Validation Project

in response to the

Call for Proposals
Support to IASI/AIRS Calibration and Validation

in the framework of the EUMETSAT Polar System.

Title:

Ground-Truthing Center Zugspitze, Germany for AIRS/IASI Validation

EUMETSAT Contract No. EUM/CO/01/892/PS

Phase II Report

Ralf Sussmann and Claude Camy-Peyret, 28 March 2003

Principle investigator

Dr. Ralf Sussmann
Institut für Meteorologie und Klimaforschung
Atmosphärische Umweltforschung (IMK-IFU)
Forschungszentrum Karlsruhe GmbH
Kreuzeckbahnstrasse 19
D-82467 Garmisch-Partenkirchen, Germany
Ralf.Sussmann@imk.fzk.de
phone: +49 (0)8821 183 159
fax: +49 (0)8821 73573

Engineering staff

Dipl.-Ing. (FH) Alexander Rockmann
Dipl.-Ing (FH) Josef-Michael Burger
Dipl.-Ing (FH) Karl Maurer
Dipl.-Met. (Univ.) Hans-Joachim Kanter
Stefan Schmid

Subcontractor

Dr. Claude Camy-Peyret
Laboratoire de Physique Moléculaire et Applications (LPMA)
Université Pierre et Marie Curie / CNRS
Tour 13, 3ème étage Case 76
4 Place Jussieu,
F-75252 Paris Cedex 05, Fance
camy@ccr.jussieu.fr
phone: +33 1 44 27 44 76
fax: +33 1 44 27 70 33

1. Introduction

This report describes the progress of the AIRS validation project "Ground-Truthing Center Zugspitze, Germany for AIRS/IASI Validation" (EUMETSAT Contract No. EUM/CO/01/892/PS) according to the work plan and schedule for the projects Phase II which has been defined in the EUMETSAT Call for Proposals, and our project proposal. We report about the ground measurements operations during the main AIRS validation campaign (19 Aug 2002 – 17 Nov 2002), post-campaign data quality assessment, refinements and reprocessing, as well as final statements/recommendations for future IASI validation.

Within our Phase I Report we had demonstrated full operationality of all instrumentation, retrieval software and data formatting software as to radio sounding, GPS, solar FTIR column measurements, in situ met data processing, and weather as well as cloud information formatting at the newly established AIRS/IASI validation site Zugspitze/Garmisch. It is a mountain site (Zugspitze, Germany, 47.4 °N, 11.0 °E, 2964 m asl.) complemented by the nearby by side ground site (Garmisch, 734 m asl.). It had been concluded that further work, before the AIRS main validation campaign envisaged for August 2002, should include investigations as to a possible wet bias of the GPS technique (deteced during the demonstration phase), especially for the high altitude Zugspitze site. Furthermore, studies for optimizing the FTIR retrieval strategy as to gaining optimum information content on the vertical water vapor VMR distribution for example cases in addition to retrieving the total columns, had to be continued. In preparation of the main validation campaign our software for retrievals and formatting had still to be further automated.

In Section 2 we therefore briefly state on the successful operationality of all our instrumentation and software as proven during the 3-months AIRS validation campaign. Section 3 explains our improvements of the ground-based GPS technique and presents insight into the quality of the GPS data via various sensitivity and validation studies. We explain the improvements implemented for a reprocessing we performed for all the campaign GPS data for both Zugspitze and Garmisch. This reprocessed data is provided as an additional deliverable attached to this report together with quality assessed met data for both Zugspitze and Garmisch. A validation study of the FTIR columns retrieval applied during the campaign by using the coincident radio sondes is given in Section 4, which adds a study on the characterization of the FTIR profile retrieval capability. In Section 5 we make recommendations for future IASI validation based upon the conclusions of this project and related technical developments of ongoing parallel projects of IMK-IFU. This includes a description of new instrumentation currently installed at Garmisch as well as possible further instrumentation which would be desirable for the Zugspitze.

2. Campaign Operations

Operationality. The 3-months validation campaign at the European AIRS validation site Zugspitze/Garmisch had been finally scheduled on 15 August 2002 by EUMETSAT to start with the afternoon overpass of 19 Aug 2002.

The ground validation activities at Zugspitze/Garmisch were run continuously 7-days a week till the campaign end on 17 Nov 2002. The campaign covered 91 days, including measurements correlative to 180 subsequent AIRS overpasses as committed in our contract. The campaign data delivery was a perfect success, i.e., we were able to deliver to EUMETSAT all the committed data within 12 hours for each of the 180 overpasses properly. FTIR measurements were run whenever possible (clear sky conditions), and lead to 27 FTIR measurement days during the campaign in total. This is about every third day of the campaign, i.e., we achieved an unexpectedly high number of FTIR measurements correlative to AIRS overpasses. Due to good luck, no instrument down times occurred during the dedicated 2-hours measurement intervals around any of the 180 overpasses. During a period with no solar FTIR measurement conditions (due to rain), a few days of FTIR down time occurred, which did not impact the campaign result at all. For a few of the 360 radio sondes launched, no GPS (trajectory) signal was received, or the full receiving station failed, but in all cases the second sonde of the pair (launched within 1 hour before overpass) could get the signal ok. So, all in all, the full validation data set for the 180 dedicated overpasses has been produced and delivered as planned ok.

In a parallel project of IMK-IFU (funded by the Bavarian Ministery of Economy) a water vapor lidar is developed, and currently (March 2003) being installed at the Zugspitze/Schneefernerhaus). It was intended that the lidar should be operational during AIRS validation. However, due to some technical delays, the lidar project is still in the implementation phase, i.e., no water vapor lidar data could be provided as an input to our project.

Campaign data. All the correlative Zugspitze/Garmisch ground data sampled during the campaign have been transferred to the EUMETSAT ftp site. Furthermore, they have been archived at the Garmisch data archive of IMK-IFU. Updated GPS data (fully reprocessed for Zugspitze and Garmisch) as well as quality assessed met data for Zugspitze and Garmisch is attached to this report.

3. GPS quality assessment and improvement

GPS receiver equipment for water sounding was installed according to the specifications of the currently established network within the German GPS Atmospheric Sounding Project (GASP, Reigber 1999-2002). This includes dual frequency GPS receivers (1.6- and 1.2-GHz signals), antenna, antenna mount, and a dedicated computer connected to the web to maintain real-time data flow via ftp. Installation of receivers both at the Zugspitze mountain site and the Garmisch ground-station allows to characterize the water columns above 734 m (Garmisch), and above 2964 m asl. (Zugspitze) respectively. The Zugspitze GPS system was purchased for this project and consists of a RegAnt-1 Choke Ring Antenna and a Legacy-H GD L1+L2 receiver (Topcon/Allsat Inc., Germany). The second system, installed at Garmisch, was provided by our partners at Geoforschungszentrum Potsdam, Germany and consists of a Ashtech Choke Ring Antenna and a TurboRogue SNR-800 receiver. A GPS receiver raw data file (sample rate 30 seconds) is stored and automatically transferred via ftp every full hour. Retrieval of water vapor vertical columns is performed automatically at Geoforschungszentrum Potsdam and provided back as a file containing the two half hourly means of each hour with a delay of 45 minutes after the full hour.

From the results of the demonstration phase campaign in March 2002 we had an indication for a significant over-estimation of the water columns above Zugspitze by the Zugspitze GPS of up to a factor of 2.54 compared to the integral of the (Tobin) interpolated pair of coincident radio sondes (see page 16 of the Phase I Report of 17 April 2002). Also the Garmisch GPS had shown a (moderate) over-estimation of the columns relative to the sonde integral by a factor of 1.07 (on 22 March), and 1.1 (on 24 March). Therefore, we present a detailed GPS data quality assessment based upon the full campaign data sets in the following.

