

GRUAN Lidar Product Development (incl. NDACC/ISSI uncertainty estimates)

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3 ongoing components and 1 "ready-to-start" component

GRUAN Lidar Guidelines (2012), now known as "GRUAN Lidar Guide" v1.1.0.1

50% of this presentation, including a review of the current revised version, and of the comments received from TT-AM members

NDACC/ISSI Team on lidar algorithms for vertical resolution and uncertainty

30% of this presentation, including (not yet published) material on approach and formulations agreed and developed by the ISSI Team

LidarRunClient

10% of this presentation

GRUAN Lidar Analysis Software Suite (GLASS)

10% of this presentation

Purpose

To establish the philosophy and overall framework under which GRUAN lidars shall operate, and under which GRUAN lidar data shall be produced

To define requirements on uncertainty, consistency, and long-term stability for the operation of all GRUAN-certified lidar instruments

To provide lidar-specific complement to mandatory requirements and guidelines on how to achieve operating protocols mandated in the GRUAN Guide

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Lidar Principle

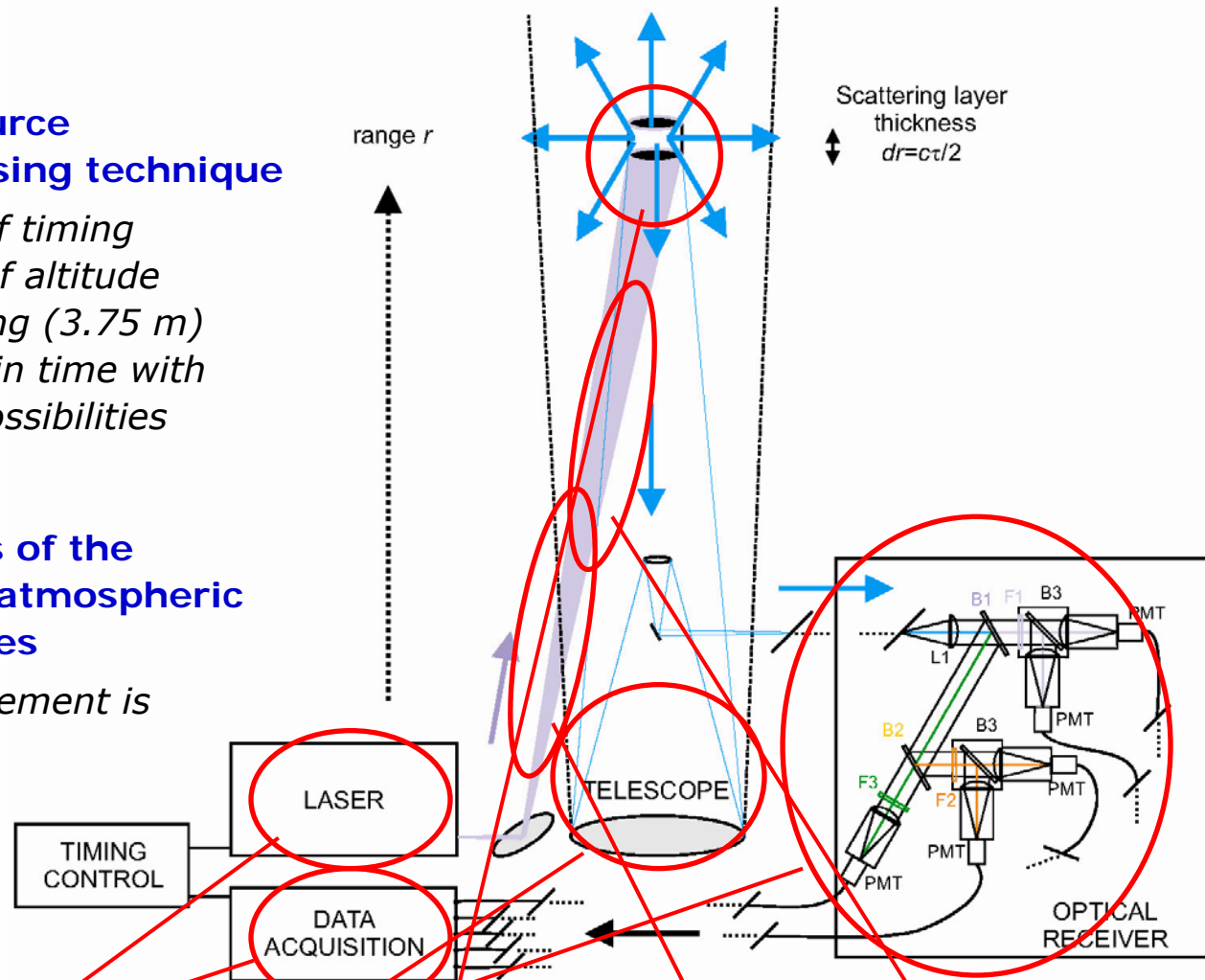
Use laser as light source

→ active remote sensing technique

- Precise knowledge of timing
= Precise knowledge of altitude
- High vertical sampling (3.75 m)
- Profile repeatability in time with flexible averaging possibilities

Use known properties of the scattering of light by atmospheric molecules and particles

- Fundamental measurement is *number density*



Lidar Equation

$$S_R(r, \lambda_R) = P_E(\lambda_E) K_R(\lambda_R) \frac{Q_R(r) A_R \delta r}{r^2} \beta(r, \lambda_E, \lambda_R) \exp \left[- \int_0^r (\alpha_{UP}(r', \lambda_E) + \alpha_{DOWN}(r', \lambda_R)) dr' \right]$$

GRUAN-relevant Lidar ECVs

Lidar fundamental measurement is number density of the scattering elements sounded by the laser beam

<i>Air number density</i>	→ <i>temperature (stratosphere + mesosphere)</i>
<i>Nitrogen and water vapor number density</i>	→ <i>water vapor mixing ratio (troposphere)</i>
<i>Laser light absorption along path</i>	→ <i>ozone number density (troposphere + stratosphere)</i>
<i>Nitrogen Raman cross-section</i>	→ <i>temperature (troposphere + stratosphere)</i>
<i>All molecules and particles</i>	→ <i>aerosols and clouds (troposphere + stratosphere)</i>
<i>Light polarization</i>	→ <i>cloud composition (troposphere)</i>

The development of the temperature, water vapor, and ozone products, (profiles and their uncertainty) is addressed in this presentation

(GRUAN) Lidar-retrieved ECVs

Water vapor (0 - 20 km)

$$S(r) = \kappa \frac{O(r)}{r^2} \sigma(r) N(r) \exp \left[- \int_0^r (\alpha_{UP}(r') + \alpha_{DOWN}(r')) dr' \right]$$

Vibrational Raman lidar: *Use fundamental measurement of **water vapor** and **nitrogen number density**, and calculate the ratio of the two to obtain mixing ratio:*

$$q(r) = \frac{N_{H_2O}(r)}{N_{N_2}(r)} = \kappa_{eff} \kappa_O(r) \kappa_\sigma(r) \kappa_\alpha(r) \frac{S_{H_2O}(r)}{S_{N_2}(r)}$$

q is mixing ratio

S_{H_2O} and S_{N_2} are the lidar signals (after some correction) received in the "water vapor" and "nitrogen" channels respectively (i.e., proportional to H₂O and N₂ number density)

*$\kappa(r)$ are multiple terms contributing to the **calibration***

(GRUAN) Lidar-retrieved ECVs

Temperature (15 - 70 km)

$$S(r) = \kappa \frac{O(r)}{r^2} \sigma_B N(r) \exp \left[- \int_0^r (\alpha_{UP}(r') + \alpha_{DOWN}(r')) dr' \right]$$

Rayleigh and vibrational-Raman backscatter lidar

Use fundamental measurement of **air number density** integrated from top of profile using hydrostatic balance and ideal gas law:

$$T(r) = \frac{p(r)}{kN(r)} = \frac{S(r_{TOP})}{S(r)} T(r_{TOP}) + \frac{M \delta r}{RS(r)} \sum_{z=r}^{r_{TOP}-1} \bar{S}(r') \bar{g}(r')$$

T is temperature

S is the lidar signal after correction

(i.e., proportional to air number density)

g is gravity, M is molecular air weight, k and R the Boltzmann and ideal gas constants

Temperature (0 - 30 km)

$$S(r) = \kappa \frac{O(r)}{r^2} \sigma_{RR}(T(r)) N(r) \exp \left[- \int_0^r (\alpha_{UP}(r') + \alpha_{DOWN}(r')) dr' \right]$$

Rotational-Raman lidar: Use the temperature dependence of the line-by-line rotational **Raman cross-section of nitrogen**, and calculate the ratio of the signals received at two different lines

$$R(T(r)) = \frac{S_{RR1}(T(r))}{S_{RR2}(T(r))} = \kappa_{eff} K_O \frac{\sigma_{RR1}(T(r))}{\sigma_{RR2}(T(r))} \approx \exp \left(\frac{c_0}{T(r)^2} + \frac{c_1}{T(r)} + c_2 \right)$$

T is temperature

S_{RR1} and S_{RR2} are the lidar signals (after some correction) received in the rotational channels RR1 and RR2 respectively

To find temperature $T(r)$, the experimental ratio at each altitude bin r is fitted to a **calibrated** modeled ratio

Ozone (0 - 50 km)

$$S(r) = \kappa \frac{O(r)}{r^2} \sigma_B N(r) \exp \left[- \int_0^r (\sigma_{O3UP}(r') + \sigma_{O3DOWN}(r')) N_{O3}(r') dr' \right]$$

Rayleigh (vibrational-Raman) Differential Absorption Lidar (DIAL)

Use the wavelength-dependent absorption of the laser beam along its path:

$$N_{O3}(r) = \frac{-\ln \left(\frac{S_{ON}(r + \delta r)}{S_{OFF}(r + \delta r)} - \frac{S_{ON}(r - \delta r)}{S_{OFF}(r - \delta r)} \right)}{2\delta r (\sigma_{O3}(r, \lambda_{E,ON}) + \sigma_{O3}(r, \lambda_{R,ON}) - \sigma_{O3}(r, \lambda_{E,OFF}) - \sigma_{O3}(r, \lambda_{R,OFF}))}$$

N_{O3} is ozone number density

S_{ON} and S_{OFF} are the lidar signals (after correction) received at the more absorbed (ON) and less absorbed (OFF)

σ is the wavelength-dependent and altitude-dependent absorption cross-sections

To retrieve ozone, the ratio of the derivative of the log of the lidar signals at the ON and OFF wavelength is calculated

The aerosol case ☹️

Lidars can easily detect aerosol and cloud layers (i.e., particles)

However, a major problem is the lack of precise information on the type, size and quantity of particles being sounded

As a result, there remains a large amount of uncertainty when correcting lidar signals for aerosols, or when retrieving aerosol properties by lidar.

