

RESULTS FROM THE LINDENBERG UPPER-AIR METHOD INTERCOMPARISON (LUAMI)

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ABSTRACT

In autumn 2008 an intercomparison campaign for in-situ and remote-sensing techniques for observing the basic meteorological variables in the upper air was conducted at the Lindenberg Meteorological Observatory in Germany.

The Lindenberg Upper-Air Method Intercomparison (LUAMI) was designed to improve our understanding of the performance and uncertainties of the different methods and to test the suitability of various options for their deployment in operational network including the GCOS Reference Upper-Air Network (GRUAN).

The LUAMI campaign delivered a number of useful results concerning the performance of different instruments for observing the atmosphere, in particular temperature and humidity. The ability of ground based instruments like microwave radiometers, GPS networks and Raman LIDAR for observing humidity profiles was demonstrated and proved useful tools for evaluation NWP products.

A highlight was the successful intercomparison between an airborne LIDAR with ground based instruments as well as with in-situ measurements which demonstrated a high degree of consistency between these independent techniques.

The radiosonde inter-comparison delivered a wealth of data for assessing the performance of different instruments. In the troposphere, the general agreement is within an average deviation of 0.2 K and 5%RH for temperature and humidity, respectively. However, a number of issues have been identified, such a radiation effect on the temperature data in the stratosphere of various instruments and a dry bias of some instruments in the humidity measurements. Some of the issues observed during the campaign have already been addressed and fixed by the radiosonde manufacturers.

The campaign also delivered data that are of scientific interest with respect to atmospheric processes. Frostpoint Hygrometer (CFH) and particle backscatter observations (COBALD) are being used to study ice cloud formation conditions. The topic is addressed using ground based

LIDAR and radiosonde data. Particularly interesting in this respect are also the measurements of the airborne LIDAR.

1. Overview

From October to December 2008 the Lindenberg Upper-air Method inter-Comparison (LUAMI) was carried out at the Meteorological Observatory Lindenberg - Richard-Aßmann-Observatory (RAO, 52.21° N, 14.12°) with the participation of a large number of companies and research institutes (see list of co-author affiliations). Beside Lindenberg also the observatories at Payerne (Meteosuisse), Cabauw (KNMI), Zugspitze (IMK-KIT) Chilbolton (RAL), Jülich (FZJ), Kiel (IFM-GEOMAR), Legnago (ARPAV), Potenza (CNR-IMAA), and Potsdam (DWD) contributed with either LIDAR or microwave profiler measurements.

The experiment was divided in three parts, an airborne-ground based intercomparison conducted during two flights of the DLR Falcon aircraft on 17th and 18th October, a remote sensing part including a large number of instruments located at Lindenberg and elsewhere, and an in-situ part, basically a radiosonde inter-comparison campaign conducted from Nov 4th to Nov 22nd Nov 2008 at Lindenberg.

1.1 Airborne - ground-based

The Falcon aircraft was equipped with a water vapour Differential Absorption LIDAR (DIAL) system which produces four different wavelength using a Nd:YAG pumped Optical Parametric Oscillator (OPO) in the 935 nm absorption band of water vapour. The water vapour profiles are determined from the differences in the absorption at the different wavelengths. The advantage of the DIAL method (over the Raman LIDAR) is that no calibration is necessary. The water vapour content is directly calculated from the differential LIDAR backscatter profiles using absorption coefficients which are known from laboratory measurements to an accuracy of 3%. Other systematic uncertainty sources are the wavelength calibration (1%), and the atmospheric density profile (1%). The statistical uncertainty depends on the vertical resolution, the H₂O profile and the background light and is of the order of 5%. These characteristics allow the use of the DIAL system as a reference for validating other techniques. The LUAMI airborne campaign therefore was planned to allow for inter-comparisons with other LIDARs and radiosonde profiles.