Impact of different antenna types. As mentioned above, we had found during the demonstration phase a significant wet bias of water vapor columns retrieved from the Zugspitze GPS compared to the results of the coincident radio sondes. Therefore, we installed at the Zugspitze during the whole duration of the campaign a second GPS system at the Zugspitze (Ashtech, identical to the Garmisch System, see above, provided by Geoforschungszentrum Potsdam). It was mounted at the Zugspitze, only about 4 m apart in horizontal distance from our own system (Topcon).

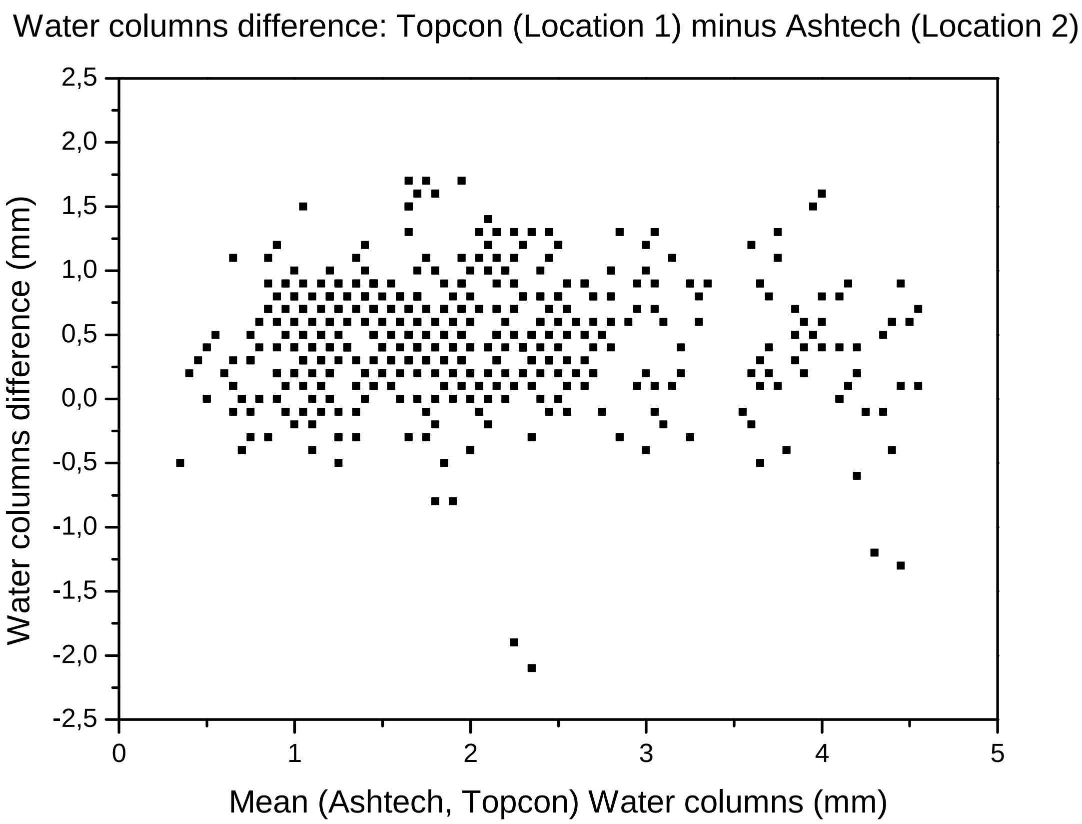

Figure 1: Bias and scatter of the difference between the coincident half hourly mean values from a period of two weeks of water column measurements from two side by side GPS systems from different companies (Topcon versus Ashtech) located a few meters apart in horizontal distance. The same pressure series has been used for both systems. Bias and scatter would be higher when using also two independent pressure sensors.

The result is shown in Figure 1. It displays the differences of all the coincident half hourly mean values retrieved from the two different GPS systems during a time span of two weeks in Feb 2003. The message of Figure 1 is twofold: i) There is a significant bias between the columns from the two different antenna types, with the Topcon antenna yielding higher (biased) columns by 0.46 mm. ii) There is a significant scatter (variance 0.8 mm) of the difference between the half hourly mean values from the collocated and coincident measurements of the two different GPS systems. It has to be stated at this point that these numbers for scatter and bias are a lower border estimate, which only monitors the scatter from the GPS technique itself. These numbers do not contain the impact of propagated errors (bias and scatter) of the pressure measurements needed as input, since for this intercomparison the identical pressure series (German Weather Service Zugspitze) has been used as input for both GPS systems. Usually, for more widely separated GPS systems different pressure sensors are used. This introduces an additional bias and scatter, since errors in pressure input propagate into water column errors through the GPS retrieval, see below for further details.

Impact of antenna location. One hypothesis to explain the bias of Figure 1 was this bias not being due to the different antenna types, but due to the different antenna mountings relative to the building: one antenna was mounted slightly above the southern edge of the roof of the building and the other one slightly above the northern edge of the roof of the same building (both antennas being about 4 meters apart in horizontal distance, see above). The idea was, that most of the GPS satellites appear in the southern azimuthal viewing range on average, and that there could be reflections from the roof impacting the GPS signal of the northern edge GPS system.

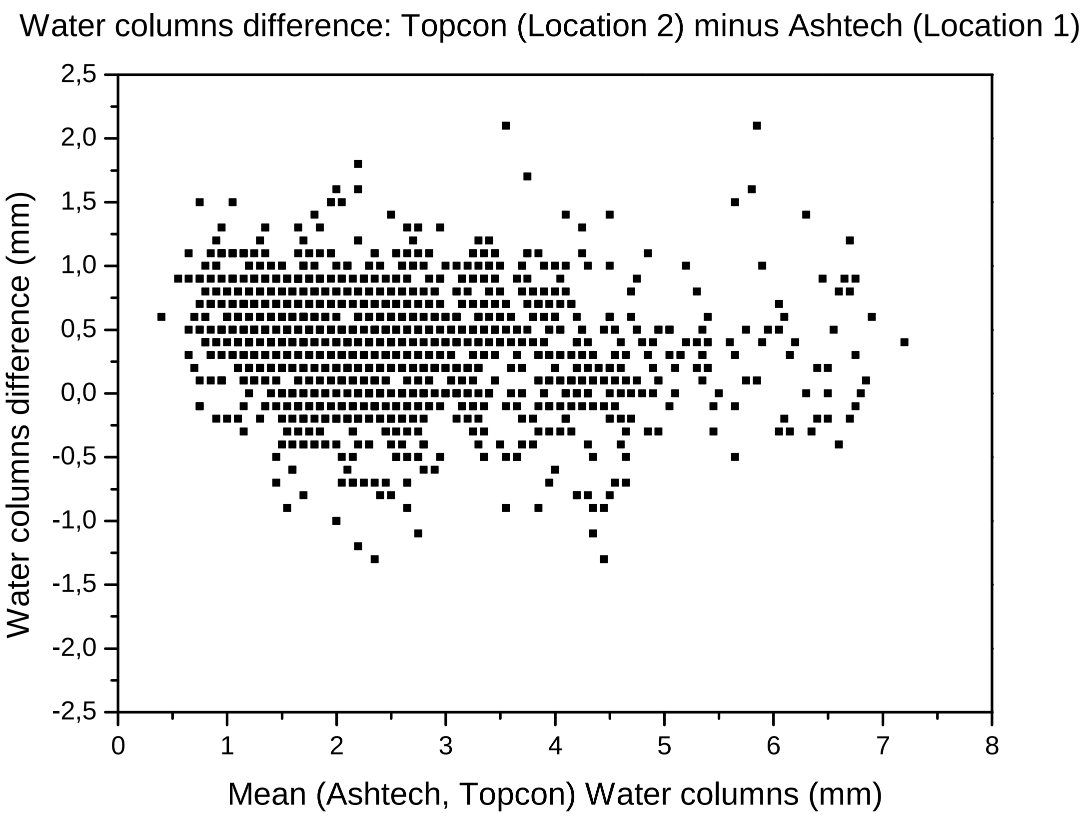

Figure 2: Same as in Figure 1 but for interchanged locations of the two different antennas for 3 weeks.