Assumptions are needed (such as extinction-to-backscatter ratio, liquid water vs. ice, marine vs. continental aerosol, shape, size, etc.) to determine the particulate composition of the layers being sounded.

If we want a consistent GRUAN lidar aerosol product, we must consider these assumptions very carefully

It is therefore suggested that aerosol microphysical properties be introduced into GRUAN lidar product to be introduced, only after water vapor, ozone and temperature are routinely on-line

*Close interaction with **EARLINET** will be a key step towards the development of any GRUAN aerosol product in the future*

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GRUAN Lidar Programmes

Definition

The overall infrastructure underlying the lidar measurement and the subsequent production of a GRUAN lidar product, from data acquisition to data product management. There is one, and only one, GRUAN lidar by GRUAN Lidar Programme and vice-versa.

Domains of application

Setup, modification and maintenance of the instrumentation, the standard operating procedures for the acquisition of the raw data and the lidar calibration, and the complete and homogenized upload of the raw data and meta-data onto the GRUAN lidar data handling center for subsequent centralized processing

Mandatory components

- A lidar instrument 😊
- Dedicated and motivated staff 😊
- An Individual GRUAN Lidar Instrumentation and Measurement Protocol (**IGLIMP**)
- The **LidarRunClient** utility for traceable data and meta data recording and upload
- A centralized GRUAN Lidar Analysis Software Suite (**GLASS**) for consistent data processing

Certification

Follows closely procedure described in GRUAN Guide for site certification

Additionally (optional?): lidar signals simulations to verify instrument capability

Training

In the form of briefings on GRUAN approach and best measurement practices

The Lidar Programme Rep. + at least 1 lidar operator must attend training

IGLIMP

Dynamic document submitted on a regular basis (minimum once a year) to the GRUAN Lead Centre and GRUAN Task Team on Ancillary Measurements (TT-AM) by the GRUAN Lidar Programme's Representative

Document must describe the full and uninterrupted history of the GRUAN Lidar Programme from the day of its certification to current date

Document shall include all aspects of the Programme such as instrumentation inventory, standard operating procedures, measurement schedule, and up-to-date data acquisition and archiving status

LidarRunClient

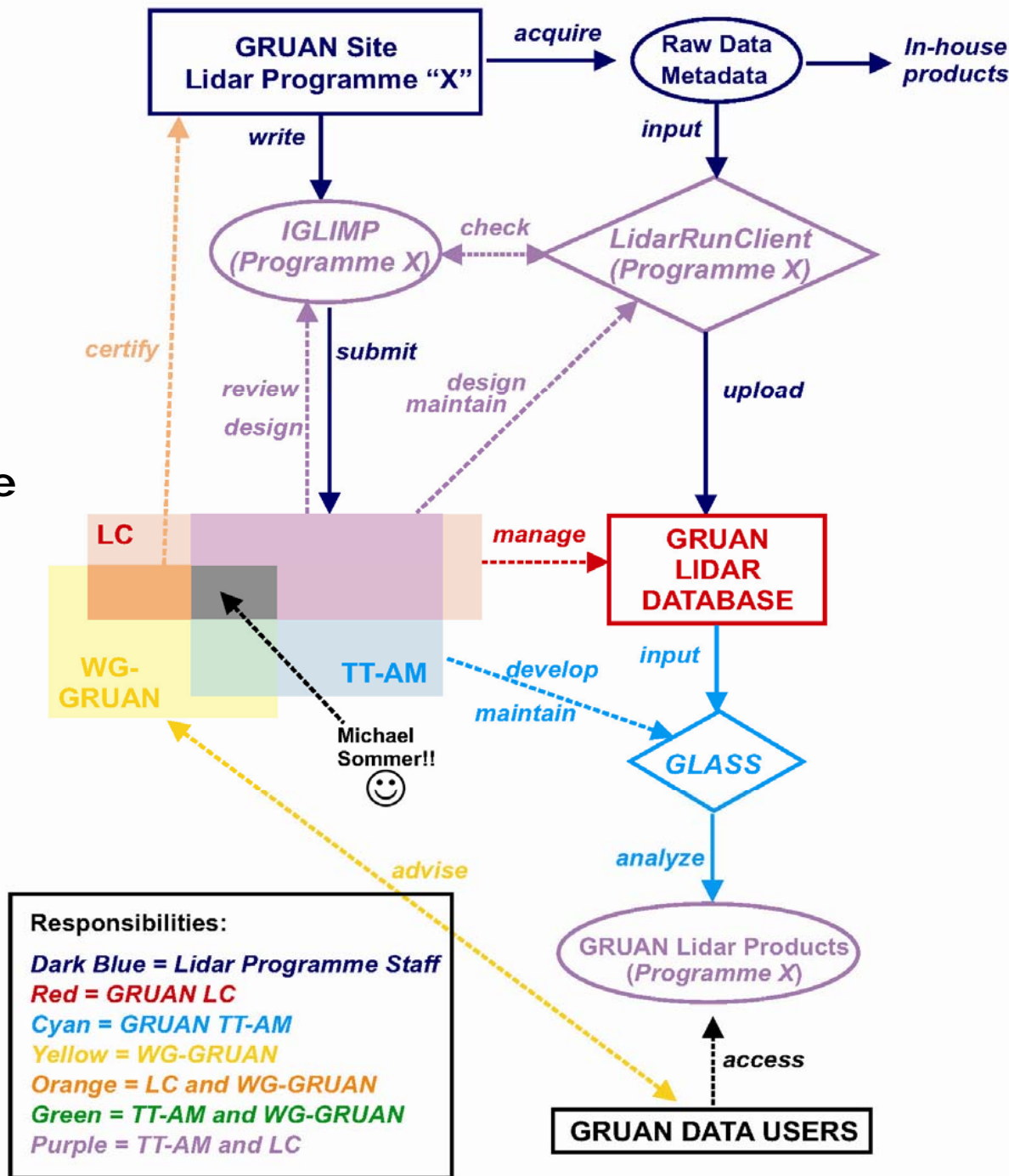
JavaScript-based interactive utility provided by the GRUAN-LC and designed to compile all metadata associated with a lidar measurement and upload them together with the raw data onto the designated GRUAN lidar handling center

GLASS

Centralized data processing software collecting and analyzing in a standardized manner the raw data of all certified GRUAN lidar instruments sent out through the LidarRunClient utility

GRUAN

Lidar Programme Modus Operandi



GRUAN Lidar Programmes

GRUAN Lidar data types

Classification follows that of GRUAN Guide:

- *Primary Raw Data (PRD): the raw data acquired during measurements (see later slide)*
- *Converted Raw Data (CRD): same as PRD but re-formatted in GRUAN-specific format*
- *Standard GRUAN Product (SGP): profiles with little or no influence of external data sets*
- *Integrated GRUAN Product (IGP): Lidar profiles combined with external data sets*

GRUAN Lidar data products

Classification driven by science applications:

- *Long-term:*
 - Does not require high temporal or vertical resolution*
 - Requires improved traceability and long-term stability*
 - Requires sufficient accuracy to detect measurable trends*
- *Process studies:*
 - Typically requires high temporal and vertical resolution*
 - Does not require improved traceability or long-term stability*
 - Requires sufficient accuracy to detect variability of the studied process*
- *Validation:*
 - Temporal, vertical resolution may match that of product to be validated*
 - Requires improved traceability*
 - Requires sufficient accuracy to validate product*

Programme versioning

A unique system of traceable version numbers for all GRUAN Lidar Programmes is proposed

Allows for a full identification and tracking of the instrumentation and operation changes that occurred since initial certification

Programme version number is decoupled and independent from the GRUAN lidar product version number

Programme version reflects changes in the instrumentation setup and/or standard operating procedures only. It does NOT reflect changes in the data processing

Version number consists of 3 sets of integer numbers separated by dots, each set corresponding to a specific component of the raw lidar data production chain:

- a 2-digit integer for the standard operating procedure configuration number*
- a 2-digit integer for the lidar emitter configuration number*
- a 2-digit integer the lidar receiver configuration number*

