More Thoughts on Total Propagated Uncertainty for Bathymetric Lidar

Grady Tuell, Ph.D.

GTRI Electro-Optical Systems Lab

June 11, 2014
Integrated Atmospheric Characterization System (IACS)

3 integrated lidars characterizing turbulence, aerosols, and water vapor in vicinity of HEL.

355 nm imaging lidar for profiling refractive turbulence

355 nm Raman lidar for profiling water vapor

aerosol lidar operating at both 1.06 and 1.625 microns.
Lidar Signal vs. range and time

Extinction coefficient vs. range

Transmittance to range
Fledgling program in Bathymetric Lidar

Large Scale Simulations to study TPU

Real-time computation of coordinates and TPU

Pathfinder lidar
TPU Procedure

Compute TPU matrix thru propagation of variance

\[
\Sigma_p = \begin{bmatrix}
\sigma_K^2 & \sigma_{EN} & \sigma_{EU} \\
\sigma_{EN} & \sigma_N^2 & \sigma_{NU} \\
\sigma_{EU} & \sigma_{NU} & \sigma_U^2 \\
\end{bmatrix}
\begin{bmatrix}
E_p \\
N_p \\
U_p \\
\end{bmatrix}
= R_Z(k)R_Y(\psi)R_X(\omega)R_Z(\theta)
\begin{bmatrix}
R_Y(\phi_A) \\
R_Y(\phi_w) \\
\end{bmatrix}
\begin{bmatrix}
0 \\
0 \\
\end{bmatrix}
+ R_Y(\phi_w)
\begin{bmatrix}
0 \\
0 \\
\end{bmatrix}
+ \begin{bmatrix}
E_A \\
N_A \\
U_A \\
\end{bmatrix}
\]
Propagation for non-linear functions

\[
\Sigma_p = \begin{bmatrix}
\sigma_E^2 & \sigma_{EN} & \sigma_{EU} \\
\sigma_{EN} & \sigma_N^2 & \sigma_{NU} \\
\sigma_{EU} & \sigma_{NU} & \sigma_U^2
\end{bmatrix} = J \Sigma_m J^T
\]

Measurements cofactor matrix (11x11) formed with the variances and covariances of the measurements

\[
SAS_{99} = 1.122 (\sigma_E + \sigma_N + \sigma_U)
\]

Jacobian matrix (3x11) formed with the partial derivatives
Measurement Matrix ($\Sigma_M$) …..?

$$
\Sigma_M =
\begin{bmatrix}
\sigma_{E_a}^2 & \sigma_{E_a} \sigma_{N_a} & \sigma_{E_a} \sigma_{U_a} & \sigma_{E_a} \sigma_{\omega} & \sigma_{E_a} \sigma_{\phi} & \sigma_{E_a} \sigma_{\kappa} \\
\sigma_{N_a} \sigma_{E_a} & \sigma_{N_a}^2 & \sigma_{N_a} \sigma_{U_a} & \sigma_{N_a} \sigma_{\omega} & \sigma_{N_a} \sigma_{\phi} & \sigma_{N_a} \sigma_{\kappa} \\
\sigma_{U_a} \sigma_{E_a} & \sigma_{U_a} \sigma_{N_a} & \sigma_{U_a}^2 & \sigma_{U_a} \sigma_{\omega} & \sigma_{U_a} \sigma_{\phi} & \sigma_{U_a} \sigma_{\kappa} \\
\sigma_{\omega} \sigma_{E_a} & \sigma_{\omega} \sigma_{N_a} & \sigma_{\omega} \sigma_{U_a} & \sigma_{\omega}^2 & \sigma_{\omega} \sigma_{\phi} & \sigma_{\omega} \sigma_{\kappa} \\
\sigma_{\phi} \sigma_{E_a} & \sigma_{\phi} \sigma_{N_a} & \sigma_{\phi} \sigma_{U_a} & \sigma_{\phi} \sigma_{\omega} & \sigma_{\phi}^2 & \sigma_{\phi} \sigma_{\kappa} \\
\sigma_{\kappa} \sigma_{E_a} & \sigma_{\kappa} \sigma_{N_a} & \sigma_{\kappa} \sigma_{U_a} & \sigma_{\kappa} \sigma_{\omega} & \sigma_{\kappa} \sigma_{\phi} & \sigma_{\kappa}^2
\end{bmatrix}
$$