To check this hypothesis, the mounting location of the two GPS systems was interchanged for a three weeks period, see Figure 2 for the result. Again nearly the same bias (now 0.36 mm) appears, i.e., Figure 2 shows that there is no additional bias resulting from differences of the mounting location. In other words, Figure 2 gives proof that the observed bias of ≈0.4 mm is due to the two different antenna types.

The impact of in situ temperature and pressure input on GPS water retrievals

Background. Details of the retrieval of precipitable water (PWV) from grond-based GPS data have been given by Bevis et al. (1992). Briefly and simplifying, the impact of surface pressure and its possible measurement errors on the retrieved water column can be understood by considering the total atmospheric path delay of the GPS signal

$$\Delta trop^{sat}_{rec} = ZHD_{rec}(p_s)\cdot m\_hyd^{sat}_{rec}\,(elev)\ +\ ZWD_{rec}\cdot\ m\_wet^{sat}_{rec}\,(elev) \qquad \text{(eq. 1)}$$

where ZHD is the hydrostatic delay (equals 2.5 m) and ZWD is the wet delay in the zenith (which is variable within a few millimeters up to 400 mm), m_hyd and m_wet are mapping functions for taking the observation geometry (elevation) into account. After retrieving the total zenith path delay ZPD = ZHD + ZWD directly from the GPS data (with a millimeter accuracy), a conversion to precipitable water (PWV) is possible, using ground values of pressure (p_s) and temperature (T_s). An approximation is used to retrieve calculate ZHD from p_s. Subtraction from ZPD yields ZWD which is related to PWV by

$$PWV = F(T_m) * ZWD \qquad \text{(eq. 2)}$$

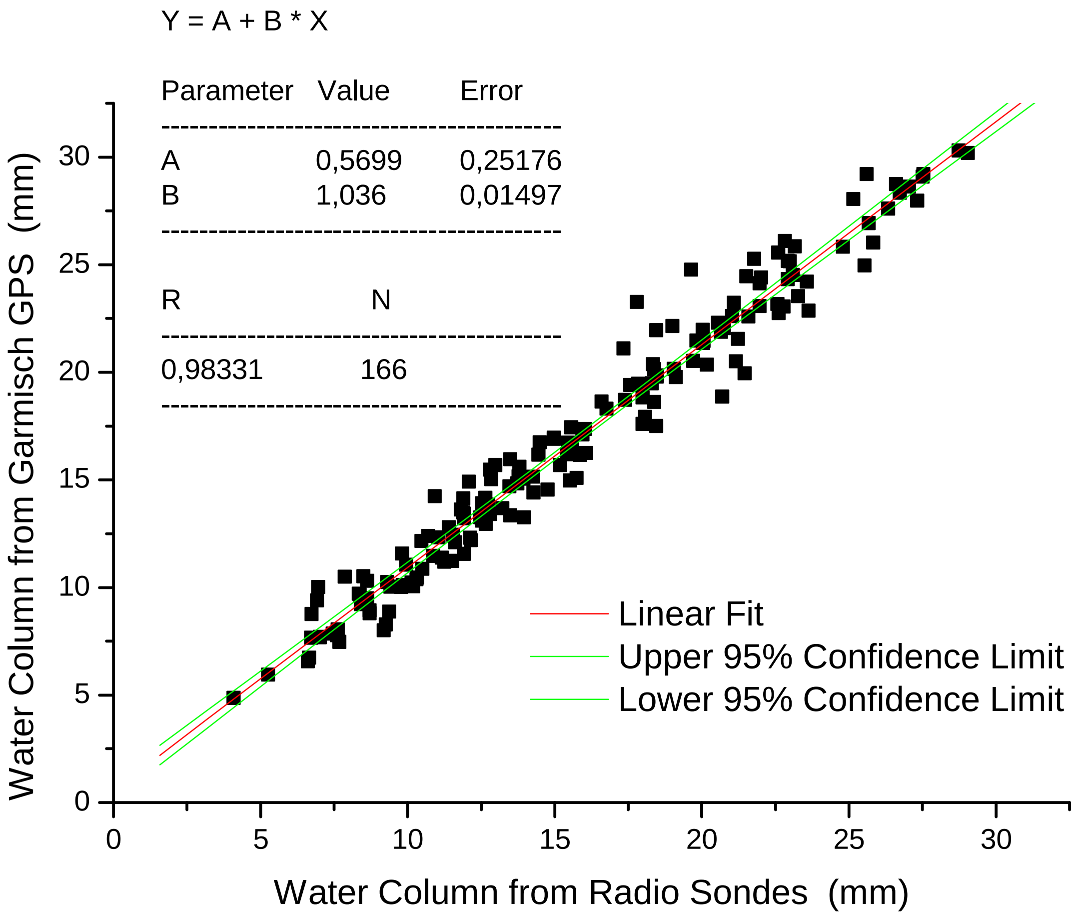

Figure 3: Correlation of coincident water vapor column measurements above Garmisch by GPS versus radio sondes. For details, see text.

where F is a dimensionless factor which depends on T_m. T_m is the average temperature of the atmosphere weighted by the partial pressure of water vapor (see Bevis et al., 1992). T_m is calculated by a regression to the surface temperature T_s.

Sensitivity studies as to T_s, T_m. We used the Potsdam standard FORTRAN routine for calculating PWV from ZPD, p_s and T_s, and performed sensitivity studies.

Using the Potsdam routine as is, we found a minor impact of measurement errors in T_s on the water column: For example, an error of T_s of 10 K propagates to an error in the water column of only 0.1 mm (calculated for a typical Zugspitze total column level of 4 mm). This means that the impact of typical measurement errors of T_s (in the order of ~K) on the retrieved water column can be neglected.

Besides measurements errors in T_s, in principle the approximations within the relation transferring T_s to T_m can impact systematically the retrieved water columns: Within the Potsdam standard retrieval routine, T_s is transferred to the mean atmospheric temperature T_m (needed in eq. 2) by the empirical relation

$$T_m \approx 70.2 + 0.72\ T_s \qquad \text{(eq. 3)}$$

This relation for T_m is the result from a linear regression between radio sondes and coincident surface temperature measurements that has been performed at various sites at a height range of 0 to 1.6 km in the United States (Bevis et al. 1992). However, since T_m is the average temperature of the atmosphere weighted by the water profile, this regression relation depends,