Example: Programme version 02.05.04

GRUAN Lidar Programme auditing

Procedure follows closely GRUAN site auditing

Lidar-specific component of auditing: Yearly review of the latest IGLIMP

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Schedules

Must consider both the lidar capability and the scientific application its measurements are intended for

Logistical and financial support permitting, GRUAN lidar instruments having a 24/7 capability should adopt the 24/7 schedule as their default schedule

When logistical and/or financial support precludes 24/7 operation, default schedules must be chosen to address one or several of the following considerations: long-term variability studies, process studies, satellite validation, and GRUAN measurement redundancy

Long-term

For routine, long-term measurements (trend detection), a minimum of 6 hours per week spread over 2 to 4 nights of operation may be suitable, which corresponds to an average integration time of 2 hours per night

Redundancy

For sites performing daily radiosonde flights, lidar does not need to be operated every day, but when operated, its running time must coincide with radiosonde

For sites performing weekly or monthly radiosonde flights: the lidar must be operated at least on the nights (days) of the radiosonde flights

For sites performing frost-point hygrometer (FPH) flights: the lidar must operate at least on the nights (days) of the FPH flights

Raw data

The rawest form of lidar data acquired by a certified GRUAN lidar shall be classified as GRUAN Primary Raw Data (PRD) and is therefore subject to all articles of the GRUAN data management policy described in Section 8 of the GRUAN Guide

Temporal sampling

Independently of GRUAN's general guiding principles on measurement scheduling, and independently of the final GRUAN lidar products to be archived, the GRUAN lidar PRD shall be sliced into time intervals comprised between 1 minute and 10 minutes

Vertical sampling

Independently of the vertical resolution of the final GRUAN lidar products, the GRUAN lidar PRD shall be vertically sampled onto a resolution grid comprised between 5 m and 75 m for tropospheric-dedicated applications, and between 5 m and 600 m for stratospheric-dedicated applications

Archiving through *LidarRunClient*

GRUAN Lidar PRD must be uploaded at the end of each identified measurement period onto the designated centralized GRUAN lidar data handling facility. When a 24/7 schedule has been adopted, it is recommended that the PRD be uploaded at least once a day

Concept

The concept and design of LidarRunClient is similar to that of RSLaunchClient, w/ additional functionality adapted to multiple lidar channels

Raw data and meta data archiving

*The PRD upload procedure must be performed using the LidarRunClient utility.
No PRD shall be accepted if they are not uploaded through the LidarRunClient utility.*

Uploading frequency

For non-continuously-operated lidars, it is recommended to upload raw data with LidarRunClient immediately after each measurement period

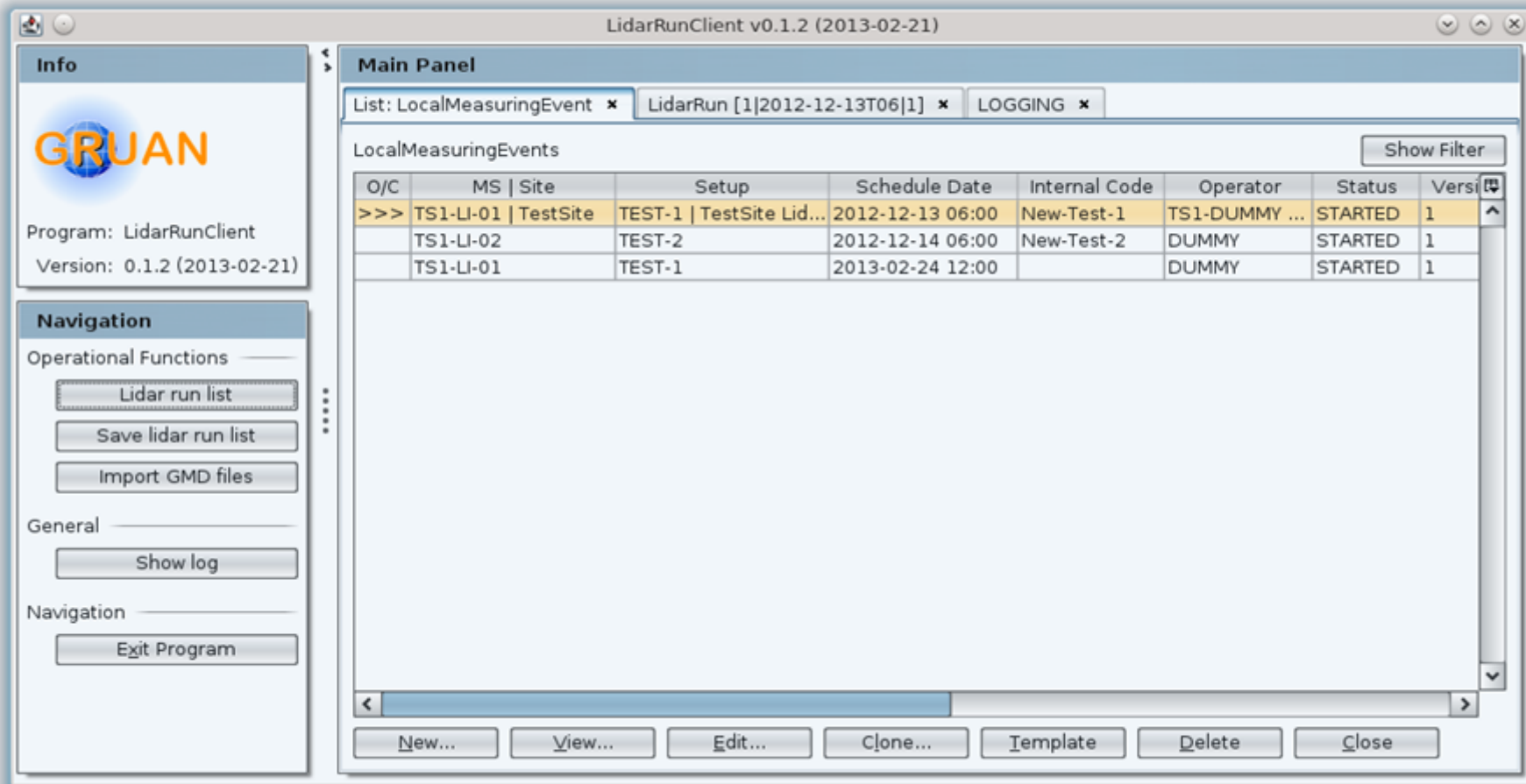
For continuously-operated lidars (24/7), it is recommended to upload raw data with LidarRunClient once a day, and if possible including data from the same UT date

Uploading before and after a change event

If one or several changes of instrumentation or operating procedure occurred during a given 24 hours cycle, the PRD must be uploaded separately for each of the multiple, uninterrupted data acquisition periods

Each of these periods shall be considered as a separate GRUAN lidar observation.

Main window



Info

GRUAN

Program: LidarRunClient
Version: 0.1.2 (2013-02-21)

Navigation

Operational Functions

- Lidar run list
- Save lidar run list
- Import GMD files

General

- Show log

Navigation

- Exit Program

Main Panel

List: LocalMeasuringEvent x LidarRun [1|2012-12-13T06|1] x LOGGING x

LocalMeasuringEvents Show Filter

O/C	MS Site	Setup	Schedule Date	Internal Code	Operator	Status	Version
>>>	TS1-LI-01 TestSite	TEST-1 TestSite Lid...	2012-12-13 06:00	New-Test-1	TS1-DUMMY ...	STARTED	1
	TS1-LI-02	TEST-2	2012-12-14 06:00	New-Test-2	DUMMY	STARTED	1
	TS1-LI-01	TEST-1	2013-02-24 12:00		DUMMY	STARTED	1

New... View... Edit... Clone... Template Delete Close

Step 1: "Observation"

Steps

1. Observation
2. Instrumentation
3. Channels
4. Instrument checks
5. Launch conditions
6. Attach files
7. Upload

Observation

GRUAN Station TS1 | TestSite

Measuring System TS1-LI-01 | TestSite Raman Lidar 1 at TestSite

Please select an observation type for which the new event should be created.

Observation Type TestSite LidarRun (Test 1) (TS1-LI-01)

Please choose the standard time (like 00, 06, 12, 18) of measuring event and add following details.

Scheduled Date (UT) 2012-12-13 06:00

Balloon No. 1

Site-internal Code New-Test-1

Main Operator TS1-DUMMY | Dummy, The

Comments

Version 1

Experiment ☐ This event is an experimental launch. (Data will not be published)

Please choose the campaign and add it with a specific code for this event.

Possible Campaigns Add campaign

Campaign-specific Code Add X

Attached Campaigns

Step 2: "Instrumentation"

Instrumentation

Instruments and Sounding Components
Add a part ▼

X
^
v

Transmitter

0 - YAGL01/Laser (12345)
1 - BEX01/Mirror/Lens (12345)
2 - MR01/Mirror/Lens (12345)
3 - LAMP01/Lamp (7-1866)

Receiver

4 - TEL01/Mirror/Lens (mmkklllo)
5 - TEL02/Mirror/Lens (12323)
6 - BS01/BeamSplitter (test-BS-000)
7 - BF01/Filter (xcvbn)
8 - FIB01/Fiber
9 - NDF01/Filter (899887)
10 - FPF01/Filter (1234)
11 - NDF02/Filter (ffrtt)
12 - FPF02/Filter (456654)
13 - NDF03/Filter (123432)
14 - FPF03/Filter (5555)
15 - PMT01/PhotoDetector (rtrt56)
16 - PMT02/PhotoDetector (09987)
17 - PMT04/PhotoDetector (111222)
18 - TRPC01/DataAnalyzer (?)

