STANDARDIZATION OF THE DEFINITIONS OF VERTICAL RESOLUTION AND UNCERTAINTY IN THE NDACC-ARCHIVED OZONE AND TEMPERATURE LIDAR MEASUREMENTS

T. Leblanc[1], S. Godin-Beekmann[2], G. Payen[2], F. Gabarrot[3], A. van Gijsel[4], J. Bandoro[5], R. Sica[5], and T. Trickl[6]

[1]*Jet Propulsion Laboratory, California Institute of Technology, Wrightwood, CA, 92397 (USA), leblanc@tmf.jpl.nasa.gov*
[2]*LATMOS, Université Pierre et Marie Curie, Paris (France), sophie.godin-beekmann@latmos.ipsl.fr*
[3]*LACy, Université de La Reunion, St Denis (France), franck.gabarrot@univ-reunion.fr*
[4]*KNMI, De Bilt (Netherlands), anne.van.gijsel@knmi.nl*
[5]*University of Western Ontario, London (Canada), sica@uwo.ca*
[6]*Karlsruher Institut für Technologie, IMK-IFU, Garmisch-Partenkirchen (Germany), thomas.trickl@kit.edu*

ABSTRACT

The international Network for the Detection of Atmospheric Composition Change (NDACC) is a global network of high-quality, remote-sensing research stations for observing and understanding the physical and chemical state of the Earth atmosphere. As part of NDACC, over 20 ground-based lidar instruments are dedicated to the long-term monitoring of atmospheric composition and to the validation of space-borne measurements of the atmosphere from environmental satellites such as Aura and ENVISAT. One caveat of large networks such as NDACC is the difficulty to archive measurement and analysis information consistently from one research group (or instrument) to another [1][2][3]. Yet the need for consistent definitions has strengthened as datasets of various origin (e.g., satellite and ground-based) are increasingly used for intercomparisons, validation, and ingested together in global assimilation systems.

In the framework of the 2010 Call for Proposals by the International Space Science Institute (ISSI) located in Bern, Switzerland, a Team of lidar experts was created to address existing issues in three critical aspects of the NDACC lidar ozone and temperature data retrievals: signal filtering and the vertical filtering of the retrieved profiles, the quantification and propagation of the uncertainties, and the consistent definition and reporting of filtering and uncertainties in the NDACC-archived products. Additional experts from the satellite and global data standards communities complement the team to help address issues specific to the latter aspect.

1. PROJECT OUTLINE

The project lifetime is about 2 years. A first meeting took place in December 2010 and consisted of a review and critical assessment of the methodologies used in the NDACC ozone and temperature lidar analysis algorithms. The discussions focused on the following tasks/topics: to review and make an assessment of the methods used to calculate vertical resolution in the NDACC lidar algorithms, then to review and make an assessment of the methods used to define and propagate uncertainties in these algorithms, then to define common grounds towards standardized definitions of vertical resolution and uncertainty and finally to elaborate an efficient approach and develop tools to implement the use of these definitions within the ISSI Team's lidar algorithms, then within all NDACC lidars' algorithms.

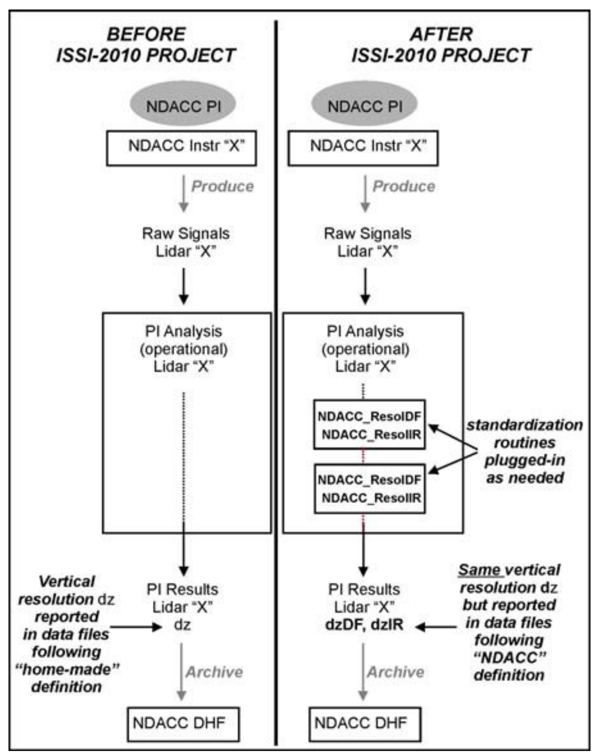

Figure 1. Schematic of the implementation within NDACC of the standardization tools for vertical resolution.