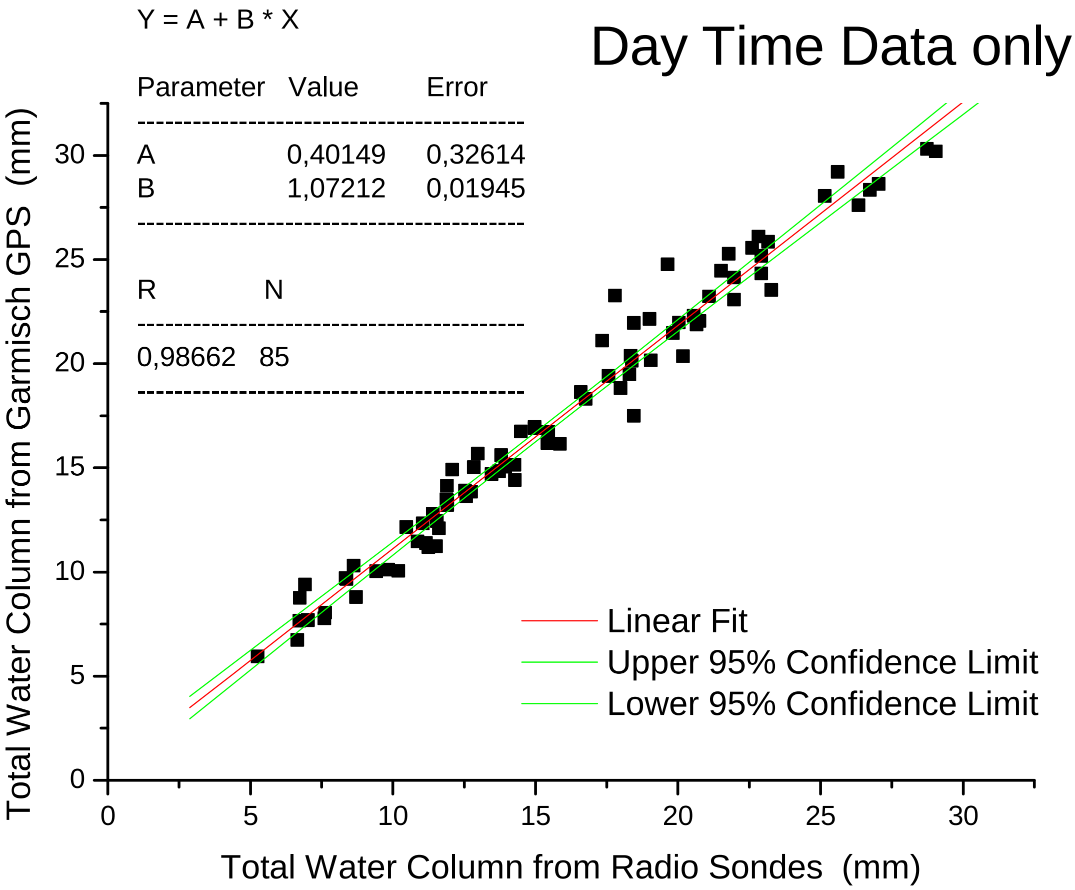

Figure 4: Same as Figure 3 but for day time measurements only.

in principle, on the season, and the specific geographic area and altitude of each GPS site. For example, from another radio sonde study at Albany, New York a slightly different relation was found: $T^{Albany}{}_m \approx 55.8 + 0.77\ T_s$. Quantitatively, however, there is no big difference, i.e., $T^{Albany}{}_m$ agrees to T_m from eq. 3 given above within 1-2 K for typical ground temperatures, which transfers to a negligible difference in the resulting water columns.

In conclusion, the impact of measurement errors of T_s is negligible, and errors due to the empirical derivation of T_m are impacting the retrieved GPS water columns by at maximum a few per cent for low altitudes sites (0 to 1.6 km, see above).

An interesting question is, whether the water columns calculated for the high altitude site Zugspitze (2964 m asl.) could be erroneous by the fact that we are using the standard relation for T_m (eq. 3), which has been constructed from low altitude site measurement data. Investigation of this question has been triggered by the fact that we are operating the first high altitude site GPS system (at Zugspitze), and we found a significant wet bias of the Zugspitze GPS columns compared to radio sondes (Phase I Report and Figure 6 below). We provide here a qualitative discussion of what we found out recently as a possible reason, in detail as follows.

Errors in T_m directly impact the retrieved water columns. In principle, for a real atmosphere, T_m is not only related to T_s as assumed in eq. 3. In reality, T_m is also a function of the altitude of the site above which it is considered. The tendency of this effect is, that for a distinct T_s the corresponding T_m will be lower in reality for a higher altitude site. This is not considered by eq .3, and is due to the fact that the water vapor partial pressure is less rapidly decreasing with altitude at higher altitudes (exponential behavior). Since T_m is calculated as a temperature mean weighted by the water vapor partial pressure profile, for higher altitude sites the higher levels of the atmosphere with lower temperature will get more weight, i.e., the

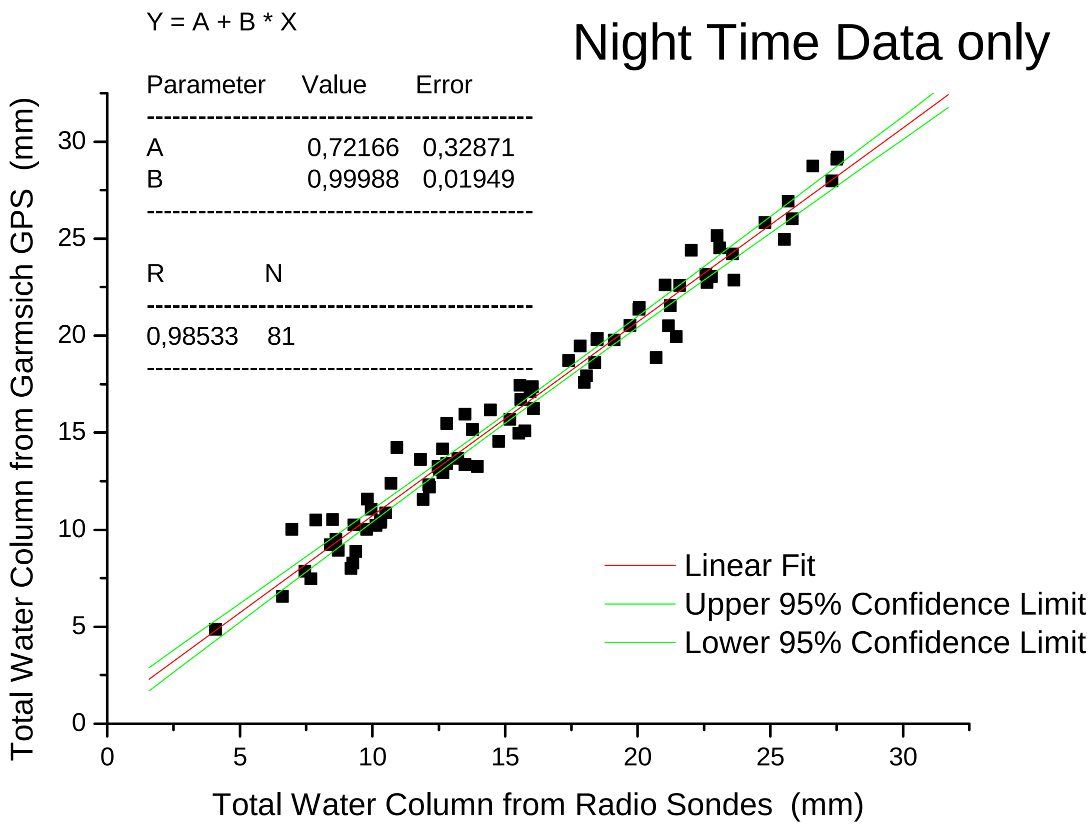

Figure 5: Same as Figure 3 but for night time measurements only.

weighted average T_m becomes smaller. This effect is not considered in eq. 3. In other words, T_m is overestimated by eq. 3 for high altitude sites, and this translates into an overestimation of the retrieved water columns finally. A quantitative investigation of this issue for the Zugspitze high altitude GPS including a direct calculation of T_m from our radio sonde measurements is currently under way (Sussmann and Gendt, to be published).