Description
Type
Instrument Change
Serial Number
Operator X
Processing X

Experiment? ☐ This instrument is experimental. (...)
Comments

Filter Full Name Add Property Clear List

Name ^	Value	Unit
Coating	TelCoating1	[-]
DesignWavelength		[nm]
Diameter		[cm]
FocalLength		[cm]
Function		[-]
IncidenceAngle		[°]
OutputAngle		[°]
Polarization		[°]
Substrate	TelSub1	[-]
Transmittance	0.6	[-]

▲ ▼

Step 3: "Channels"

Channels

Available Components

- 0 - YAGL01/Laser (12345)
- 1 - BEX01/Mirror/Lens (12345)
- 2 - MR01/Mirror/Lens (12345)
- 3 - LAMP01/Lamp (7-1866)**
- 4 - TEL01/Mirror/Lens (mmkklllo)
- 5 - TEL02/Mirror/Lens (12323)
- 6 - BS01/BeamSplitter (test-BS-000)
- 7 - BF01/Filter (xcvbn)
- 8 - FIB01/Fiber
- 9 - NDF01/Filter (899887)
- 10 - FPF01/Filter (1234)
- 11 - NDF02/Filter (ffrrtt)
- 12 - FPF02/Filter (456654)
- 13 - NDF03/Filter (123432)
- 14 - FPF03/Filter (5555)
- 15 - PMT01/PhotoDetector (rtrt56)
- 16 - PMT02/PhotoDetector (09987)
- 17 - PMT04/PhotoDetector (111222)
- 18 - TRPC01/DataAnalyzer (?)**



Measurement Channels

- [-] Channel 1
 - 00: 0 - YAGL01/Laser (12345)
 - 01: 1 - BEX01/Mirror/Lens (12345)
 - 02: 7 - BF01/Filter (xcvbn)
 - 03: 6 - BS01/BeamSplitter (test-BS-000)
 - 04: 15 - PMT01/PhotoDetector (rtrt56)
- [-] Channel 2
 - 00: 16 - PMT02/PhotoDetector (09987)
- [-] Channel 3
 - 00: 0 - YAGL01/Laser (12345)
 - 01: 2 - MR01/Mirror/Lens (12345)**
 - 02: 8 - FIB01/Fiber
 - 03: 14 - FPF03/Filter (5555)
 - 04: 17 - PMT04/PhotoDetector (111222)
- Channel 4

Information about Channel 3

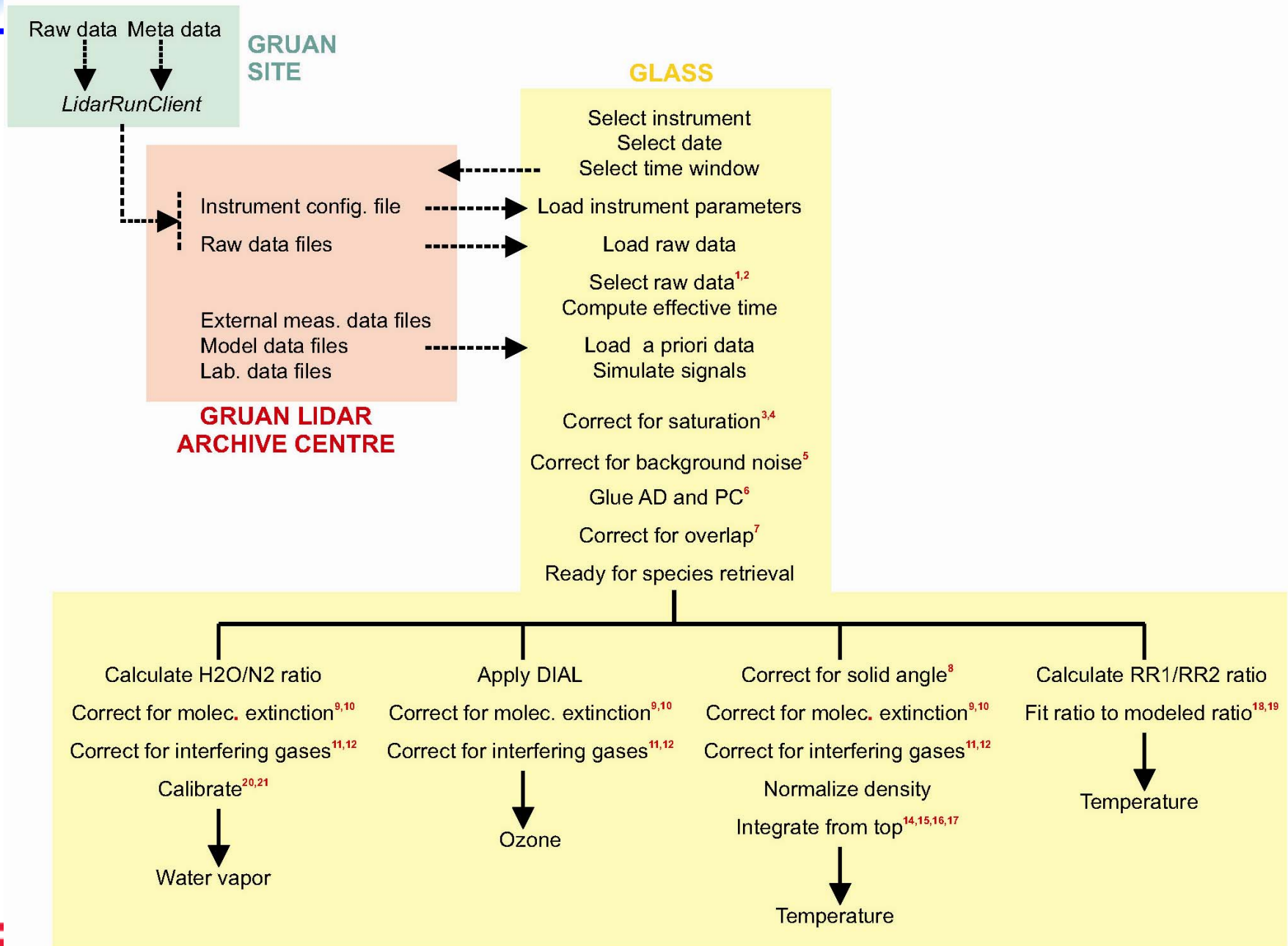
General Information

- Channel
- Test1
- Test2
- Test3

Another things

- Test4
- Test5
- Test6

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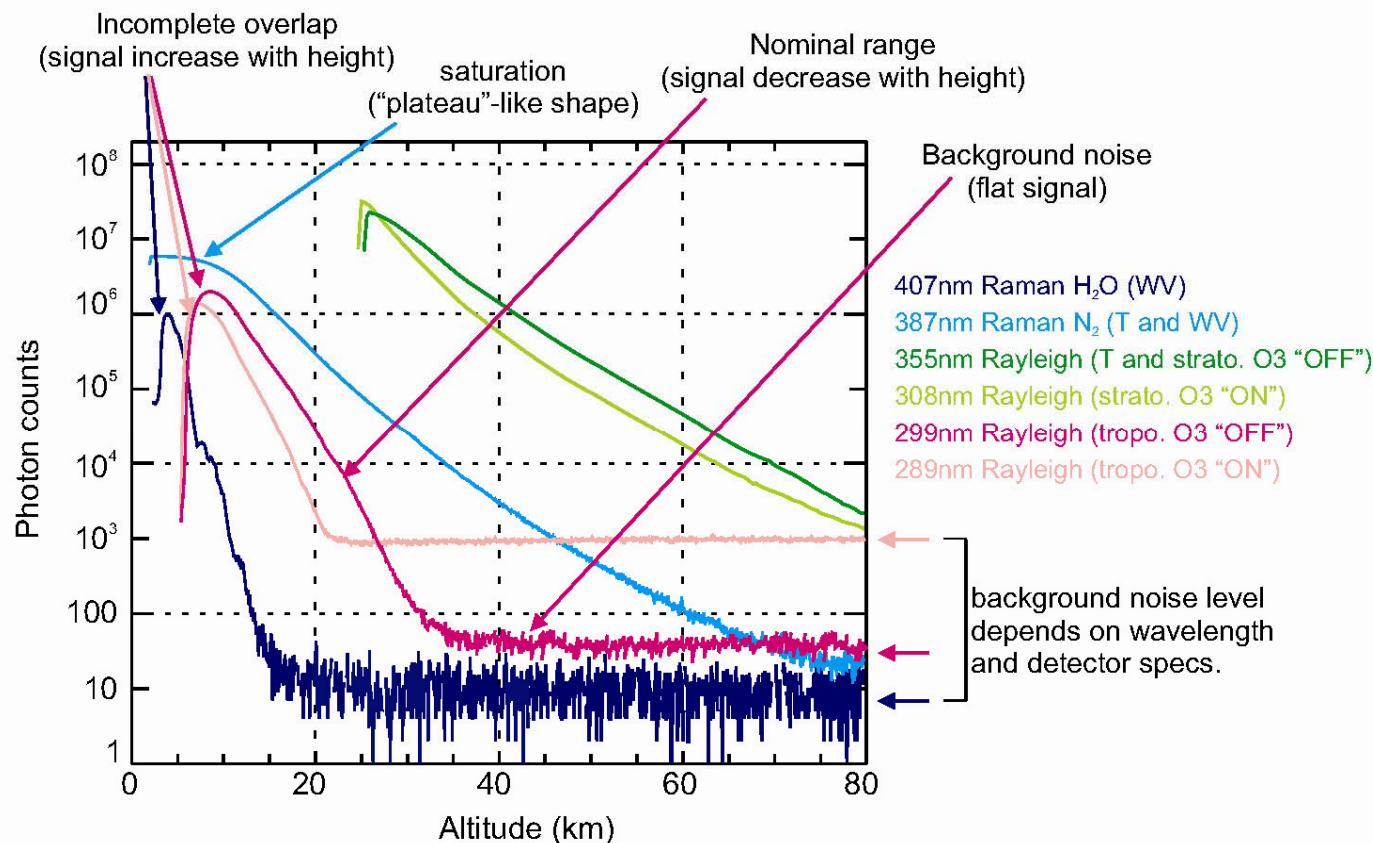
From raw lidar signals to ECV retrieval: signal corrections

In all previous slides, it was mentioned "corrected signals", not "raw signals". Why's that?