- navigation
- pointing calibration
- ranging performance
- environment

GTRI/ EOSL - 7
Example: effect of variance on incidence angle at sea surface

variance in "in-water" incidence angle

- $\sigma = 0$
- $\sigma = 2\text{ deg}$
- $\sigma = 3\text{ deg}$
- $\sigma = 4\text{ deg}$

Path length in water (m)

SAS99 (m)
We developed a procedure to rapidly compute FOV loss by parameterizing in terms of FOV and $c^1$.

\[ S_{\text{max}} = P_0 \cdot \frac{\rho_{532}}{\pi} \sum \frac{e^{-2l_A}}{(Hn+D)^2} \eta (1 - \rho_{fr})^2 e^{-2(a+b)b} F(D, H, \text{FOV}, b_f, m) \cdot \frac{1}{M^s} \]

- With new technique, we generate 1000 waveforms in 20 sec. (1650x faster than Eq (2)).

Examples: Analysis of Variance

- Higher energy does not result in smaller variance
- Higher attenuation does not result in larger variance
- ……but probability of detection affects results

Some progress……

<table>
<thead>
<tr>
<th>( \Sigma_m = )</th>
<th>( \sigma_{E_A}^2 )</th>
<th>( \sigma_{E_A} \sigma_{N_A} )</th>
<th>( \sigma_{E_A} \sigma_{U_A} )</th>
<th>( \sigma_{E_A} \sigma_{\omega} )</th>
<th>( \sigma_{E_A} \sigma_{\phi} )</th>
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<tr>
<td>( \sigma_{U_A}^2 )</td>
<td>( \sigma_{U_A} \sigma_{\omega} )</td>
<td>( \sigma_{U_A} \sigma_{\phi} )</td>
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<tr>
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<td></td>
</tr>
<tr>
<td>( \sigma_{\kappa}^2 )</td>
<td>( \sigma_{\kappa} \sigma_{\phi} )</td>
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</table>

**Ranging Variance**

1. Varies with POD as \( E_0 \) and \( c \) vary
2. Varies with rugosity and \( \rho \)
3. FOV
4. Algorithms

**Environment**

1. Wind speed and direction
2. Depth

**Navigation**

- \( \sigma_{E_A} \)
- \( \sigma_{E_A} \sigma_{N_A} \)
- \( \sigma_{E_A} \sigma_{U_A} \)
- \( \sigma_{E_A} \sigma_{\omega} \)
- \( \sigma_{E_A} \sigma_{\phi} \)
- \( \sigma_{E_A} \sigma_{\kappa} \)

**Pointing Calibration**

- \( \sigma_{\omega} \sigma_{\phi} \)
- \( \sigma_{\omega} \sigma_{\kappa} \)
- \( \sigma_{\phi} \sigma_{\kappa} \)
- \( \sigma_{\kappa} \sigma_{\phi} \)
GTRI pathfinder real-time lidar
GTRI pathfinder real-time lidar
Processing software developed with simulated waveforms successfully processed waveforms from Pathfinder.

GT Target with Mounting Frame Deployed in Water Tank

3D Point Cloud Reconstruction
We could not demonstrate real-time computation at the water tank, but ............
Emulating Real-Time Acquisition

ARB: M8190A

Digitizer: M9703A

NVIDIA Tesla K20

3.7M PPS with TPU written to media

GT Pathfinder waveforms from water tank @ 20kHz

3.7M PPS with TPU written to media

GT Pathfinder waveforms from water tank @ 20kHz
Latency diagram

Block of 1024 waveforms @20kHz, GPS, INS

Continuous acquisition loop

Digitizer/FPGA
(Filtering, Smoothing, Interest Points, Ranging)

CPU (data conversion)

GPU (Coords + TPU)

output

0

51

94.5

141.5

1024x1024 block @20kHz takes 51ms to be generated

1024x1024 block read into CPU RAM in 43.5ms

Coordinates and TPU calculated, plus file output in 47ms
- DC-coupled digitizer with a 12 bit resolution and 3.2GSPS sample rate.
- Easily-programmable onboard FPGA for every pair of analog channels with sufficient processing power for real-time coordinate and TPU computation.
- Development Environment: MentorGraphics HDL Author and ModelSim with Xilinx ISE (GTRI EOSL is a beta test site for these tools)

Next Steps: Focus on water surface

Study the effects of micro–and macro surface structure on variance of refraction angle and in-water path length – and on transfer functions for imaging.
Anticipated mods to Pathfinder

