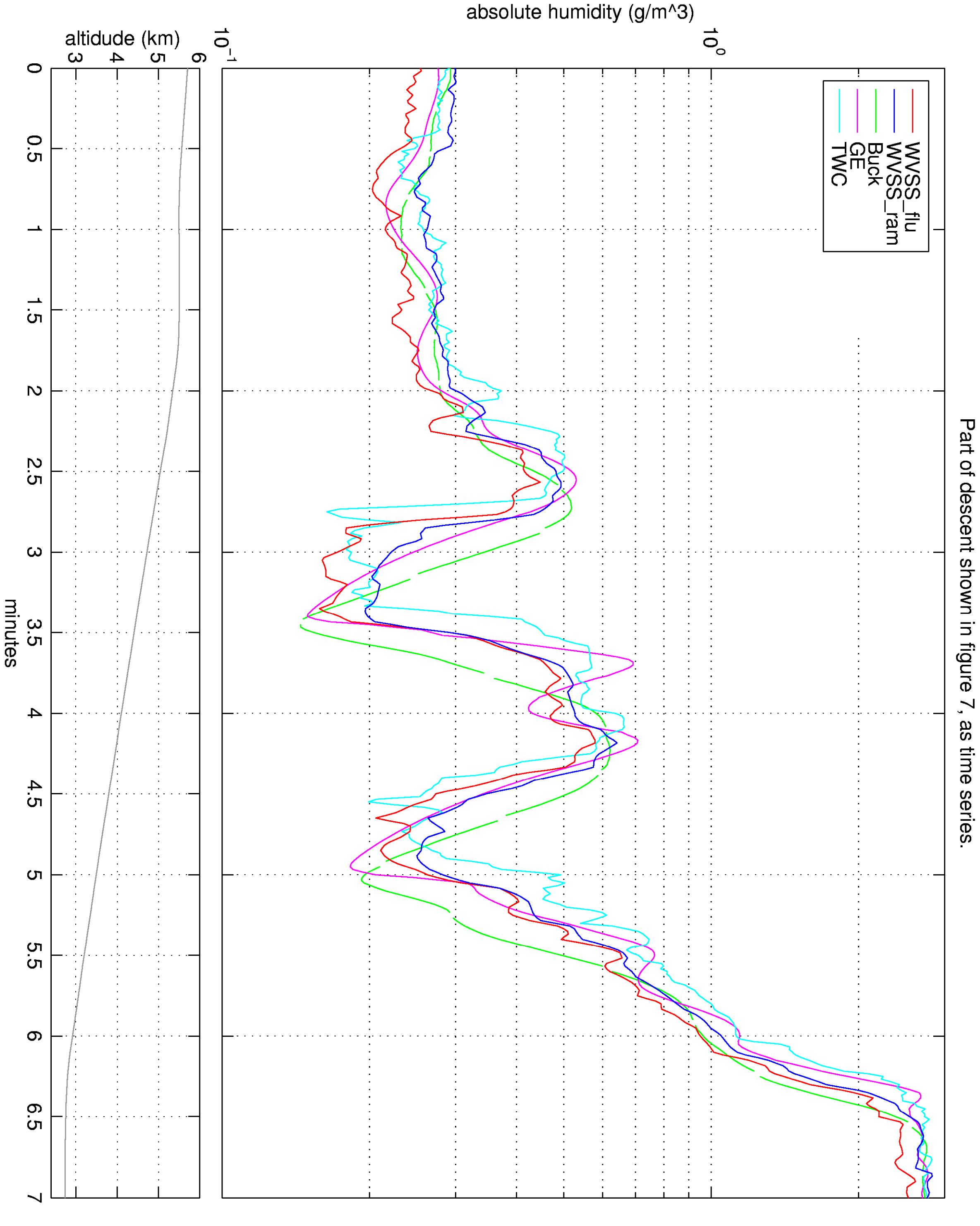

Figure 11. Time series of part of profile shown in figure 9.