Sensitivity studies as to p_s. We used the Potsdam standard FORTRAN routine for calculating PWV from ZPD, p_s and T_s, and performed sensitivity studies as to the impact of errors in p_s on the retrieved water columns. We found a propagation relation of +0.35 mm upon the water column per +1 mbar error of p_s.

Accuracy and precision of in situ pressure series. For both Zugspitze and Garmisch we compared the pressure series of our own sensors to that of the Zugspitze and Garmisch stations of the German weather service, which are located only about 100 m (Zugspitze) and 2 km (Garmisch) apart in horizontal distance. We found continuous drifts of the bias between the different pressure series of more than 0.3 mbar on the time scale of the campaign (3 months). Furthermore, we found event-like short-term drifts of the difference between the sensors of more than 1 mbar on the time scale of 1-2 weeks.

The scatter of the pressure measurements (1-min averages) was found to be eventually for certain time periods at least twice as high for the Zugspitze (eventually above +/-0.4 mbar) as compared to the Garmisch case (scatter below +/-0.2 mbar). This is due to the higher wind speeds encountered at the Zugspitze which introduce dynamically induced wind changes of up to 1 mbar on the minute time scale.

The German Weather Service stations are using the following technique for their pressure measurements, which gives a good probability for achieving an accuracy of better

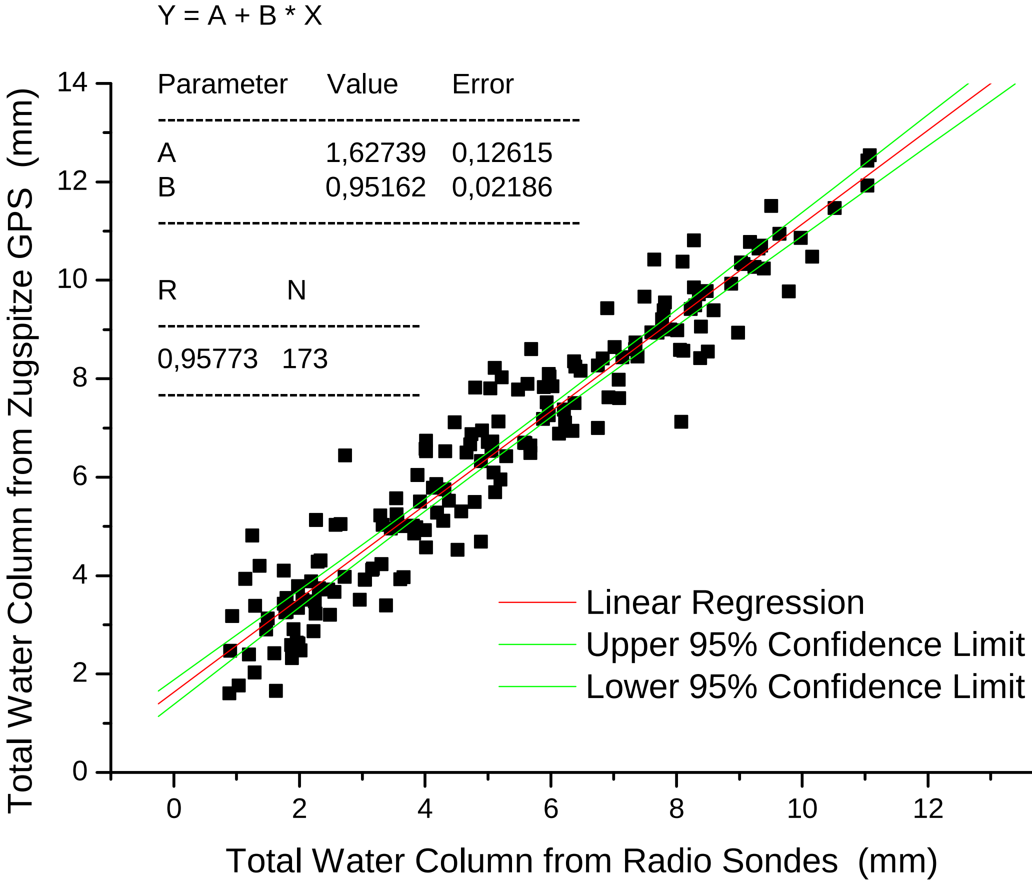

Figure 6: Same as Figure 3 but for the Zugspitze GPS. Note the significant wet bias, for details, see text.

than 0.5 mbar. Each newly installed sensor is calibrated against a mercury barometer once at the beginning of its operations. The sensor values are then compared to the mercury barometer three times a day at Zugspitze and once a week at Garmisch, respectively. In case that a difference of more than 0.5 mbar is encountered for the first time, the sensor is outsourced and replaced by a new one. It is by his reason, that we decided to use the pressure series of the German Weather Service (hourly means) for reprocessing of our GPS data (next section).

GPS reprocessing. During and after the validation campaign we found the following critical issues which allowed for slight improvements by performing a GPS data reprocessing:

1. Error in altitude correction calculations. The GPS antennas are placed at different altitudes than the pressure sensors. We found the required altitude correction of the measured pressures be coded in the standard GPS software by a linear factor of 0.126 mbar per meter in altitude difference. This is a linearization of the barometric equation which holds for sea level approximately. However, for the high altitude Zugspitze case, this introduced an error of 0.37 mbar per meter in the altitude-pressure correction. In the Zugspitze case the actual altitude difference between the pressure sensor and the GPS antenna is 5.2 m which transferred to an effective error of 0.2 mbar by using the above approximation for sea level. To eliminate this problem, the simplified barometric equation p(z)=p0*exp(-z/8000m) has been coded into the operational GPS software.
2. Errors in pressure sensor and antenna altitudes. The actual altitude difference used between the Garmisch pressure sensor and the Garmisch GPS antenna used for pressure correction had been off by 24.3 m at the beginning of the campaign due to wrong information about the altitude of the pressure sensor of the German Weather

Service. This transferred to an error in pressure correction of 2.8 mbar. This has been corrected.

3. Improved pressure data set. The GPS reprocessing was performed for both the Garmisch and the Zugspitze GPS series using the pressure information from the German weather service, due to the high quality assurance level of the German Weather Service pressure measurements, see above.

The fully reprocessed GPS data for Zugspitze and Garmisch for the time span of the 3-months campaign are attached to this report within the file "GPS_reproc.txt". Furthermore, we attach as an updated deliverable the pressure/temperature data sets of the German Weather Service containing hourly mean values for Zugspitze (pressure sensor located at 2962.6 m), file "met_synop_zugs.txt", and for Garmisch (pressure sensor at 720.2 m), file "met_synop_garm.txt".

GPS validation by radio sondes. During the campaign, dedicated to each overpass a pair of radio sondes was launched, the first sonde 1 hour before overpass and the second one 5 min before overpass. The two sonde profiles were interpolated to the time of overpass, and the resulting "Tobin profile" integrated to obtain the vertical water column (see Phase I Report, for details).

Figure 3 shows the intercomparison of the Garmisch GPS columns (GPS average over 1.5 hours starting with the launch time of the first sonde) with the coincident radio sonde columns. The statistical data of the correlation are given in the Figure, i.e., a rather high correlation coefficient, and a small wet bias of the GPS of 0.57 mm.

Figures 4 and 5, respectively, show that there is no significant difference for night-time versus day-time intercomparisons to radio sondes. This means that the radiation correction applied to the radio sonde measurements implemented within the VAISALA software is working perfectly well.