On both occasions the Falcon passed the sites Payerne (CH), Zugspitze (D), Cabauw (NL), and Lindenberg (D) all of which are equipped with water vapour LIDAR systems (DIAL at Zugspitze and Raman LIDARs at the other sites). On the 17th October all instruments were operating.

At RAO a balloon was launched on 17th October at about 19:00 LT which carried CFH, RS-92FN, RS-90 FN, DFM-06, and a Vaisala RS-92. The Falcon followed the flight track of this balloon for a while to allow for optimum conditions for a comparison. First results show very good agreement between the profiles measured with the airborne DIAL, the ground based LIDARs and the CFH.

1.2 Ground-based Remote sensing

One major focus of the campaign was the comparison between ground based remote observations and *in situ* techniques. Major components of this part, described in more detail below, were the water vapour Raman LIDAR RAMSES, the microwave profiler network and a small scale network of GPS receivers that were used for water vapour tomography. The RAO routinely operates a large number of instruments including Microwave radiometer (MWR), LIDARS and RADARS. All of these instruments were fully operational during LUAMI and provided data.

The Raman LIDAR RAMSES is a ground-based instrument located in Lindenberg that emits a laser beam with transmission wavelength of 355 nm vertically into the atmosphere. The output power is 9 W at a repetition rate of 30 Hz. The light backscattered from the atmosphere is detected

with a near- and a far-range telescope to both of which two identical receivers are coupled that detect elastically backscattered (at 355 nm), Raman-scattered light from N₂-molecules at 387 nm, and from H₂O- molecules at 408 nm. The system in its current configuration operates at night time, and is fully automated. In 2008 RAMSES performed measurements during 130 nights with acceptable data quality. The LIDAR is calibrated using radiosonde data at low altitude (1-3 km) which are launched in Lindenberg every 6 hours. The calibration is performed whenever co-incident LIDAR and radiosonde data are available.

A Multichannel Microwave Radiometers operates at 22-31GHz and 51-59 GHz and retrieves temperature and water vapour profiles as well as the vertical structure of liquid water. It provides high temporal resolution and operates during nearly all weather conditions (no rain) in unattended mode and therefore has a high degree of availability. During November 2008 the MWR from 9 stations (Chilbolton, Jülich, Kiel, Legnago, Lindenberg (NN), Lindenberg (REGobs), Payerne, Potenza, and Potsdam) were combined. The pooled data was analyzed in a consistent way and compared to the output of numerical weather forecast models in order to demonstrate the capabilities of passive microwave profiler systems for their use in operational meteorological networks.

The GFZ installed a small-scale network of 18 GPS receivers in the area around Lindenberg with a dimension of about 10km x 15km. Together with the operationally available data of the German GPS network (~300 stations) these observations were used by the GPS water vapour tomography to reconstruct spatially resolved humidity fields and water vapour profiles.

1.3 *In-situ* soundings

Radiosondes are small size, light-weight disposable sensors that are launched by a balloon and measure the basic meteorological variable (Pressure, Temperature, Humidity and Wind) and transmit the data by radio signals at 403 MHz to a ground receiving station. The goal of the LUAMI campaign was to assess the uncertainty of commercial radiosonde in particular with regards to systematic effect like radiation on temperature by inter-comparison and using reference instrumentation. Another issue was the assessment of the performance and accuracy of different reference instruments in particular with regards to water vapour in the upper troposphere and the stratosphere. The basic concept of this part of LUAMI followed the guidelines for radiosonde inter-comparisons from CIMO. All radiosonde manufacturers worldwide were invited to participate by an invitation letter that was distributed by the Association of Hydro-Meteorological Equipment Industry (HMEI). Those that responded (Vaisala, MeteoLabor, GRAW, InterMet) were supported with local logistics and by allowing the use of the entire infrastructure of the observatory.

Vaisala tested its newly developed DRYCAP® humidity sensor (formerly APS). The DRYCAP® is a capacitive sensor that is designed to measure humidity in the upper troposphere and the stratosphere.

