IMAGIN'LABS CORPORATION

530 S Lake Ave., Suite 320
Pasadena, CA 91101, USA

July 27th, 2011

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

CC: Dr. Hannah Brackley, Dr. Shaun Levick

Dear Dr. Beavan,

This letter is to confirm the completion of the work specified in the contract between GNS Science and Imagin'Labs Corporation dated from June 27th, 2011. The work specified and accomplished consisted in analyzing six 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 six LiDAR data set processed where acquisitions from:

- 2003-2010
- 2003-2011a
- 2005-2010
- 2005-2011a
- 2010-2011a – central extent
- 2010-2011a – northern extent

Note that the work agreement originally included the processing of the 2011b data, which was replaced by the 2005 data since the 2011b data could not be delivered to Imagin'Labs Corporation. This modification was approved by GNS over electronic correspondence.

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

Chief Executive Officer
IMAGIN'LABS CORPORATION
Sebastien.leprince@imaginlabs.com

For general information and inquiries:
Tel: +1 (626) 600-1038
Email: info@imaginlabs.com

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Summary of work for the data sets:

- **2003-2010**
- **2003-2011a**
- **2010-2011a – central extent data set:**
- **2010-2011a – northern extent**

All methods were optimized to deliver the 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 postspacing of 4m, which was found sufficient to visually show all the information present in the data.

- The Lidar data contains jitter artifacts, e.g., along the EW direction, and along a ~16 degrees N orientation for the 2010-2011a Central Extent data set, which should correspond to the flight path of both aerial surveys. 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.

- 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).

- 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 pattern 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 not bias 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.

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- Two different implementations were compared to derive dilatational strain. The first one is the direct implementation of the common mathematical formula, that is, the trace of the strain tensor, which is itself derived from the gradient of the displacement field. The displacement field gradient was implemented as a centered 3 point finite difference. However, the resulting areal strain was quite noisy as the derivative (high pass filter) brings out the noise from the data (although the displacement field was carefully filtered as described by all the steps above). A different implementation that does not rely on explicit computation of the derivative to deduce the areal strain was then used. Given an area A deformed into an area D, local dilation can be geometrically approximated by (D-A)/A. This quantity was computed for varying initial area sizes ranging from 3x3 pixels to 9x9 pixels (12x12m to 36x36m). Strain maps were deduced using this last method over 3x3 and 5x5 pixel windows.

- Arrow-plots were generated by averaging and sampling the displacement field measured at every 15 pixels, i.e., 15x4 = 60m. 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 northern part of the 2010-2011a is quite noisy due to decorrelation around the river area but it seems that some signal can still be recovered.

- The 2003 dataset has huge stripping artifacts. Best practices were applied to reduce them but it was not always possible to completely eliminate them because patterns are not constant in the images.

- Overall, the 2010-2011a Central Part appears to be the data set with the most reliable measurements.

Summary of work for the data sets:

- **2005-2010**
- **2005-2011a**

- These data sets were particularly difficult to correlate due to the many temporal changes between the dates, and mostly due to the sparsity of features in the topography. Some areas over the city have drastically changed (presence or absence of buildings between the dates), and the landscape presents large agricultural zones with no clear features to correlate on. Also, the areas that seem to have moved the most are covered with vegetation, which has considerably changed in 5-6 years. In many areas, the correlation produced sparse results (at best), or many outliers.

- As with the other data set several correlation scales were tested, i.e., 128x128, 64x64, and 32x32 pixel windows. The traditional 64x64 pixel correlation window scheme was selected, but with higher measurement density to densify the measurements whenever they were correct.

- Areas with too many poor correlations were manually masked to avoid impairing interpretation.

- Measurements were then locally averaged, filtered, and re-scaled for the output maps to share the same resolution as other results, i.e., a correlation measurement every 4m.

- The arrow vector field was generated by averaging the displacement measurement using 25x25 pixel (100m) and sampled at every 15 pixels (60m).

Conclusion for the 2005-2010 and 2005-2011a data sets:

- They were very challenging data set, but useful information should nevertheless be extracted from the results. In particular, consistent in both 2005-2010 and 2005-2011a results, there exists a strong strain "line" at the north-west of the large decorrelated (white) area in the center of the map. In the South and North-East of that area you will also see clear displacement trends.

- Both analysis present clear and strong motion trends in the eastern areas. These should be evidence for ground motion as well.

A word of caution:

Some jitter residuals are distinguishable, with small amplitude. However, due to the sparsity of measurements, a clear estimation of the artifacts was impossible and the correction turned out to be worse than no correction. It is therefore possible that some values may suffer from jitter residual, artificially increasing the ground displacement measured, or slightly impacting their direction.