The radio sonde validation for the Zugspitze GPS is displayed in Figure 6. It shows a significant wet bias of the Zugspitze GPS of 1.6 mm for small columns. A possible reason for this has been identified to be the impact of the high altitude of the Zugspitze site upon the simplified calculation of T_m in the standard GPS processing, as detailed above (see "Sensitivity studies as to T_s, T_m"). A detailed quantitative treatment is under way (Sussmann and Gendt, to be published).

4. Zugspitze Solar FTIR Measurements

FTIR column measurements validation. The details of the solar FTIR measurements and newly established total column retrievals have already been presented in the Phase I Report.

Figure 7 shows a perfect correlation and a close to zero bias of the water columns retrieved by the solar FTIR technique compared to the integrated coincident pair of radio sondes.

It should be noted that retrieving water columns from solar FTIR is a new approach not documented in the literature so far, and the validation result shown in this report at the same time gives evidence, that the solar FTIR technique appears to be one of the most accurate and precise techniques at all for measuring columnar water vapor.

It appears, that the solar FTIR accuracy for water even exceeds that of the well established technique of micro-wave water vapor radiometry. This can be understood in general physical terms, since the sensitivity using remote sounding in the infrared spectral region should in principle be biased to lower atmospheric levels compared to the sensitivity expected from techniques in the micro-wave spectral domain, and the total column is dominated by the lowest few kilometers of the atmospheric profile.

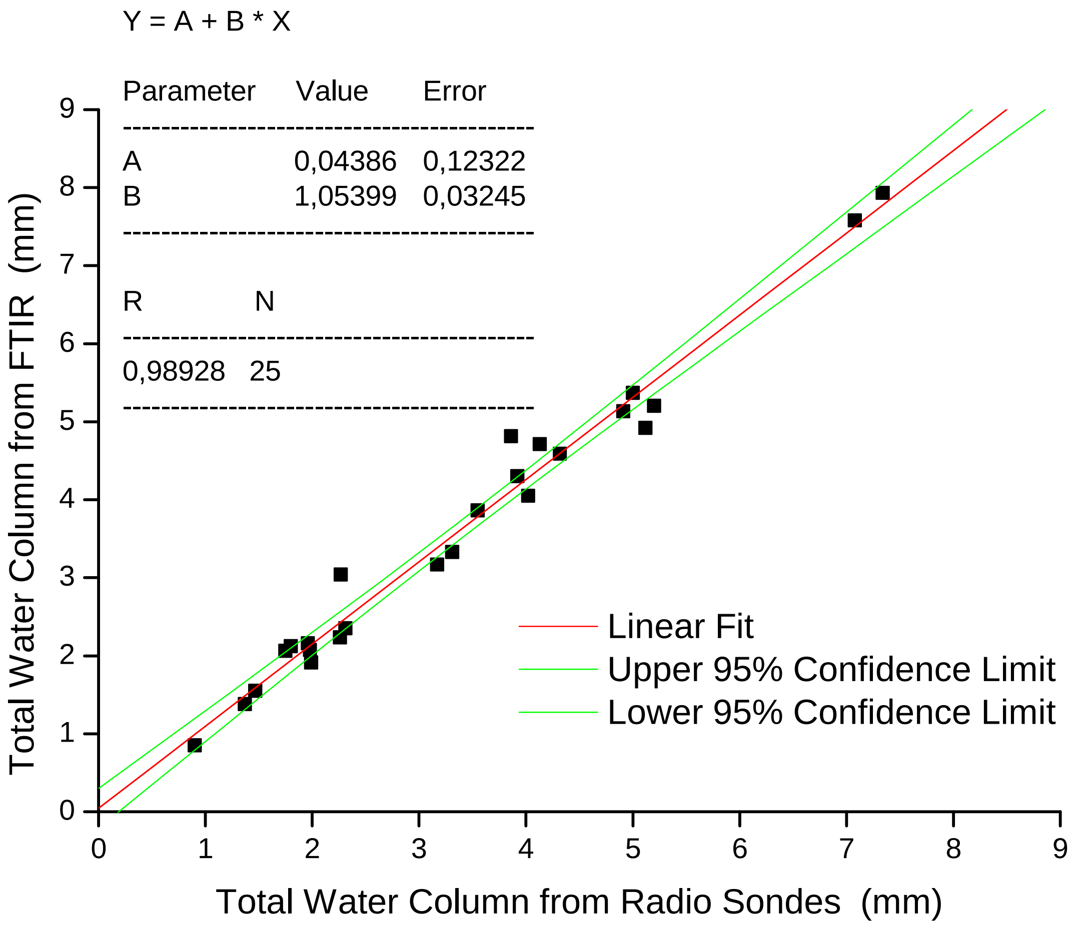

Figure 7: Correlation of coincident solar FTIR water vapor column measurements above Garmisch versus radio sondes. Note the perfect agreement.

FTIR profile retrieval studies. For retrieval of trace gas vertical column abundances and profiles from the ground-based spectra the code SFIT2 is operated by IMK-IFU which is at the same time the standard code used within the NDSC. While retrieval of a variety of atmospheric species is performed on a routine basis, in the case of water vapor the retrieval approach has still to be maturated to some extent, i.e., (i) the optimized spectral retrieval intervals for gaining quantitative tropospheric information need to be investigated, and (ii) some spectroscopic issues (line shape anomalies, line strengths, pressure broadening coefficients) have still to be accounted for, in order to achieve an accurate retrieval result – these have been two goals of this project.

As to i) we had found three micro-windows in the 800 – 900 cm^{-1} spectral domain that allow, in combination, a perfect column retrieval, as described in detail in the Phase I Report, and which is now validated by Figure 7 of this report. These micro-windows contain medium to strong intensity absorptions and are able constrain the total column for all humidity conditions encountered above the Zugspitze perfectly (Figure 7).

However, in order to retrieve not only the total column but retrieve additional information about the vertical distribution of water vapor for levels as high as possible within the atmospheric water profile, additionally weak spectral lines have to be considered for inclusion into the retrieval process. Only for weak spectral lines the center of the absorption feature containing information above the highest levels within the atmosphere (low pressure broadening) is not masked by the water absorption of the lowest levels of the atmosphere. In the Phase I Report we had provided a first sensitivity study of a weak line at 841.9 cm^{-1} of the pure rotation band of water.