Number density → in first approximation, a "perfect" raw lidar signal should be log-linear with height (r^2 factor taken care of)

Plot below shows that real lidar signals are NOT log-linear:

→ **several corrections necessary**



Saturation correction

At low altitudes, where the signal is intense, the hardware's limited bandwidth cannot count all the photons that are received on the detectors:

The number of photon recorded (counted) is a non-linear function of the number of photon received. This function can take different forms, most of them coming from the following most general form:

$$S_U(z) = S_C(z) \exp(-\tau S_C(z)) \left[(1-d) + \left(d - \frac{d^2}{2} \right) \tau S_C(z) + \sum_{j=2}^{\infty} \frac{1}{j!} \left(\frac{d^j}{j!} - \frac{d^{j+1}}{(j+1)!} \right) [\tau S_C(z)]^j \right]$$

S_C is the corrected signal (the true number of photon counts, the number we want)

S_U is the uncorrected signal (the recorded number of photon counts)

τ (dead-time) and d (discriminator) are determined by the type of hardware used

τ is usually known within 5%, d is more difficult to quantify and usually determined empirically

The above equation is non-linear and cannot be reverted analytically.

However, it can be approximated to the first order:

$$S_U(z) = (1-d) S_C(z) \exp(-\tau S_C(z))$$

In some cases (non-paralyzable systems and $d \ll 1$), it can be further approximated and reverted to:

$$S_C(z) = \frac{S_U(z)}{1-d-\tau S_U(z)}$$

Background noise correction

At high altitudes, the lidar loses sensitivity, the signal goes below noise coming from sky light or noise originating within the detectors:

The number of photon recorded (counted) does no longer reflect the collection of the backscattered laser light, and must therefore be subtracted:

$$S_C(z) = S_U(z) - b(z)$$

S_C is the corrected signal, i.e., the number of photon counts backscattered from the laser beam (the number we want)

S_U is the uncorrected signal, i.e., the total number of photon counts received (already corrected for saturation)

b (background noise) is estimated by fitting a linear or non-linear function to the total signal S_U then subtracting it to obtain S_C

Viewing geometry limitation

***At low altitudes** the narrow field-of-view of a lidar telescope usually does not include the entire laser beam. This is a region of "partial overlap", and a signal correction is required to maintain the validity of the Lidar Equation.*

This correction depends on the geometric configuration of the telescope vs. laser beam, on the aperture type, telescope type, and assumed field-of-view and beam divergence, and is therefore highly empirical

Recommendation for a pragmatic approach

Because this correction usually yields high uncertainty, it is highly recommended to design the receiver in such a way that the expected region of useful measurement is not subject to partial overlap

The best estimation of the overlap function of a narrow f.o.v. channel is obtained using a two-channel correction method, using a wide f.o.v. channel as a reference

No analytical formulation provided

Correction for molecular extinction

The laser beam gets “slightly absorbed” as it propagates through the atmosphere
 The extinction correction is expressed differently, depending on the species retrieved

For Rayleigh and vibrational-Raman temperature:

$$S_C(z) = S_U(z) \exp \left((\sigma_{UP} + \sigma_{DOWN}) \delta z \sum_{k=0}^z N(k) \right)$$

S_C and S_U are the corrected and uncorrected lidar signals respectively, σ is the wavelength-dependent molecular extinction cross-section, N is air number density

For vibrational-Raman water vapor:

$$R_C(z) = R_U(z) \exp \left[\delta z \Delta \sigma_{DOWN} \sum_{k=0}^z N(k) \right]$$

R_C and R_U are the corrected and uncorrected signal ratios respectively, N is air number density, $\Delta \sigma$ is the wavelength-dependent molecular extinction cross-section differential

For DIAL ozone:

$$N_{O3C}(z) = N_{O3U}(z) - \frac{(\Delta \sigma_{UP} + \Delta \sigma_{DOWN}) N(z)}{\delta z \Delta \sigma_{O3}(z)}$$

N_{O3C} and N_{O3U} are the corrected and uncorrected ozone respectively, $\Delta \sigma_{UP}$ and $\Delta \sigma_{DOWN}$ are the wavelength-dependent molecular extinction cross-section differential, N is air number density, $\Delta \sigma_{O3}$ is the wavelength-dependent ozone absorption cross-section differential

Correction for absorption by minor constituents (“interfering gas”)

It is expressed differently, depending on the species retrieved

For Rayleigh and vibrational-Raman temperature:

$$S_C(z) = S_U(z) \exp \left((\sigma_{IG_UP}(z) + \sigma_{IG_DOWN}(z)) \delta z \sum_{k=0}^z N_{IG}(k) \right)$$

S_C and S_U are the corrected and uncorrected lidar signals respectively, σ is the interfering gas absorption cross-section (wavelength- and altitude-dependent), N_{IG} is the interfering gas number density

For vibrational-Raman water vapor:

$$q_C(z) = q_U(z) \exp \left[\delta z \Delta \sigma_{IG_DOWN}(z) \sum_{k=0}^z N_{IG}(k) \right]$$

q_C and q_U are the corrected and uncorrected mixing ratios respectively, $\Delta \sigma_{O_3}$ is the wavelength-dependent, altitude-dependent interfering gas absorption cross-section differential, N_{IG} is the interfering gas number density

For DIAL ozone:

$$N_{O_3C}(z) = N_{O_3U}(z) - \frac{(\Delta \sigma_{IG_UP} + \Delta \sigma_{IG_DOWN}) N_{IG}(z)}{\delta z \Delta \sigma_{O_3}(z)}$$

N_{O_3C} and N_{O_3U} are the corrected and uncorrected ozone number densities respectively, $\Delta \sigma_{IG_UP}$ and $\Delta \sigma_{IG_DOWN}$ are the interfering gas' absorption cross-section differentials, N_{IG} is interfering gas number density, $\Delta \sigma_{O_3}$ is the ozone absorption cross-section differential

Ozone (DIAL) and Temperature (Rayleigh/vibrational Raman)

No Calibration needed (self-calibrated)

Water Vapor (Raman) and Temperature (Rotational Raman)

Default is to use external source of measurement, e.g., radiosonde

Lidar profile accuracy and long-term stability tied to that of source used for calibration

Choice of calibration source depends on availability, but should always take into account accuracy and long-term stability of external source

→ Prioritized list in Lidar Guide: CFH, Radiosonde, MWR, GPS, FTS

First principle calibration: not default choice for GRUAN but should remain in scope of future improvements

Next ~ 15 slides:

**Proposed contributions of the NDACC/ISSI Team
to the development of the GRUAN Lidar Products**

NDACC/ISSI Team

What is an ISSI Team?

The International Space Science Institute (ISSI) of Bern, Switzerland provides limited funds to support time-limited focused projects involving a team of ~10 persons

ISSI Team Project Title:

"Critical Assessment and Standardized Reporting of Vertical Resolution and Uncertainty Propagation in the Data Processing Algorithms of the NDACC Lidars"

ISSI Team main contributors:

*T. Leblanc, Team Leader (JPL Lidars, NDACC)
S. Godin-Beekmann, M. Pastel and G. Payen (OHP O3 lidar, NDACC)
F. Gabarrot (Reunion Isl. Lidars, NDACC)
A. van Gijssels (Lauder O3 lidar, NDACC)
B. Sica and J. Bandoro (UWO T lidar, NDACC)
G. Liberti (Rome T lidar, NDACC)
A. Haefele (DDU and Payerne lidars, NDACC)
T. Trickl (Garmisch-Partenkirchen O3 lidar, NDACC)
C. Retscher (EUMETSAT) and I. Boyd (U.Mass., NDACC) for GEOMS*

Roadmap:

- 2011/2012: Assessments completed, **tools for vertical resolution completed**
- *Sept. 2012: Meeting 3, standardized expression and propagation of **uncertainty defined***
- mid-2013: Tools for the implementation of standardized uncertainty expected
- *June 2013, Editorial meeting: Finalization of **report** and peer-reviewed **publications***
- 2013-2014: **NDACC-lidar-wide implementation** (and **GRUAN-lidar-wide?**)

Deliverables:

- One **report** and two peer-reviewed publications (**AMT**)
- **Conversion tools** in IDL, MATLAB, FORTRAN, and PYTHON
(to be provided to NDACC lidar PIs with full documentation)
- Full **GEOMS-compatibility** for implementation in new NDACC lidar **HDF files**

Standardized, consistent, and GEOMS-compliant definition and reporting of vertical resolution