Standardization tools were developed for vertical resolution between the Team's first and second meetings, then validated during the second meeting in June 2011. Raw lidar signals with a varying degree of noise and interference were simulated, then analyzed by each lidar representative. The results from the analysis were compared to the original profiles used to simulate the signals. First, the consistency of all the forward/reverse algorithms was checked. Then the standardization tools were "plugged-in" each data processing software, and the output vertical resolution and the theoretical NDACC definitions were compared for each software. A schematic of the implementation concept is given in **figure 1**.

During the final year of the Project, tools similar to those developed for vertical resolution will be developed for the definition and reporting of uncertainty. A third (last) ISSI Team meeting is scheduled for September 2012, during which a Technical Report will be elaborated. This report will be used as a Reference Guide by NDACC lidar data providers, and by data users within both the NDACC and satellite communities.

2. PROJECT RESULTS TO DATE

2.1 NDACC-lidar Standardized Definitions of Vertical Resolution

The formulation of standardized definitions for vertical resolution adopted by the ISSI team is based on the universality of these definitions, and on the practicality of their implementation within the NDACC lidar community. Two definitions widely used among the atmospheric science community were selected: one definition is based on the cut-off frequency of digital filters (later referred to as "DF-based"), and another definition is based on the full-width at half-maximum (FWHM) of a finite impulse response (later referred to as "IR-based"). **Figures 2 and 3** summarize for each definition respectively, the procedure that leads from the action of vertically filtering the lidar signals or products to the action of reporting the corresponding vertical resolution in the NDACC lidar data files.

In the case of DF-based definition (**figure 2**), a Laplace Transform (FFT) is applied to the filter coefficients to obtain the filter's transfer function (for differentiation filters, the transfer function is additionally divided by the frequency). The filter's cut-off frequency, which corresponds to a transfer function amplitude of 0.5, is identified, and vertical resolution is then given by the product of the sampling resolution by the inverse of this cut-off frequency (in the normalized frequency domain using a Nyquist frequency of 0.5) [4].

In the case of IR-based definition (**figure 3**), a Delta Function (Dirac) is convolved with the filter coefficients to obtain the impulse response function (for differential filters, the Delta function is replaced by the Heaviside step function). Vertical resolution is then given by the product of the sampling resolution by the full-width at half-maximum of the response (in number of sampling bins).

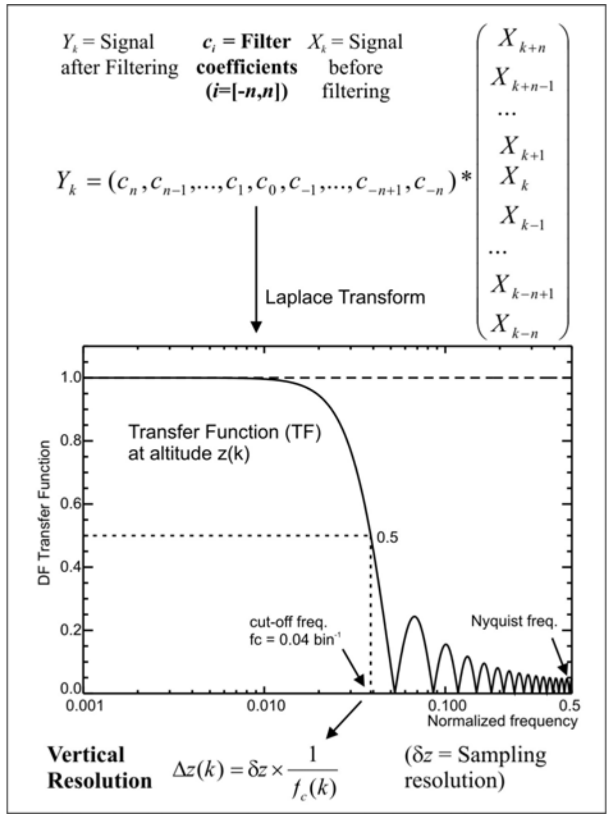

Figure 2. Procedure that leads from the action of vertically filtering the lidar signals or products to the action of reporting the corresponding standardized vertical resolution (DF-based definition) in the NDACC lidar data files.

