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May 6, 2012

Dr. Hannah Brackley
GNS Science - Te Pu Ao,
1 Fairway Drive,
PO Box 30368, Lower Hutt,
New Zealand

CC: Dr. John Beavan

Dear Dr. Brackley,

This letter is to confirm the completion of the work specified in the contract between GNS Science and Imagin'Labs Corporation dated from April 17th, 2012. The work specified and accomplished consisted in analyzing three LiDAR data set, for which displacement maps, strain maps, vector arrow fields, and visualization output have been delivered electronically in previous correspondence. If you have not received some of the agreed upon results, please inform us within 10 days of receiving this letter. Without further notice within this time, Imagin' Labs Corporation will consider that GNS Science has effectively received, and is satisfied with, the results of the aforementioned contract.
In accordance with GNS Science, the seven LiDAR data set processed consisted of:

- 2003-2012a
- 2011b-2012a
- 2011c-2012a

The following pages summarize the processing and work accomplished by Imagin' Labs Corporation, along with directions for basic assessment of quality of the results. We hope you are satisfied with the products delivered, and be assured that satisfaction of our clients is very important to us.

Sincerely,

Dr. Sébastien Leprince

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Summary of work for the data sets:

- **2003-2012a**
- **2011b-2012a**
- **2011c-2012a**

All methods were optimized to deliver best overall compromises between accuracy of results, high spatial density of measurements, low measurement uncertainty, and adequate rejection of spurious measurements. After investigating sub-pixel correlation at several scales (i.e., using correlation windows of 128x128, 64x64, 32x32, and 16x16 pixels), and after testing different filtering and correction methods, we have settled on the following procedures to extract relevant horizontal information from the gridded LiDAR data provided:

- Sub-pixel correlation using 64x64 pixel windows. Since windows are weighted by a Hanning window, this processing produces independent measurements at about every ~40 pixels. The measurements at smaller scales were too noisy to produce adequate strain measurements. Since measurements are only independent every about 40 pixels (40m) the displacement maps are delivered with a spatial sampling of 4m, which was found sufficient to visually show all the information present in the data.

- The Lidar data contains jitter artifacts due to inaccurate aircraft attitude variations. These artifacts were mostly removed by destripping, i.e., by subtracting the mean value along the direction of artifacts, considering their amplitude constant in the other directions. This assumption has proven to hold reasonably well. To avoid introducing additional artifacts from outliers in the destripping, the destripping model was estimated from heavily filtered measurements. The jitter correction was then applied to the raw measurements. Destripping was done in several directions, from up to four iterations with different azimuthal directions.

- Poor correlation values (low confidence as estimated by the correlation signal-to-noise ratio), and correlation values presenting large unphysical displacements (outliers) were discarded and replaced with 'Nan' values (missing data). In addition to removing unphysical values, measurements extracted from areas of low data coherence (such as water areas) were classified and removed to produce cleaner output.

- Of particular interest, the work delivered under this contract benefited from an improved algorithm to better detect spurious (outliers) measurements. As a result, small featureless areas that used to produce erroneous measurement that were hard to remove are better identified and removed in the delivered data.

- Resulting displacement fields were filtered using a modified version of the Non-Local mean filter. This filter preserves edges without introducing artifacts or excessive blurring. Only patterns with similar characteristics are averaged. In practice, results are much better than standard anisotropic diffusion filters. The NL-Means filter was modified to accept data with missing values, and a linear implementation was used. The 'linear implementation' takes into account the linear trend of the data in an effort to avoid biasing the gradient information from the underlying

data (as opposed to simply denoising the data itself). Several parameters were tested to achieve best compromise between noise reduction and loss of spatial resolution.

- Isolated missing values were extrapolated using a 3x3 pixel median filter. The size of the filter was kept small to maximize spatial information. Filling small gaps avoids propagating them when computing the strain and produces strain maps with fewer missing data.

- Additional filtering using the Non-Local Means filter was added in a last round using very small noise estimates (6-10cm) and large windows to allow for best rendering of the strain.

- Due to our new and improved detection of decorrelation zones, no manual removal of poor correlation values was necessary.

- Strain was derived using 3x3 (12x12m) pixel windows.

- Arrow-plots were generated by averaging and sampling the displacement field measured at every 56m. Displacement field was averaged over 200x200m windows for the 2003-2012a data set, and over 100x100m windows for the 2011b-2012a and the 2011c-2012a data set. It was found to be a good compromise between readability of the results and density of the information delivered.

Some considerations about the results:

- The 2003-2012a data confirms the general ground motion recovered from previous studies.

- Displacement maps from the 2011b-2012a data set show some lateral motion around the Avon river and the horse shoe bend, that seem consistent with the displacement at earlier dates. Large displacements reported on the East side of the 2011b-2012a data set (along the shore) are artificial and caused by jitter residuals that could not be removed. Lateral motion may have occurred in those places, but the large residuals make this assessment impossible.

- The 2011c-2012a correlation results are dominated with jitter artifacts that could not be removed due to a phase inversion of the jitter residuals. Jitter residuals are up to about 15 cm in amplitude, and within that range, ground lateral motion could not be reported.

- In all data set, the random error of the measurements is overwhelmed by the pattern error of the jitter residuals, which can account for 10-20 centimeters of bias.