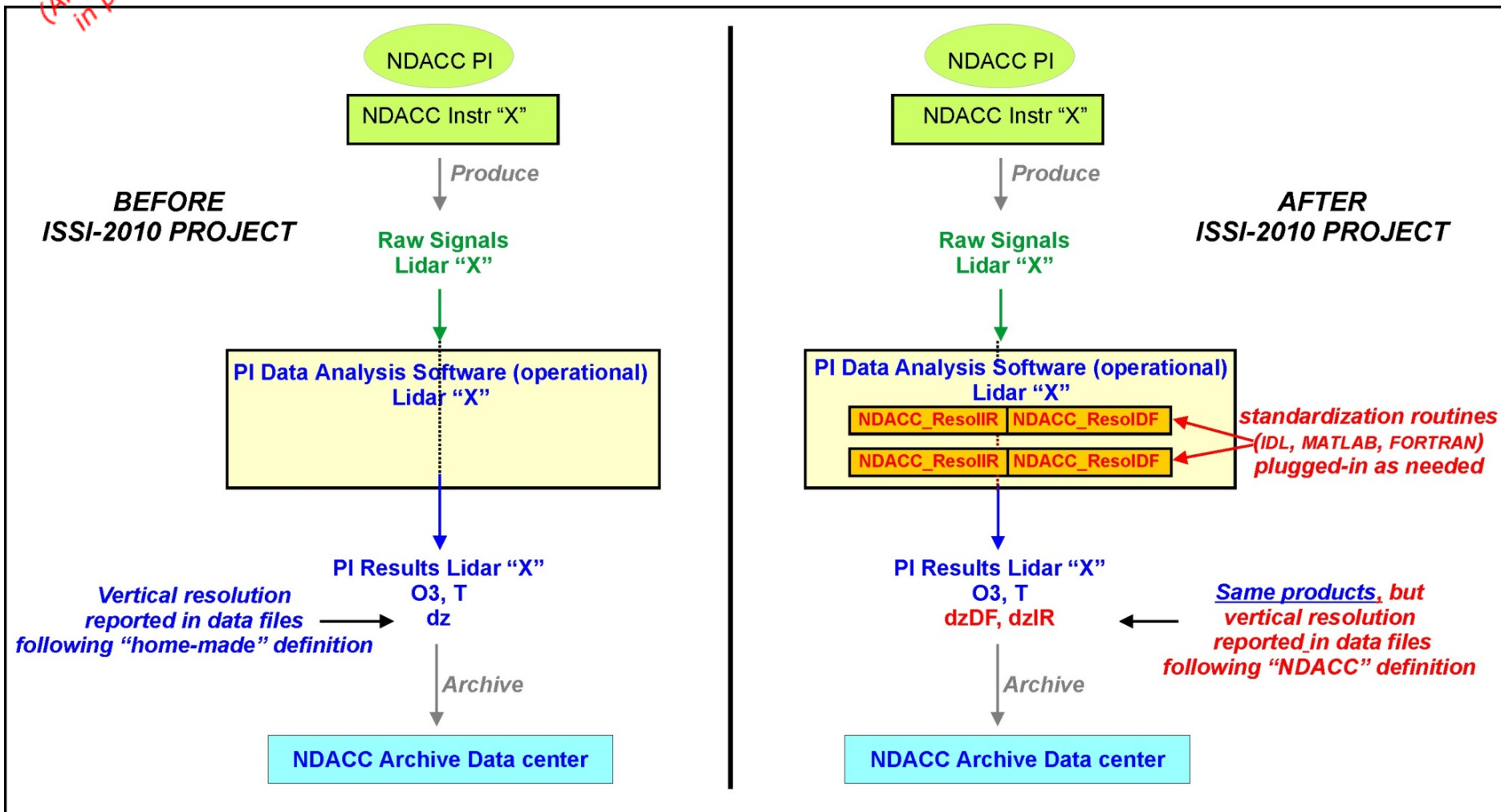
A consistent and thorough approach for the formulation used in the treatment of uncertainties

Tools for the implementation of the agreed formulation

Standardized, consistent, and GEOMS-compliant definition and reporting of uncertainty

“Standardized” vertical resolution technical implementation

Using creation/conversion tools



Tools tested and validated in 2011/2012

Terminology and general approach

Agreed Terminology:

1. The NDACC-lidar-standardized uncertainty is the **combined standard uncertainty** u as defined by the **BIPM** technical documents **JCGM-100** (2008) and **JCGM-200** (2008)
2. u must be obtained from known, **traceable** standard uncertainty components u_x associated with multiple sources of uncertainty x
3. If no traceable standard uncertainty is available for x , u_x must be taken as the standard deviation σ_x of the normally distributed probability function describing x
4. The contribution of multiple standard uncertainty components u_x to the combined standard uncertainty u must follow the fundamental law of variance propagation, i.e.:

If y is defined as a function of the independent variables x_1, x_2, \dots, x_n :

$$y = f(x_1, x_2, \dots, x_n) = y_0 + \sum_{n=1}^N \frac{\partial y}{\partial x_n} x_n$$

And if $u_n = u(x_n)$ is the standard uncertainty for the source x_n , then the combined uncertainty for y is:

$$u_y = \sqrt{\sum_{n=1}^N \left| \frac{\partial y}{\partial x_n} \right|^2 u_n^2 + \sum_{m=1}^N \left(\sum_{n=1(n \neq m)}^N \frac{\partial y}{\partial x_n} \frac{\partial y}{\partial x_m} \text{cov}(x_n, x_m) \right)}$$

Introducing uncertainty sources into the NDACC lidar data processing chain

Generic approach:

- 1. For each identified source of uncertainty x , the ISSI Team will quantify the individual contribution of x on the lidar signals, the O3 and temperature profiles using Monte Carlo simulations*
- 2. For each identified source of uncertainty x , the ISSI Team will review existing "reference" data or models x_{mod} including their standard uncertainty u_{xmod} or standard deviation σ_{xmod}*
- 3. For each identified source of uncertainty x , the ISSI Team will recommend the use of one or several "reference" data or model(s) with the most likely value(s) x_0 and uncertainty u_{x0} , which can be either:*
 - its combined standard uncertainty u_{x0} (preferred choice), or*
 - its standard deviation σ_{x0} inferred from a normal distribution of x (second choice if the first option is not available)*

Introducing uncertainty sources into the NDACC lidar data processing chain (cont.)

4. For each identified source of uncertainty x , each NDACC PI will identify their in-house-defined source and uncertainty $\{x_{PI}; u_{xPI}\}$ and compare it to the recommended reference $\{x_0; u_{x0}\}$:

a) If the NDACC PI choses to **use** the **reference data**, then the contribution of x must be computed as follows:

$$\{x; u_x\} = \{x_0; u_{x0}\}$$

b) If both x_{PI} and u_{xPI} exist and the NDACC PI choses to **use them**, the contribution of x must be computed as follows:

$$\{x; u_x\} = \{x_{PI}; u_{xPI}\}$$

c) If only x_{PI} exists and the NDACC PI choses to **use it**, then the contribution of x must be computed as follows:

$$\{x; u_x\} = \{x_0; \text{Max}(u_{x0}, \text{abs}(x_{PI}-x_0))\}$$

d) If no source x_{PI} exists (i.e., no correction applied), then the NDACC PI must use 100% of the "reference" model, i.e., the contribution of x must be computed as follows:

$$\{x; u_x\} = \{0; x_0\}$$

5. For each identified source of uncertainty x , the NDACC PI must report in the NDACC archived files whether or not the contribution of x was taken into account

Uncertainty treatment of the fundamental physical constants

Reference values and their uncertainty

From the updated list of the CODATA Working Group by the BIPM

Accessible at: <http://www.bipm.org/extra/codata/>

NDACC/ISSI “zero-uncertainty” 😊 principle for standardized physical constants

A physical constant shall be considered as a number with “zero-uncertainty”, i.e., its value, as reported by the CODATA Working Group of the BIPM, shall be rounded at a decimal level so that addition or subtraction of its uncertainty (as reported by the CODATA Working Group of the BIPM) does not incur any change in its rounded value.

Example

The molar gas constant R value, as reported by BIPM/CODATA, is:

$R = 8.314\,4621(75) \text{ Jmol}^{-1}\text{kg}^{-1}$ with a relative uncertainty of $\delta R / R = 9.1 \cdot 10^{-7}$

We therefore have: $R - \delta R = 8.314\,4613 \text{ Jmol}^{-1}\text{kg}^{-1}$ and $R + \delta R = 8.314\,4631 \text{ Jmol}^{-1}\text{kg}^{-1}$

The NDACC/ISSI standardized constant for R will therefore be: $R = 8.314\,46 \text{ Jmol}^{-1}\text{kg}^{-1}$

With the above NDACC/ISSI “zero-uncertainty” principle, there is no uncertainty propagation associated with fundamental physical constant

Identified sources ("measurement" uncertainty)

7 uncorrelated sources of uncertainty for signals before any species retrieval (i.e., applies to ALL species, referred to as "measurement" uncertainty)

1. PC statistical noise (Poisson)
2. AD noise (quantization)
3. Saturation (pile-up): dead-time τ
4. Saturation (pile-up): discriminator d
5. Background correction: fitting coefficients b_j
6. PC and AD gluing: gluing (fitting) coefficients w_j
7. Overlap and shutter correction: $O(z)$, fitting coefficients o_j

In addition to these sources of "measurement" uncertainty, there are additional sources, not all the same depending on the species retrieved...

Identified sources ("retrieval uncertainty", cont.)