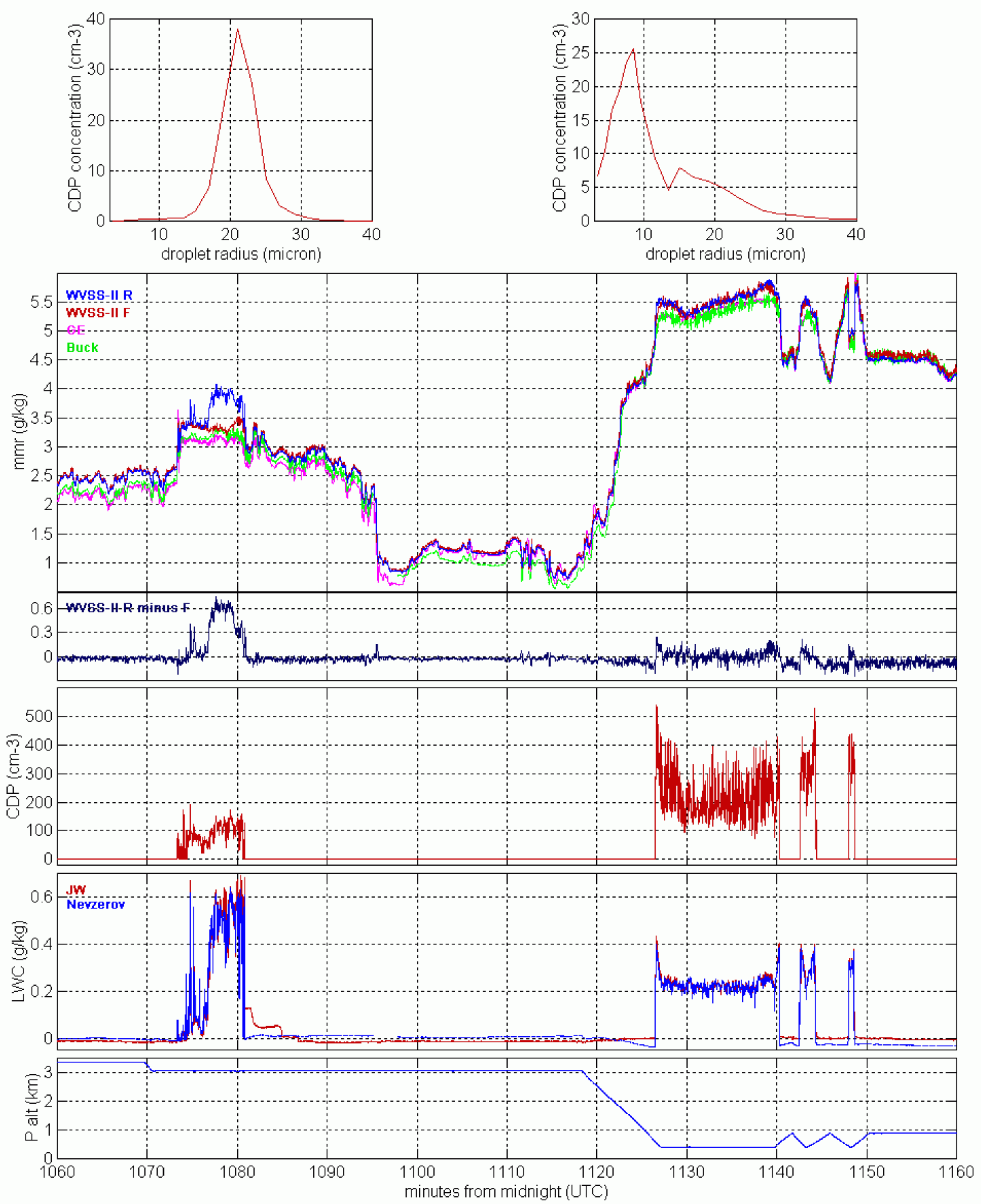

Figure 12. Time series from flight B584 showing different behaviour from WVSS_ram in two successive liquid cloud penetrations. Mean size spectra from the CDP are shown for the two penetrations.