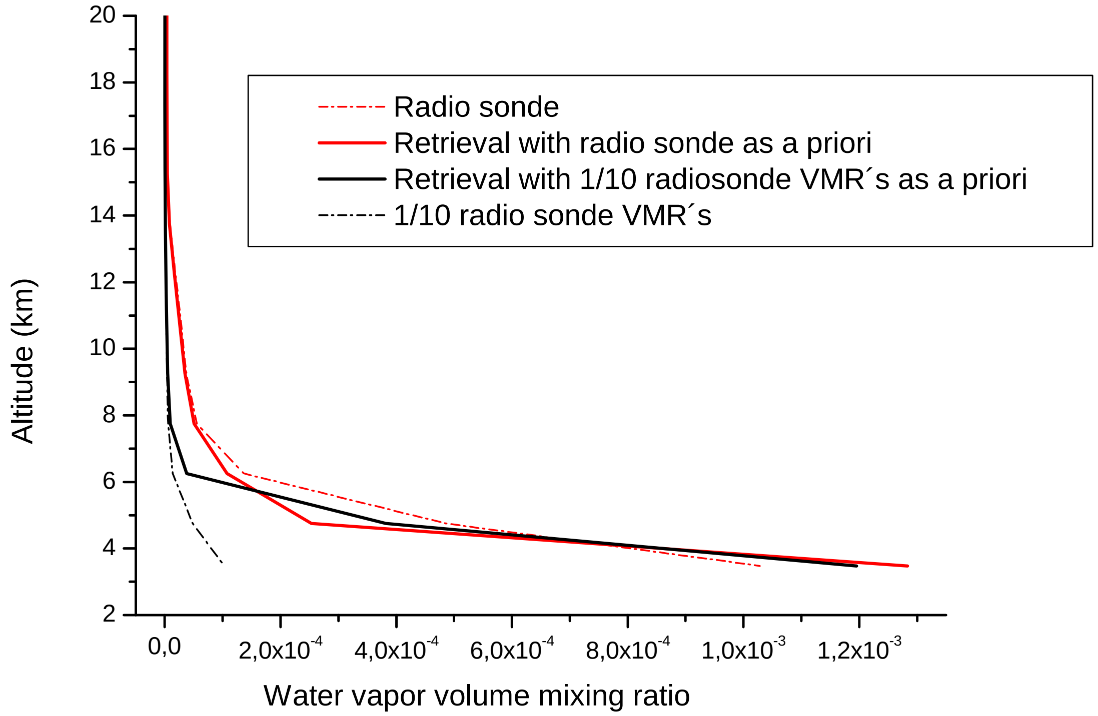

Figure 8: Radio sonde profile (red dash-dotted line) and FTIR profile retrieval (solid red line) starting from the radio sonde profile as a priori. The black solid line is an FTIR retrieval with the same algorithm settings starting from an a priori (black dash-dotted line) with all VMR values reduced by a factor of 10. The Figure shows that the retrieved area below the profile (i.e., the total column) does not depend significantly on the a priori profile.

We continue this study as follows. Figure 8 shows in red (dash-dotted line) the radio sonde profile from a Tobin-interpolated pair of radio sondes (see Report I, for details). This can be assumed to present a good approximation of the real water profile below 8 km altitude at this time. Integration of the radio sonde profile yields a total column of 3.64E+21 molec/cm^2. The full red line shows the FTIR profile retrieval using the single weak line mentioned above and starting from the radio sonde profile (dash-dotted line) as an a priori profile. The column resulting from this retrieval is 3.49E+21 molec/cm^2 which agrees within 4 % to the radio sonde result. Figure 8 shows in black (solid line) the FTIR retrieval starting from using a priori information which is definitely far off from the true state of the atmosphere, i.e., an a profile constructed from the sonde profile volume mixing ratios divided by a factor of 10 (see dash-dotted line in black). The Figure shows nicely, that in spite of starting from a completely unrealistic a priori, being off by a factor of 10 (!), the FTIR inversion is able to retrieve a realistic profile (resulting column 3.32E+21 molec/cm^2) at least in the sense that its integral (area below the profile) monitors the expected column (3.64E+21 molec/cm^2) quite satisfactorily within 10 %.

Figure 9 shows exactly the same as Figure 8, but in a logarithmic presentation of the water volume mixing ratio axis. Here the impact of the intentionally wrong a priori (black dash-dotted line) on the retrieval (solid balck line) can be judged in more detail. Up to about 6 km altitude, the “real” profile (red dash-dotted line) is estimated quite well. Above this altitude the “real” profile (i.e. it´s VMR values) is more and more underestimated due to the a priori being much to small. However, the figure shows, that there is still information about the real water content retrieved up to an altitude of about 14 kilometers. Above 14 kilometers just the a priori information is obtained back by the retrieval without any additional information.

The study discussed before used only one weak line for the inversion process, in order to investigate the altitude information that can be attained. Using a weak line, however, leads in principle to less stable total column results, since the signal to noise is in principle worse

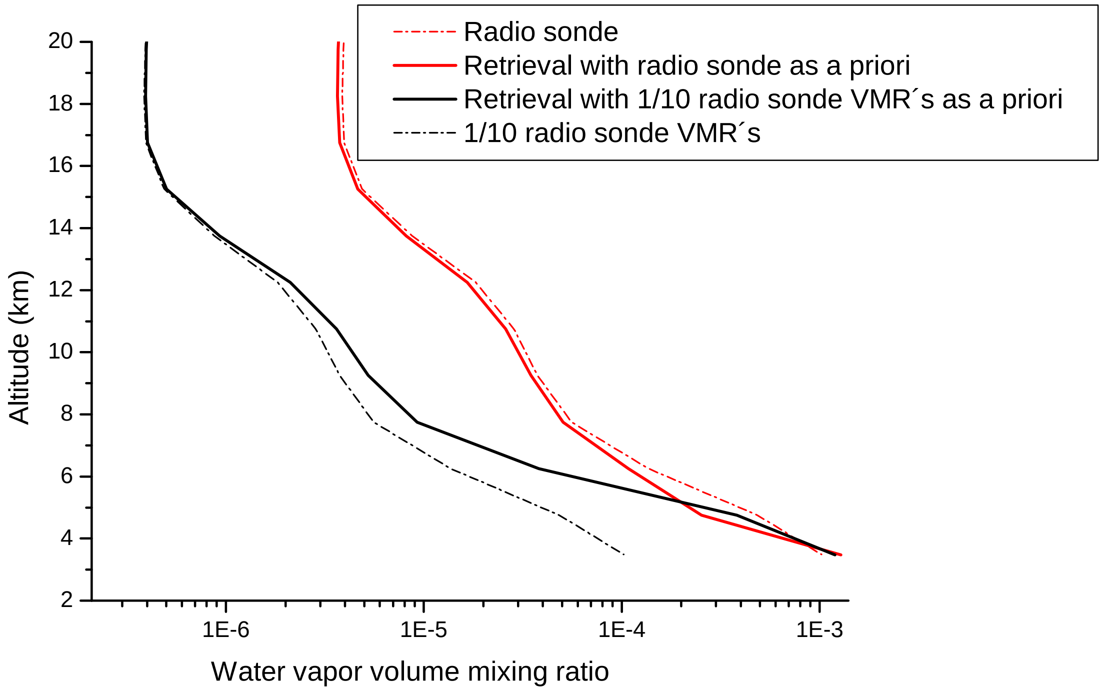

Figure 9: Same as Figure 8 but with a logarithmic presentation of the volume mixing ratio axis. The Figure shows that information is contained in the retrieval up to an altitude of about 14 kilometers.

than for stronger absorption lines. Therefore in our ongoing work we will combine in one fitting procedure together this weak line with a selection out of the neighbored strong lines used so far for total column retrieval. This has still to be implemented and a few technical problems to be overcome: Errors in line parameters, e.g., non-consistent intensities and line positions which lead to an unstable operation of a combined fitting run, have to be corrected for. This will be presented in an upcoming publication (Sussmann and Camy-Peyret, to be published).

6. Conclusions and Recommendations for future IASI Validation

In conclusion, we have documented successful operation of the newly established AIRS/IASI validation site “Zugspitze/Garmisch” continuously for 7-days-a-week during the 3-months AIRS validation campaign between 19 Aug – 17 Nov 2002, covering 180 day and night time overpasses, and performing full data delivery within 12 hours after each overpass. Therefore, for IASI validation, as a minimum requirement, operation of at least the same, established instrumentation is recommended. However, we recommend the following additional instrumentation for an improved characterization of the state of the atmosphere, see Figure 10, explained in detail as follows.

1. Zugspitze FTIR retrievals of vertical profiles of water will be operational in near future, and it is recommended to operate profile retrievals on a daily routine basis during IASI validation in an automated batch mode, similar to the automated column retrievals that were operated during this project. FTIR retrieval studies have shown that information up to an altitude of approximately 14 km can be retrieved by the solar FTIR technique.