10 uncorrelated sources of uncertainty for Rayleigh temperature retrieval

8. Altitude range registration: $z - z_{\text{site}}$
9. Molecular extinction: cross-sections values σ_R
10. Molecular extinction: a priori air density $N_a(z)$
11. Absorption by absorbing or interfering gases (DIAL and T): cross-sections $\sigma_A(T(z))$
12. Absorption by absorbing or interfering gases (DIAL and T): a priori density $N_{IG}(z)$
13. Particulate extinction: None (not negligible but not quantifiable at the moment)
14. Temperature integration: Gravity $g(z, \text{lat})$
15. Temperature integration: A priori (tie-on) air density or pressure $T_a(z)$, $N_a(z)$, $p_a(z)$
16. Temperature integration: Air molecular weight variation with height $M_a(z)$
17. Temperature integration: Molecular extinction cross-section height dependency $\sigma_R(z)$

2 uncorrelated sources of uncertainty for Rotational Raman temperature retrieval

18. Calibration curve: Raman backscatter cross-section temperature dependence $\sigma(T(z))$
19. Calibration curve: Spectral stability of the RR lines

Identified sources ("retrieval" uncertainty)

10 uncorrelated sources of uncertainty for water vapor retrieval

9. Molecular extinction: cross-sections values σ_R
10. Molecular extinction: a priori air density $N_a(z)$
11. Absorption by absorbing or interfering gases (DIAL and T): cross-sections $\sigma_A(T(z))$
12. Absorption by absorbing or interfering gases (DIAL and T): a priori density $N_{IG}(z)$
13. Particulate extinction: no quantification at present
20. Water vapor calibration: A priori reference water vapor q_a
21. Water vapor calibration: Calibration method (scaling parameters/coefficients c_j)
22. Fluorescence: laser-induced atmospheric fluorescence (no quantification at present)
23. Fluorescence: Receiver-inherent fluorescence (no quantification at present)
24. Water vapor calibration: Raman backscatter cross-section temperature dependence $\sigma(T(z))$

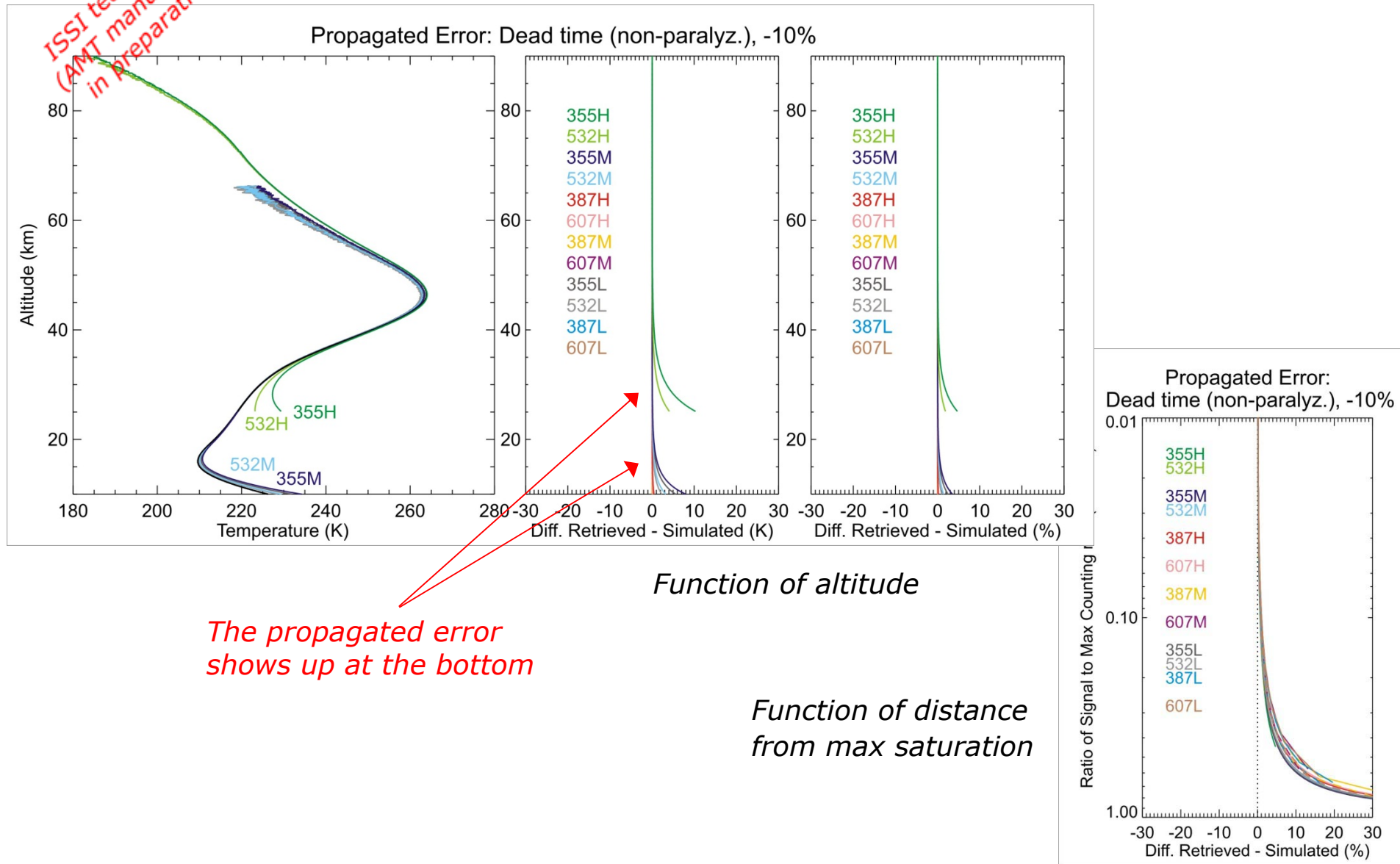
Indeed closely related to T. Gardiner's report on co-location error!

5 uncorrelated sources of uncertainty for ozone retrieval ...

9. Molecular extinction: cross-sections values σ_R
10. Molecular extinction: a priori air density $N_a(z)$
11. Absorption by absorbing or interfering gases (DIAL and T): cross-sections $\sigma_A(T(z))$
12. Absorption by absorbing or interfering gases (DIAL and T): a priori density $N_{IG}(z)$
13. Particulate extinction: no quantification at present

Saturation correction

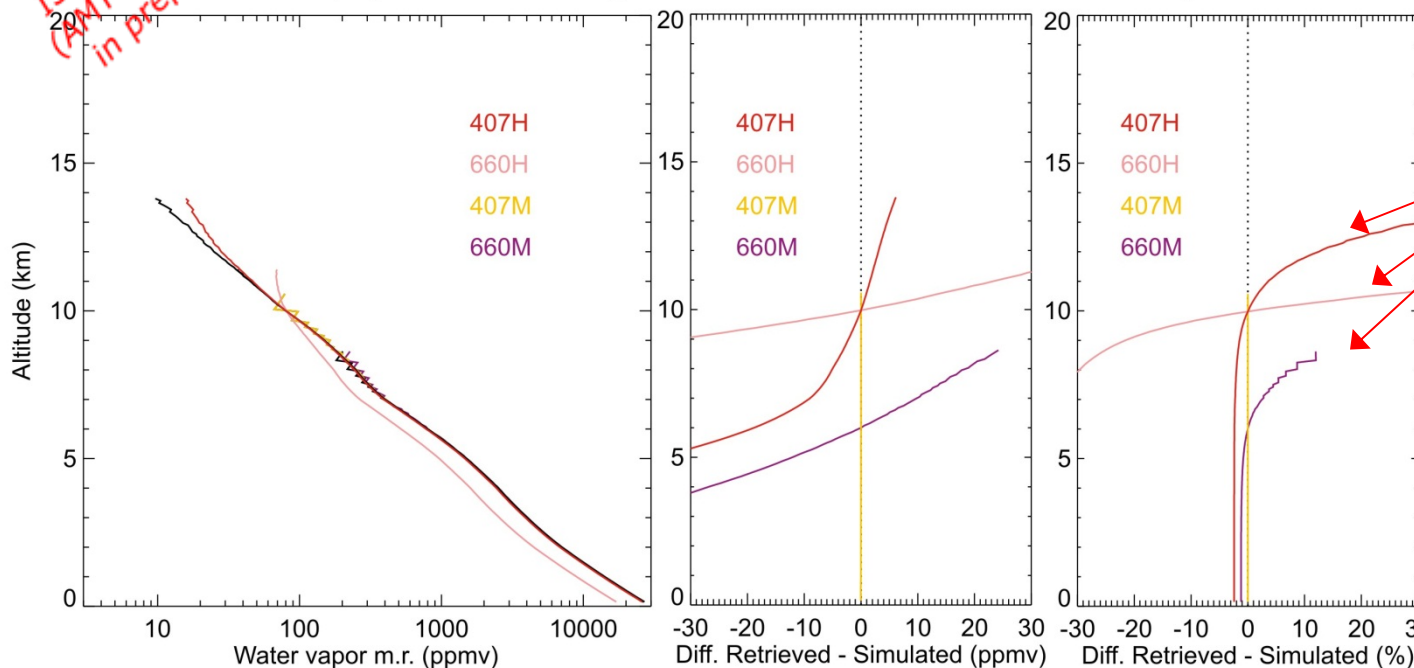
Example of its impact on temperature



Background noise correction

Example of its impact on water vapor

Propagated Error: Background noise, -10%, on H₂O channels only

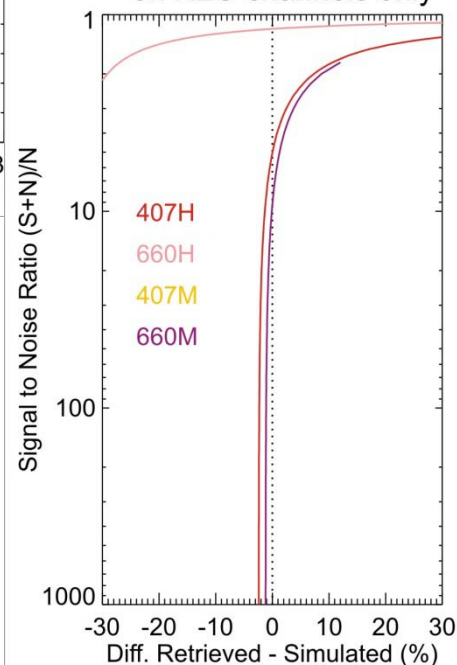


The propagated error shows up at the top

Function of altitude

Function of STNR

Propagated Error:
Background noise, -10%
on H₂O channels only



Quantification, based on existing models and datasets, of the standard uncertainty introduced for each identified source of uncorrelated uncertainty (e.g., cross-sections, NP models, hardware specs, etc.)