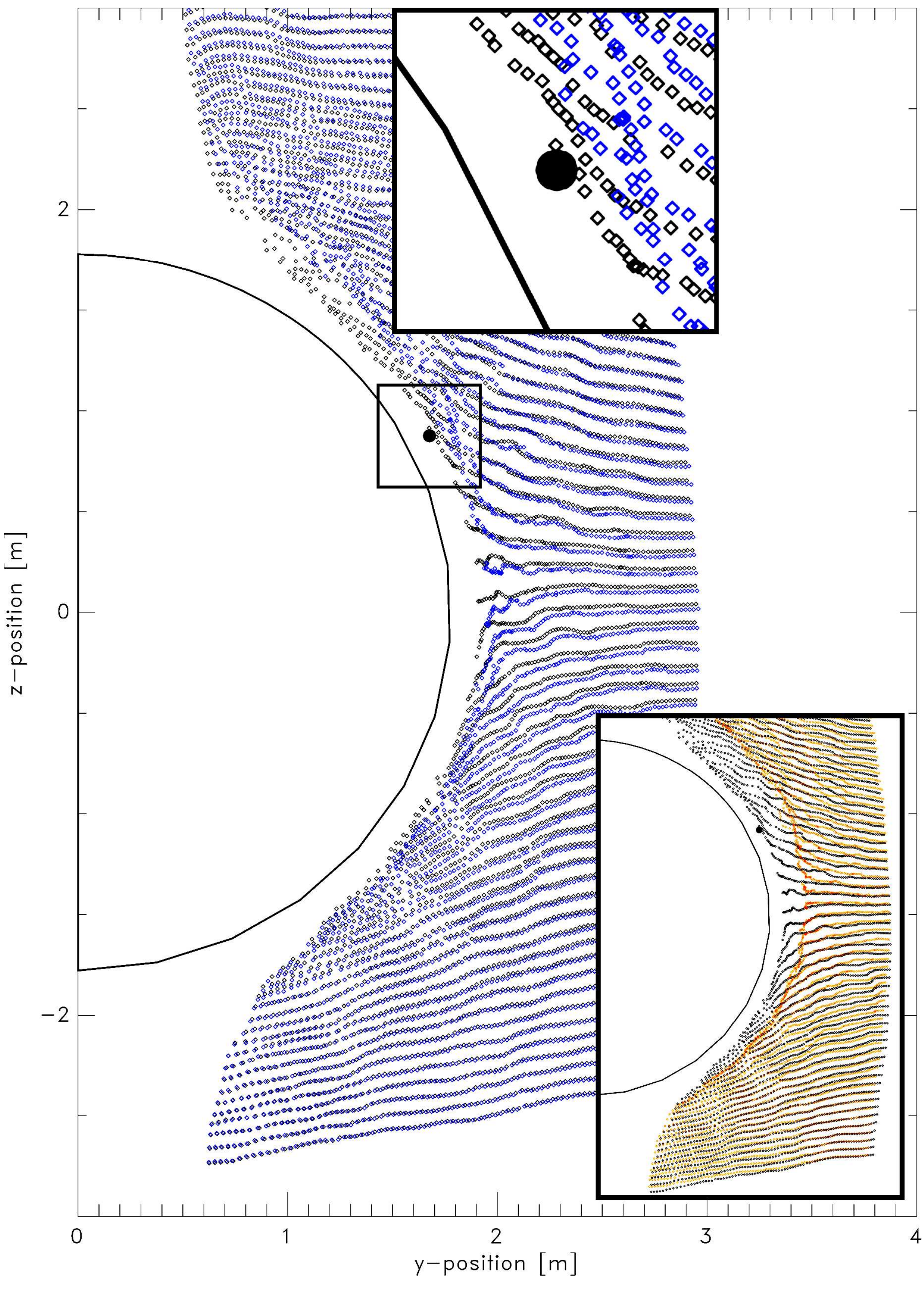

Figure 13. Results of CFD modelling carried out for an instrument similarly located to the WVSS-II. Figure shows a section through the aircraft fuselage and a uniform array of particles, perturbed by the passage of the aircraft. Black diamonds indicate 5 µm, blue 20 µm, and orange (inset, lower right) 50 µm droplets. Instrument location is denoted by a black spot in main figure and expanded in inset (top).