2.2 Standardization Tools for Vertical Resolution

Easy-to-use plug-in routines have been developed to ensure a smooth implementation. The routines, called *NDACC_ResolDF* and *NDACC_ResolIR* for the DF-based and IR-based definitions respectively, were written in three programming languages: IDL, MATLAB, and FORTRAN. A PYTHON version is under consideration. The routines are flexible enough to be inserted anywhere in the flow of individual NDACC PIs' data processing softwares, and can be plugged-in multiple times if necessary. The set of coefficients of a smoothing or differentiation filter at a given altitude is input to the subroutine. The vertical resolution at this altitude, following one of the standardized definitions, is output from the subroutine and can be reported as is in the NDACC-archived data files. In the case of multiple instances and DF-based definition, the transfer function output from the routine after its first call is input during its second call, where it is multiplied by the transfer function associated with the second filter.

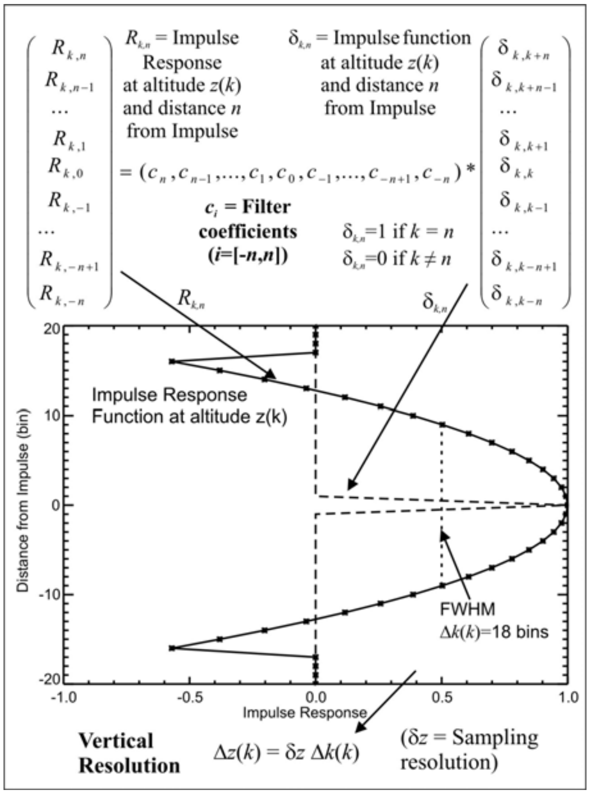

Figure 3. Same as figure 2, but for the IR-based definition.

Vertical resolution is thus recalculated taking into account two calls to the routine, not just one. This procedure is repeated each time the signal or product is being affected by smoothing or differentiation. In the case of the IR-based definition, the impulse response is propagated by successively outputting and inputting it to the routine, call after call.

The standardization tools were validated using simulated lidar signals [5]. Five lidar groups contributed to the validation efforts, which correspond to 11 different NDACC lidar products. Three examples are presented in figures 4-6. The grey solid curve in figure 4 shows the transfer function calculated from the ratio of the FFT of the filtered to unfiltered temperature profiles retrieved by the data processing software of the stratospheric ozone lidar at Mauna Loa, Hawaii. The black dashed curve shows the theoretical transfer function directly calculated from the filter coefficients and output by the routine *NDACC_ResolDF*. The two curves match very well which indicates that the vertical resolution reported by this data processing software using the DF-based definition is compliant with the NDACC standardized definition. Another example using the DF-based definition is shown in Figure 5 for the tropospheric ozone lidar at Reunion Island. Finally, an example for the standardization tool following the IR-based definition (*NDACC_ResolIR*) is given in Figure 6 (stratospheric ozone lidar in Lauder, NZ).

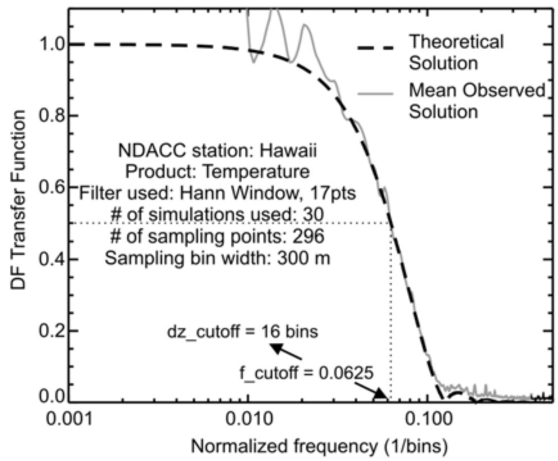

Figure 4. Theoretical and actual transfer functions compared for the JPL-Mauna Loa lidar temperature data processing software during the validation phase of the vertical resolution standardization tool *NDACC_ResolDF*.