Full Monte Carlo simulations of the individual effect of each identified source of uncorrelated uncertainty on both the signals and the products

Report and publication write-up

**This concludes the
proposed contributions of the NDACC/ISSI Team
to the development of the GRUAN Lidar Products**

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Managing changes

Guiding principles

Follow closely guiding principles from Section 2.3.1 of the GRUAN Guide

Changes in instrumentation, operator, and operating procedures

Operators and/or operating procedure changes must be reflected into an updated version of the LidarRunClient utility in order to appropriately constrain the data processing options of the GLASS and ensure full traceability

If a change in operating procedures, including the acquisition of raw-data, follows from a change in operator and/or a change in instrumentation, this change must be reported at the instrumentation, operator, and operating procedure levels of an updated IGLIMP, and reflected in updated versions of the LidarRunClient utility and the GLASS

Changes in processing algorithms (GLASS)

The GLASS must be transparent, i.e., developed and optimized in consultation with all GRUAN Lidar Programmes investigators.

These investigators shall meet regularly to discuss the implementation of updates to the GLASS, whether they pertain to one or all of the GRUAN lidars.

Protocols must be established by the designated central lidar data processing centre to indicate when reprocessing of the full measurement record at any site is justified or required

Uncompromising GRUAN lidar Programme certification

GRUAN Lidar Programmes rely on four critical components that should never be compromised or shortcut: IGLIMP, Training, LidarRunClient, and GLASS

Raw data quality checks

Quality control at the raw data level is performed in two steps:

- *through near-real time uploads of the most recently acquired raw data and associated meta-data through the LidarRunClient utility,*
- *through the signal quality checks of the early processing stage of the GLASS*

The following three indicators should be monitored systematically:

- *the signal level of each channel at one (or several) arbitrary reference altitude(s)*
- *the noise level of each channel*
- *the signal-to-noise ratio of each channel at one (or several) arbitrary reference altitude*

Lidar Product validation

GRUAN lidar data products must be primarily validated using the available redundant instrumentation of GRUAN: radiosonde and frost-point hygrometer water vapor profiles, GPS and microwave total columns, radiosonde and lidar temperature profiles, ozonesonde and lidar ozone profiles.

GRUAN lidars should also participate to field campaigns involving non-GRUAN instruments

Individual GRUAN Lidar Measurement Protocol

Purpose

An up-to-date review document of all aspects associated with a candidate or certified GRUAN lidar to guarantee that meta data associated with this instrument are properly, consistently and permanently recorded for long term use by GRUAN

Areas of application

- *Mandatory component of any certified GRUAN Lidar Programme*
- *Initial IGLIMP doc must be submitted as part of GRUAN Lidar Programme certification process*
- *IGLIMP doc must be updated in NRT whenever a Programme change event occurs*
- *Latest IGLIMP version used in NRT by the GLASS*
- *Latest IGLIMP version used at time of GRUAN Lidar Programme auditing/re-certification*

Overview of content

- *IGLIMP contains 10 generic tables*
- *Tables 1 through 3: specifics on Programme management and configuration*
- *Table 4: detailed, up-to-date history of all aspects of the Programme*
- *Tables 5 through 10: detailed hardware and software inventory w/ their operating time*

Example of IGLIMP Table 3

Neverland GRUAN Lidar Programme configuration at start of Programme (Programme configuration version: 01.01.01)

Category	Type	Value/Name	Publications
Infrastructure	WV Raman Lidar	SuperRam	Smith et al., The SuperRam water vapor Raman lidar, AMT, 2001
Personnel	PI Co-I Operator	Smith, J. Duck, D. Curious, G.	Smith et al., Just another title, AMT, 2011 Duck et al., Yet another title, ACP, 2006
Sponsor	NDACC GRUAN	Weather Services WMO	
Geo-location	GRUAN site Longitude Latitude Elevation (m a.s.l.) Programme Start Date	Neverland -11.1 44.4 2222.2 2010/12/14	
Proposed Schedule	Routine Satellite validation Field inter-comparisons Radiosonde launch	3 times per week Upon request Once per year 5 times per month	Smith et al., Still another title, AMT, 2012 Duck et al., Just another title JGR, 2010 Mouse et al., Yet another title JTech., 2011
Proposed SOP	Warm up Alignment Acquisition	30 minutes 15 minutes 120 minutes	Smith et al., Still another title, AMT, 2012
Other Infrastructure	Radiosonde GPS Microwave FP sonde	RS92K GNSS WVMS03 CHF	White et al. Almost last title,, JGR, 2005 Black et al., Now really last title, GRL, 2009

GRAN Lidar Programme history of changes between start of Programme and current date

Template of IGLIMP Table 4

	Change events
Column 1	Date/Time change
Column 2	New Programme configuration version
Column 3	Change event: Category
Column 4	Change event: Type
Column 5	Change event: New value
Column 6	Change event: Old value
Column 7	Change event: Comments

Instrumentation components properties: Light sources

Template of IGLIMP Table 5

	Laser	Lamp
Column 1*	Part ID	Part ID
Column 2	Date/Time Start	Date/Time Start
Column 3**	Date/Time End	Date/Time End
Column 4*	Type	Type
Column 5	Function	Function
Column 6	Manufacturer	Manufacturer
Column 7	Model	Model
Column 8	Part Number	Part Number
Column 9	Medium	Medium
Column 10	Seeder (Y/N)	Window substrate
Column 11	Wavelength (nm)	Min. wavelength (nm)
Column 12	Bandwidth (nm)	Max. wavelength (nm)
Column 13	Pulse Rate (Hz)	Wattage (W)
Column 14	Polarization (deg)	Polarization (deg)
Column 15	Divergence (mrad)	Diameter (cm)
Column 16	Pulse Energy (mJ)	Length (cm)
Column 17	Diameter (cm)	Positioning (fixed/scanning)
Column 18	Seeder Wavelength (nm)	Radiation direction (deg)
Column 19	Seeder Bandwidth (nm)	/

Template of IGLIMP Table 6

Optical components properties: Emitter

	Raman Cell	Beam Expander	Mirror/Lens
Column 1*	Part ID	Part ID	Part ID
Column 2	Date/Time Start	Date/Time Start	Date/Time Start
Column 3**	Date/Time End	Date/Time End	Date/Time End
Column 4*	Type	Type	Type
Column 5	Function	Function	Function
Column 6	Manufacturer	Manufacturer	Manufacturer
Column 7	Model	Model	Model
Column 8	Part Number	Part Number	Part Number
Column 9	Substrate	Substrate	Substrate
Column 10	Coating	Coating	Coating
Column 11	Wavelength (nm)	Expansion factor	Design wavelength (nm)
Column 12	Bandwidth (nm)	Length (cm)	Focal length (cm)
Column 13	Efficiency (%)	Transmittance	Transmittance†
Column 14	Polarization (deg)	Polarization (deg)	Polarization (deg) †
Column 15	Diameter (cm)	Diameter (cm)	Diameter (cm)
Column 16	Incidence angle (deg)	Incidence angle (deg)	Incidence angle (deg)
Column 17	Output angle (deg)	Output angle (deg)	Output angle (deg) †
Column 18	Length (cm)	/	/

Template of IGLIMP Table 10

Instrumentation components properties: Channels

	Channel
Column 1	Channel #
Column 2	Date/Time Start
Column 3*	Date/Time End
Column 4	Channel short name
Column 5	Data analyzer part ID
Column 6	Data analyzer hardware address
Column 7	Data analyzer detection mode (PC/AD)
Column 8	Data analyzer memory #
Column 9	Number of sampling bins
Column 10	PC: Max. counting rate (MHz); AD: Bin shift
Column 11†	Emitter path
Column 12††	Receiver path
Column 13	Acquisition software name and version

GRUAN Lidar Product Development is ongoing

Overall Framework (= Lidar Programme) has been defined in the Lidar Guide (v1.1.0.1)

A revised version (1.1.0.2) of the Lidar Guide (after TT-AM review) is to be released just after this meeting, then to be submitted to WG-GRUAN

The Lidar Guide (as it is now) is expected to be significantly edited throughout 2013 as the GLASS is being developed

First GRUAN Lidar product is expected by ICM-6 😊