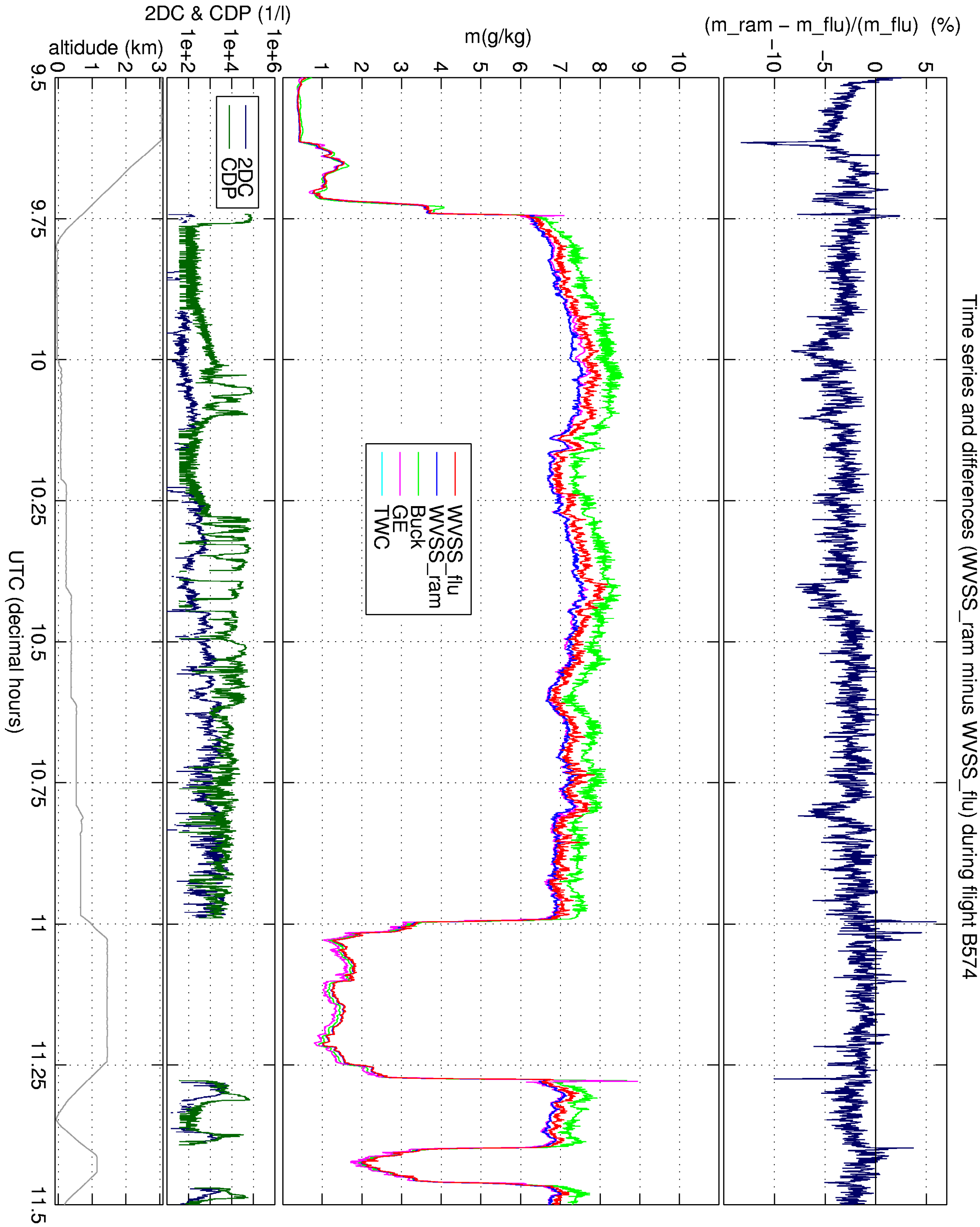

Figure 14. Time series from the four hygrometers in clear air, liquid cloud and drizzle, from B574.