- **Fielded Receiver**
  - Neutral Density Filter
  - Aperture Stop
  - Narrow Band Filter
  - Beamsplitter for system characterization
  - End of Fiber Bundle to PMT

- **Redesigned Receiver**
  - Neutral Density Filter
  - Reduced Aperture Stop
  - Dichroic Beamsplitter
  - 32x32 GmAPD Camera Array
  - End of Fiber Bundle to PMT
Optical Re-design of Pathfinder

- Only minor optical and mechanical modifications will be needed

Transmitter

Receiver

1064nm transmitter path will exit in 1” lens tubes here

Princeton Lightwave GmAPD camera (without lens) will go here
2015 – UNESCO International Year of Light

TOWARDS 2020 – PHOTONICS DRIVING ECONOMIC GROWTH IN EUROPE

Multiannual Strategic Roadmap 2014–2020

Optics and Photonics
Essential Technologies for Our Nation

FAST-TRACK ACTION COMMITTEE ON OPTICS AND PHOTONICS:

Building a Brighter Future with Optics and Photonics

APRIL 2014

PRODUCT OF THE
Committee on Science
OF THE NATIONAL SCIENCE AND TECHNOLOGY COUNCIL
**Course Title:** Introduction to Laser Radar  
**Program ID:** DEF 3506P  
**Subject:** Infrared Training and Electro Optical  
Affiliated with the [SENSIAC Education Program](http://www.pe.gatech.edu).

<table>
<thead>
<tr>
<th>Registration Deadline</th>
<th>Section Dates</th>
<th>Format &amp; Location</th>
<th>CEUs</th>
<th>Fee</th>
<th>Status</th>
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<tbody>
<tr>
<td>Jun 24, 2014 (Tue)</td>
<td>Jun 24, 2014 (Tue) - Jun 27, 2014 (Fri)</td>
<td>Atlanta (Georgia Tech Global Learning Center) (this is an onsite course)</td>
<td>2.45</td>
<td>$1,495</td>
<td>OPEN</td>
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</table>

**Course Title:** Atmospheric Lidar Engineering  
**Program ID:** DEF 3005P  
**Subject:** Infrared Training and Electro Optical

**Active Sections**  
Atlanta (Georgia Tech Global Learning Center) (OPEN) Sep 30, 2014 (Tue) - Oct 3, 2014 (Fri)

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http://www.pe.gatech.edu

grady.tuell@gtri.gatech.edu
• BACKUP SLIDES
Using this proxy function we can simulate 1000 waveforms in 20 sec (vs. 8 hours)

How best to interpret TPE?

\[
\Sigma_p = \begin{bmatrix}
\sigma_x^2 & \sigma_{xy} & \sigma_{xz} \\
\sigma_{xy} & \sigma_y^2 & \sigma_{yz} \\
\sigma_{xz} & \sigma_{yz} & \sigma_z^2
\end{bmatrix}
\]

<table>
<thead>
<tr>
<th>Accuracy Measures</th>
<th>Formula</th>
<th>Probability</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEP (Spherical Error Probable)</td>
<td>[0.51(\sigma_y + \sigma_z + \sigma_z)]</td>
<td>50%</td>
<td>The radius of sphere centered at the true position, containing the position estimate in 3D with probability of 50%</td>
</tr>
<tr>
<td>MRSE (Mean Radial Spherical Error)</td>
<td>[\sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2}]</td>
<td>61%</td>
<td>The radius of sphere centered at the true position, containing the position estimate in 3D with probability of 61%</td>
</tr>
<tr>
<td>90% Spherical Accuracy Standard</td>
<td>[0.833(\sigma_y + \sigma_z + \sigma_z)]</td>
<td>90%</td>
<td>The radius of sphere centered at the true position, containing the position estimate in 3D with probability of 90%</td>
</tr>
<tr>
<td>99% Spherical Accuracy Standard</td>
<td>[1.122(\sigma_y + \sigma_z + \sigma_z)]</td>
<td>99%</td>
<td>The radius of sphere centered at the true position, containing the position estimate in 3D with probability of 99%</td>
</tr>
</tbody>
</table>

Novatel, 2003, APN-029 Rev 1
Current Gimbal allows for 90 degrees of azimuth rotation
Pathfinder: Mechanical Design

- FAZTEK Extruded Aluminum Frame
- Motorized Linear Stage
- Motorized Rotary Stage
- Fixed Mounting 20° from the vertical-axis
- Inclinometer
- Transmitted Beam
- Wedge Laser with Fans
- Receiver Telescope