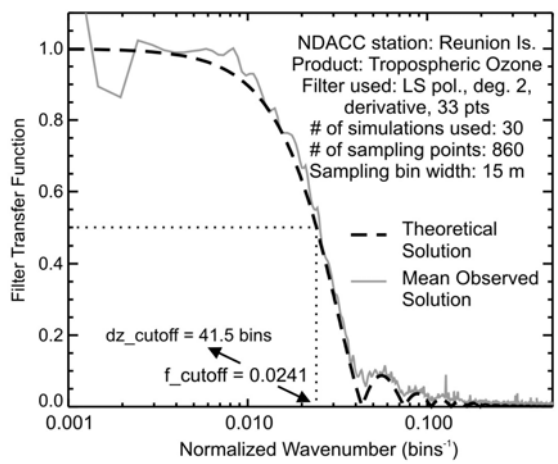

Figure 5. Same as figure 4, but using the data processing software of the tropospheric ozone lidar in Reunion Island.

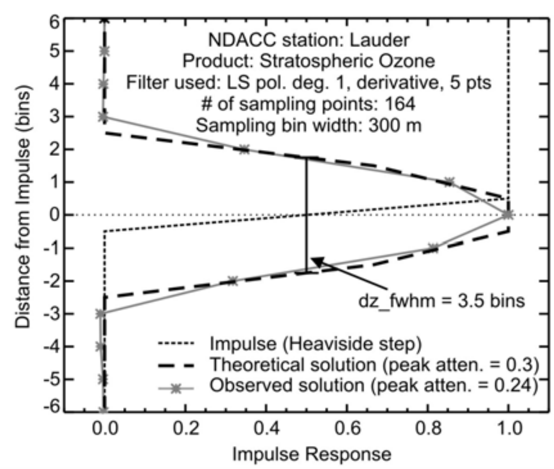

Figure 6. Same as figure 5, but for the IR-based definition, and for the stratospheric ozone lidar in Lauder, NZ.

2.3 New NDACC Data File Information Content

The NDACC lidar data format is slowly merging from ASCII (Ames) to HDF format. The new HDF format is fully compliant with several atmospheric science and satellite community data format standards, including GEOMS and AVDC. The data files in this format can contain vertical resolution using both the original (non-standardized) and NDACC-standardized definitions. Additionally, both the DF-based and IR-based definitions can be reported in the HDF files.

2.4 Definition of Uncertainties and Propagation Rules: Preliminary Formulations

Though no consensus was reached within the ISSI Team on individual uncertainty sources (work is still ongoing), a number of standardization procedures were agreed upon in the early days of the Project. The first decision made was to adopt the most recent terminology defined in the Metrology Guide for the expression of Uncertainty (GUM) [6]. Recommendations include (but are not limited to) the "randomization" of biases whenever possible in order to provide uncertainty components that can be propagated and combined, and the inclusion of co-variances when combining uncertainty components from multiple sources wherever these components appear to be correlated.

As of today, the standardization of uncertainty estimates, their propagation and their combination into a total uncertainty, are being investigated for the following sources: photon counting noise, saturation (pile-up) effect, background noise extraction, molecular extinction, absorption by constituents, cross-sections, and temperature tie-on. Other sources such as telescope-beam misalignment and particulate extinction require more careful consideration and will be treated last, possibly outside the scope of this ISSI Team Project.

3. EXPECTED OUTCOME

The results from our ISSI Team are expected to impact significantly the way the NDACC lidar data are used in the future. Further work however is needed to transfer knowledge and experience acquired by the ISSI Team to the NDACC data providers and users. A final report on the standardization of vertical resolution is currently under preparation. A similar report on the standardization of the treatment of uncertainty will be written once a sound approach for a full and consistent uncertainty budget has been adopted. These Technical Reports will serve as Reference Guidelines for future NDACC data originators and users. They will not only contain detailed information on the work done by the ISSI Team, but also detailed information on the recommendations made for the production and use of future NDACC lidar measurements. Through well detailed templates, these reports are expected to be included in the set of supporting tools made available by the national and international space agencies such as NASA, and ESA.

Additionally, a "pilot" version of a lidar data processing software using the appropriate definitions and recommended methodologies will be produced and offered to all members of the NDACC lidar community. The results and outcome of the ISSI Team will not only be used by the NDACC community, but will also be proposed as a working standard for the GCOS Reference Upper Air Network (GRUAN) [7], and other communities.

ACKNOWLEDGMENTS

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