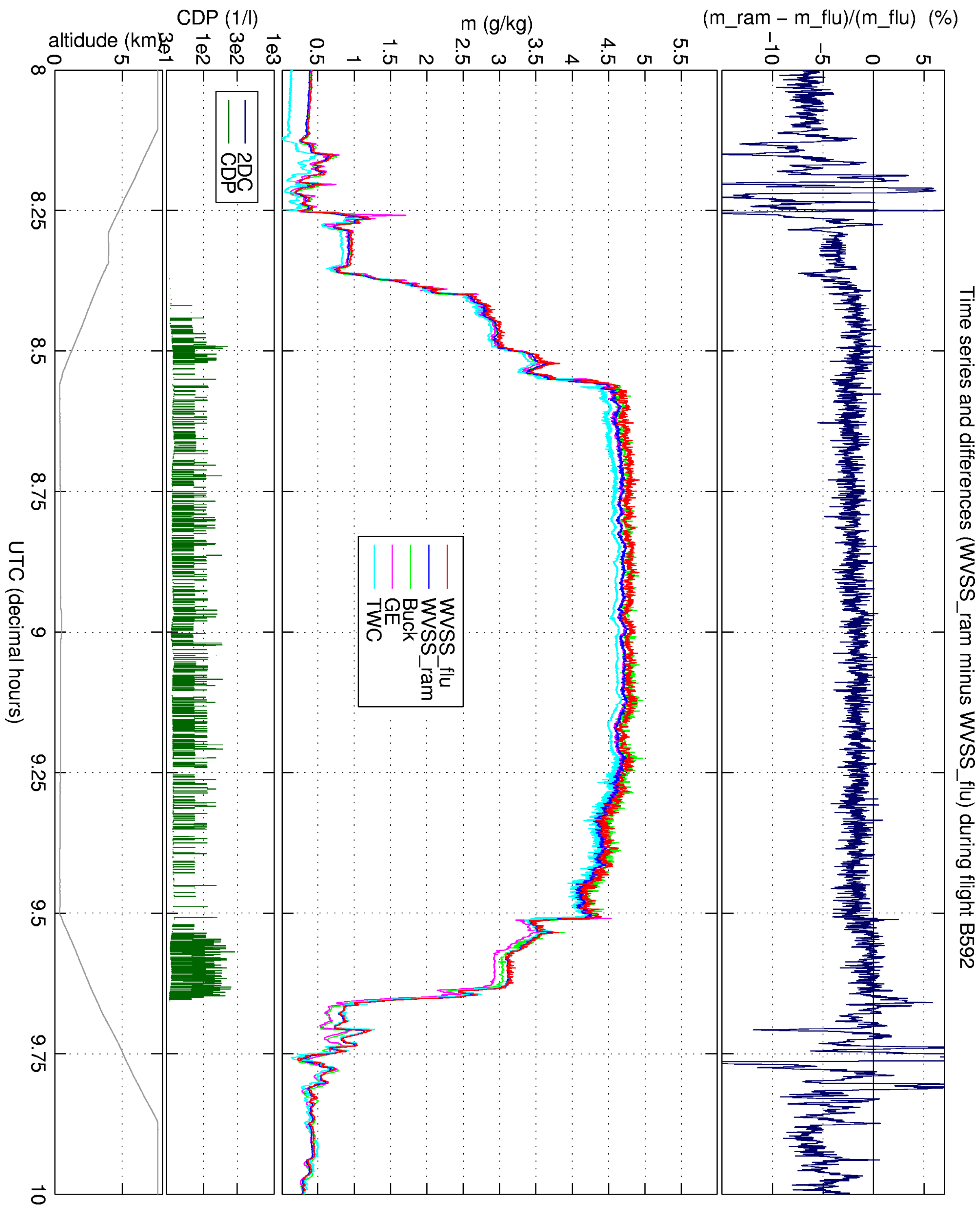

Figure 15. Time series from the four hygrometers plus TWC in clear air and mineral dust, from B592.