2. Profiling of the additional (climate relevant) trace species measured by IASI in addition to water vapor has already been shown by using ground based solar FTIR in our group and this is highly recommended to be included for IASI validation.
3. A second high resolution solar FTIR in addition to the Zugspitze system is currently installed at the Garmisch ground site for coincident measurements with the Zugspitze

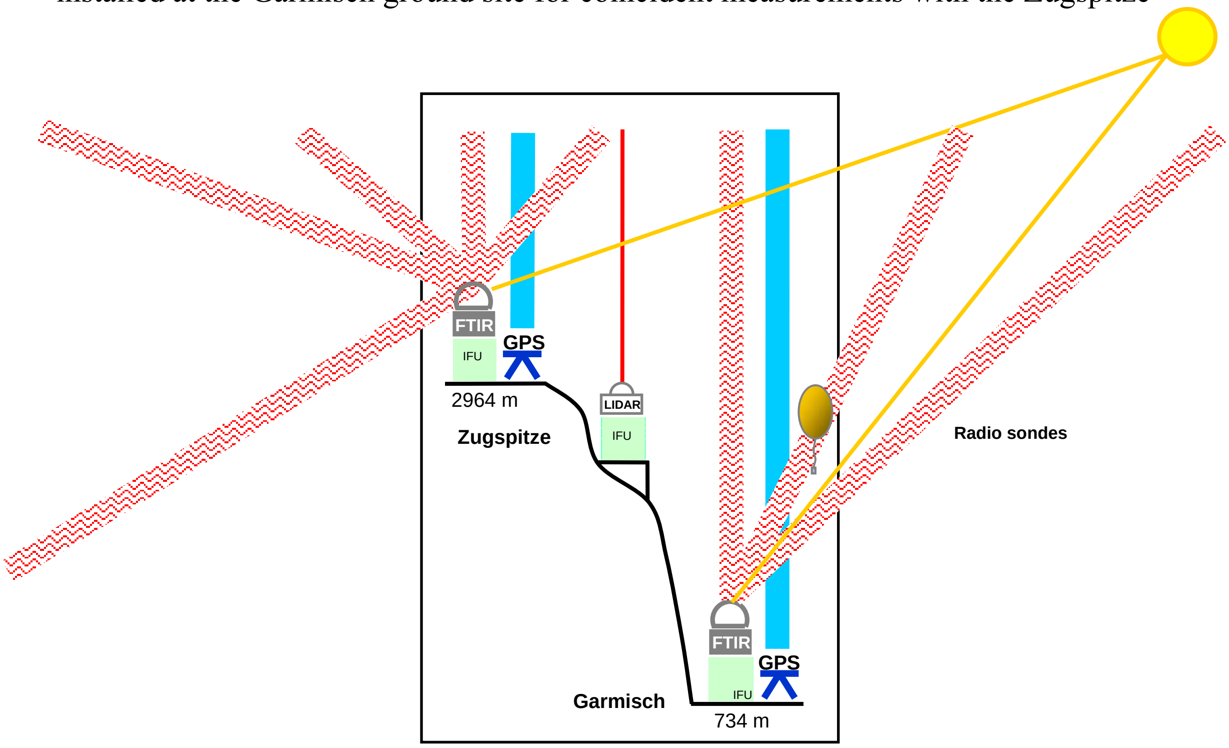

Figure 10: Recommended instrumentation at the IASI validation site at Zugspitze (47.4 °N, 11.0 °E, 2964 m asl.)/Garmisch (47.5 °N 11.1 °E, 734 m asl.) for $VMR_{h2o}(z)$, T(z), and profiles of climate gases.

solar FTIR. Its operation is recommended since it allows to retrieve the total water column and profiles above our ground site with much more accuracy and precision compared to what we could provide during AIRS validation, where we had only a GPS and sondes at Garmisch available. Also profiles of the further climate gases can be retrieved down to the ground. Coincident operation of the Zugspitze (high altitude) and Garmisch (low altitude) system and combined analysis will allow for advanced retrievals of altitude information.
4. The new Garmisch FTIR system is, in addition to the solar absorption mode, equipped with a radiation calibration system (i.e., it is an FTIR-radiometer) which allows for thermal emission measurements. This opens two advantages for IASI validation: i) It allows for night time measurements, and ii) it allows for angular scanning of larger atmospheric volumes, in order to better make the retrieved results comparable to the areas/volumes (pixels) probed by the satellite technique.
5. Similarly, we like recommend the operation also of a thermal emission FTIR radiometer at the Zugspitze summit. This would allow to utilize the advantages described under 4) also for the free tropospheric measurement site Zugspitze. In addition, this system at the mountain summit could be operated in a down looking viewing geometry, in order to characterize the surface emissivity of the vicinity of the Zugspitze.
6. The utilization of the water vapor differential absorption lidar currently installed at Zugspitze/Schneefernerhaus, which will be providing water profiles up to 12 km, is strongly recommended for IASI validation. Due to the high technical effort, its operation will be restricted to validation case studies on the details of the vertical water profiles shapes. Combined studies are suggested to complement the highly operational solar FTIR

technique, which yields a more limited altitude resolution but highly accurate partial and total columns of water.

7. As explained in Section 3 of this report, we intend to make use of the radio sonde profiles and coincident surface temperature measurements at the Zugspitze from the campaign data set for calculating the average temperatures above Zugspitze. This should allow for nearly bias-free GPS retrievals, even at the high altitude site Zugspitze. Operation of the improved GPS system for Zugspitze (plus the one in Garmisch) is recommended for IASI validation.
8. Finally, we note a detail on the use of in-situ pressure measurements as an input to GPS retrievals. We formulate as a general recommendation from what we learnt during the sensitivity studies within this project not to just read out 1-minute average values from a pressure time series coincident to half hourly mean GPS intervals, but use averaged values of the in situ pressures (e.g. half hourly means). This improves the precision of the GPS technique slightly, especially for a high altitude site where dynamically induced pressure variations of the order of 1 mbar on the 1-minute time scale can occur.

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The following publications of IMK-IFU are an output of this project or of direct relevance to it:

Sussmann, R., and C. Camy-Peyret, Establishing an AIRS/IASI validation site at Zugspitze/Garmisch: Ground-based sounding of water vapor by FTIR spectrometry, GPS, and radio sondes, in "Proceedings Eurotrac Symposium 2002", P.M. Midgley and M. Reuter (Eds.), Margraf 2002, ISBN 3-8236-1385-5, CD-ROM.

Sussmann, R. and C. Camy-Peyret, Ground-Truthing Center Zugspitze/Garmisch for AIRS/IASI Validation, invited talk at 16th Meeting of the IASI Science Sounding Working Group, Saint-Raphael, France, 23 - 25 October 2002.

Sussmann, R., and G. Gendt, Ground-based GPS water sounding at high and low altitude sites: a validation study at Zugspitze/Garmisch, to be published.

Sussmann, R., and C. Camy-Peyret, Water vapor total column and profile retrievals at the Zugspitze, to be published.

Trickl, T., and H. Vogelmann, The Zugspitze Lidar: On the Way to Ground-Based Water-Vapour Measurements throughout the Free Troposphere, in "Lidar Remote Sensing in Atmospheric and Earth Sciences", Reviewed and Revised Papers presented at the 21th International Laser Radar Conference, Québec, Canada, July 8 to 12, 2002, L.R. Bissonette, G. Roy, G. Vallée, Eds., Defence R&D Canada-Valcartier (Val-Bélair, QC G3J 1X5, Canada, 2002), pp. 81-84.