GRAW Radiosondes participated with its DFM-06 Radiosonde which is a standard GPS sonde (without pressure sensor) that is used by some national Meteorological services and military for routine sounding.

The South-African branch of InterMet Systems participated with its Routine Radiosonde BAT-4G. Which is similar to the GRAW Radiosonde in that it uses a 'E'&E polymer sensor for humidity and that it derives pressure from GPS height

Meteolabor tested in cooperation with MeteoSuisse a new humidity sensor (HC2) on the SRS-C34 Radiosonde and provided SnowWhite chilled mirror instruments as reference.

More reference instruments were provided by the Richard-Assmann-Observatory which supplied six Cryogenic frostpoint hygrometers (CFH) and the Central Aerological Observatory in Moscow which started four optical (Lyman- α) Hygrometers FLASH-B.

During the intensive period (4th Nov - 22nd Nov 2008) two launches were carried out each day, one around noon and one around midnight. Radiosondes from different manufactures as well as reference instruments were attached to a rig and launched with one balloon. 4.5 kilogram payload could be launched that way simultaneously. For larger loads two rigs were prepared and launched with a short time delay of a few minutes. During the intensive period a total of 24 single rig launches and 3 double rig launches were carried out. The meta data for each launch like weather conditions, equipment (balloon type, payload, etc) were collected.

The radiosonde data were collected as soon as possible after the launch by the GRUAN lead centre and made available to all participants using a ftp server. However, access was given only to the teams that have submitted their own data. A common data format (*.ldf) was developed by the lead centre and all radiosonde data has been transformed to that format in order to facilitate data access for the participants.

An evaluation tool has been developed in the IDL language that is also available to all participants on the FTP server. Synchronization is achieved on the time scale by interpolating the data on a common time axis and automatically determining delays. Optionally, synchronization can also be obtained along the altitude (for example for simultaneous flights on different balloons). The software package creates synoptic plots and statistical analysis of parallel ascents.

2. Conclusions

The LUAMI campaign was an extended experiment involving many international meteorological organizations for conducting inter-comparison of different type of observational methods for the troposphere: balloon-borne in-situ instruments as well as ground based and airborne remote sensing techniques.

The potentials of a number of instruments and methods, including GPS tomography, microwave profiler networks, Raman-, and Doppler-LIDAR were demonstrated.

The differences between the airborne LIDAR and the in-situ frost-point hygrometer (CFH) water vapour mixing ratio were within the uncertainties of the single instruments of about 5%. Thus the possibility of conducting complex inter-comparisons of very different types of measurements to a high degree of accuracy was demonstrated.

The reference instruments FLASH-B and CFH showed very good agreement in the stratosphere, well within their individual uncertainties of about 10% of the water vapour mixing ratios. This consistency demonstrated the capability of two hygrometers, based on very different techniques, to accurately measure stratospheric H₂O, which is known to be technically challenging.

The Vaisala DRYCAP sensor also showed some ability to measure water in the stratosphere. The commercial radiosondes that participated (Vaisala RS-92, GRAW DFM-06, Internet Africa BAT-G4, and MeteoLabor SRS-C34) performed well for measuring temperature and tropospheric humidity, they generally agreed within their stated accuracies. The focus of the radiosonde inter-comparison was on the evaluation of correction schemes for temperature and water vapour as well as on the estimation of the total measurement uncertainties. Major sources of uncertainty in temperature profiles obtained e.g. from Vaisala RS92 sondes is the calibration accuracy of the temperature sensor of about 0.1 K and, above 25 km during day-time, the radiation bias, which causes an uncertainty of up to 0.5 K.

In the case of humidity measurements the major sources of uncertainty for polymer-sensors are the radiation dry bias during day time and the time-lag problem. Also, calibration accuracy over the entire temperature range was found to be an important issue. If proper correction schemes are applied to the RS92 humidity data is essentially bias-free with respect to the reference (CFH), the overall uncertainty of the RS92 in the troposphere was found to be on the order of 5%RH.