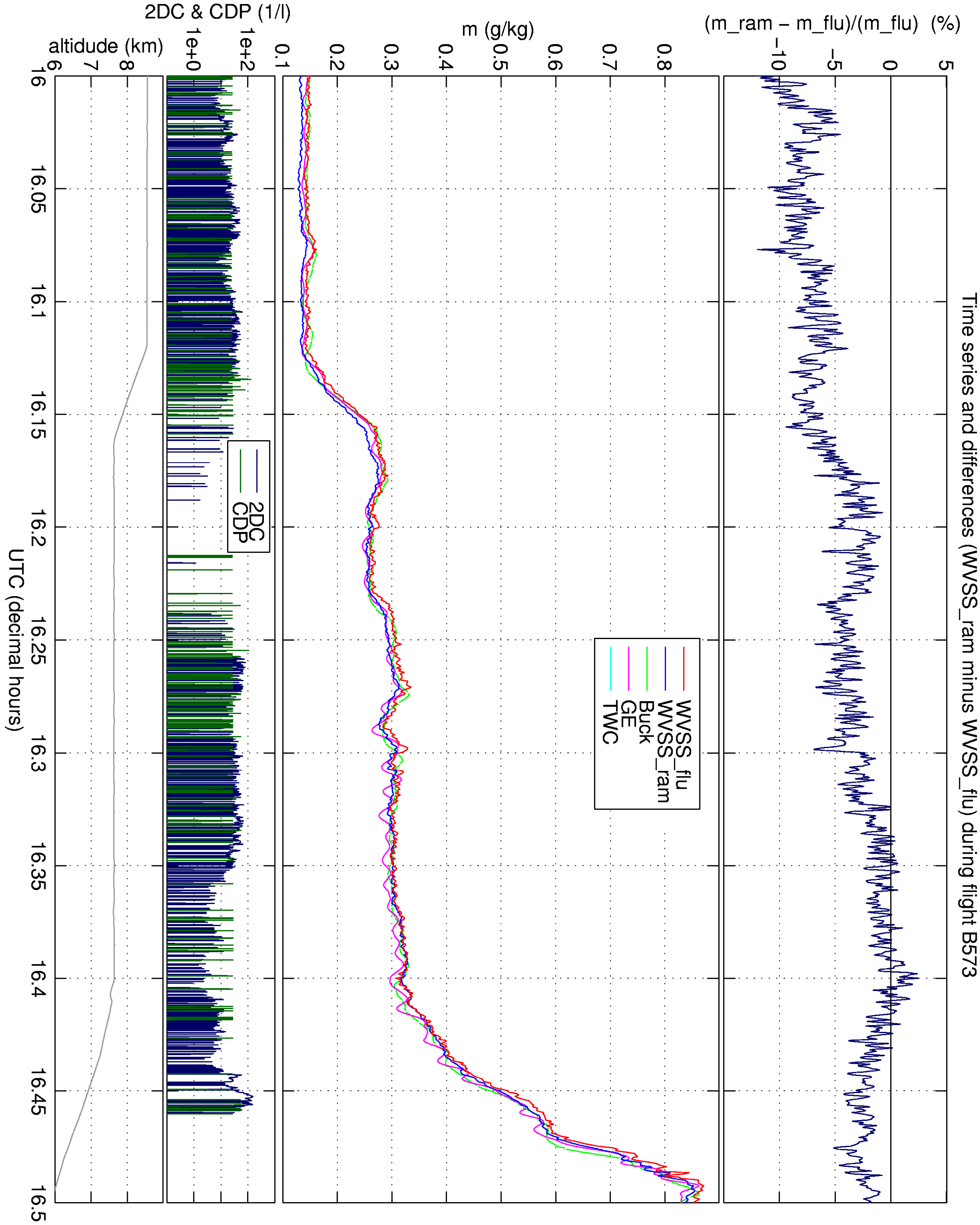

Figure 16. Time series from the four hygrometers in clear air and ice cloud, from 23rd February.

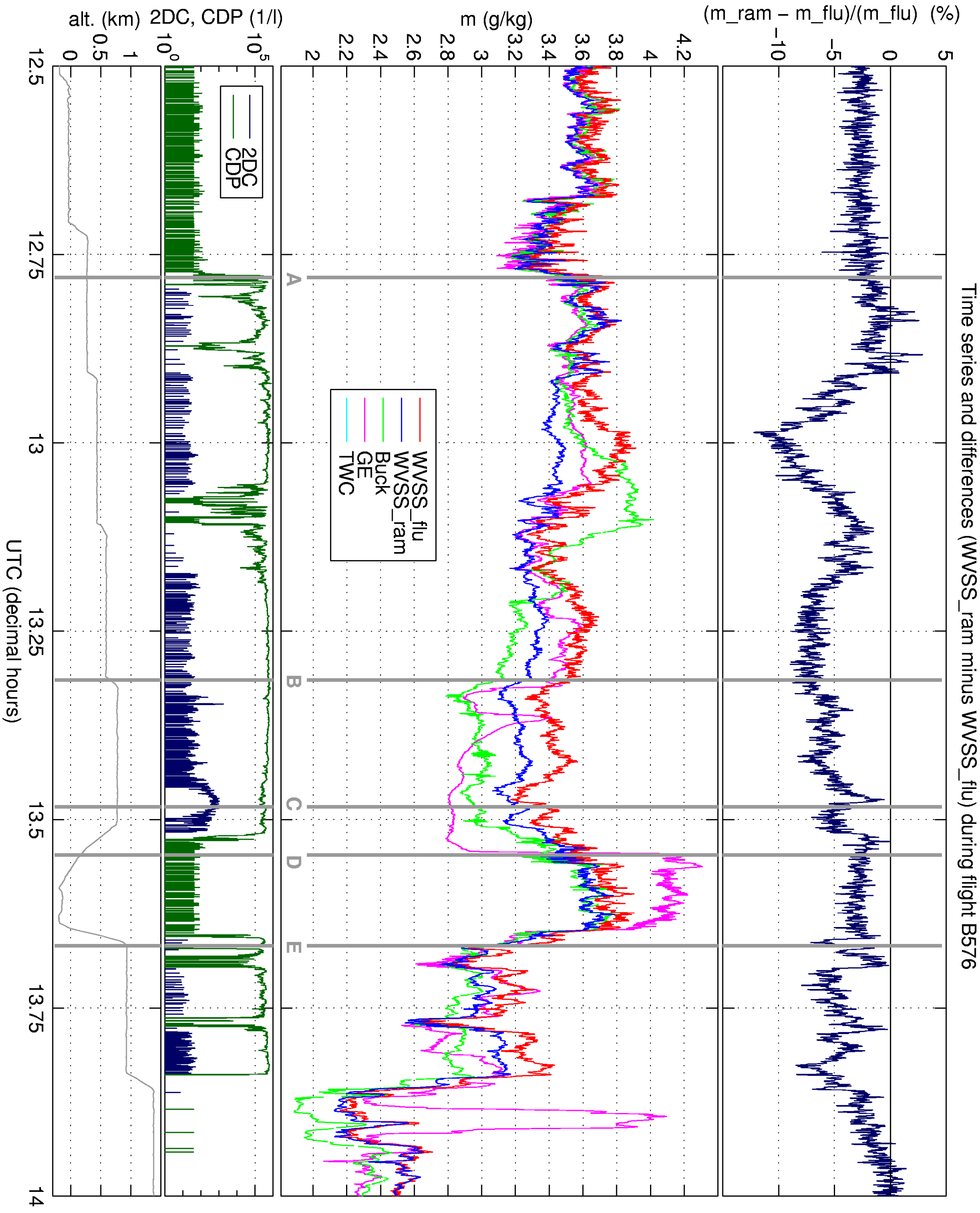

Figure 17. Time series from the four hygrometers in drizzle, liquid cloud and icing conditions, from 1st March.

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