Precise ground-based GNSS-reflectometry water level measurements using multiple low-cost antennas

Dave Purnell
Natalya Gomez
William Minarik
Gregory Langston

Earth & Planetary Sciences
Institut Spatial de McGill
McGill Space Institute
Fisheries and Oceans Canada
Pêches et Océans Canada
PORT TROIS-RIVIÈRES

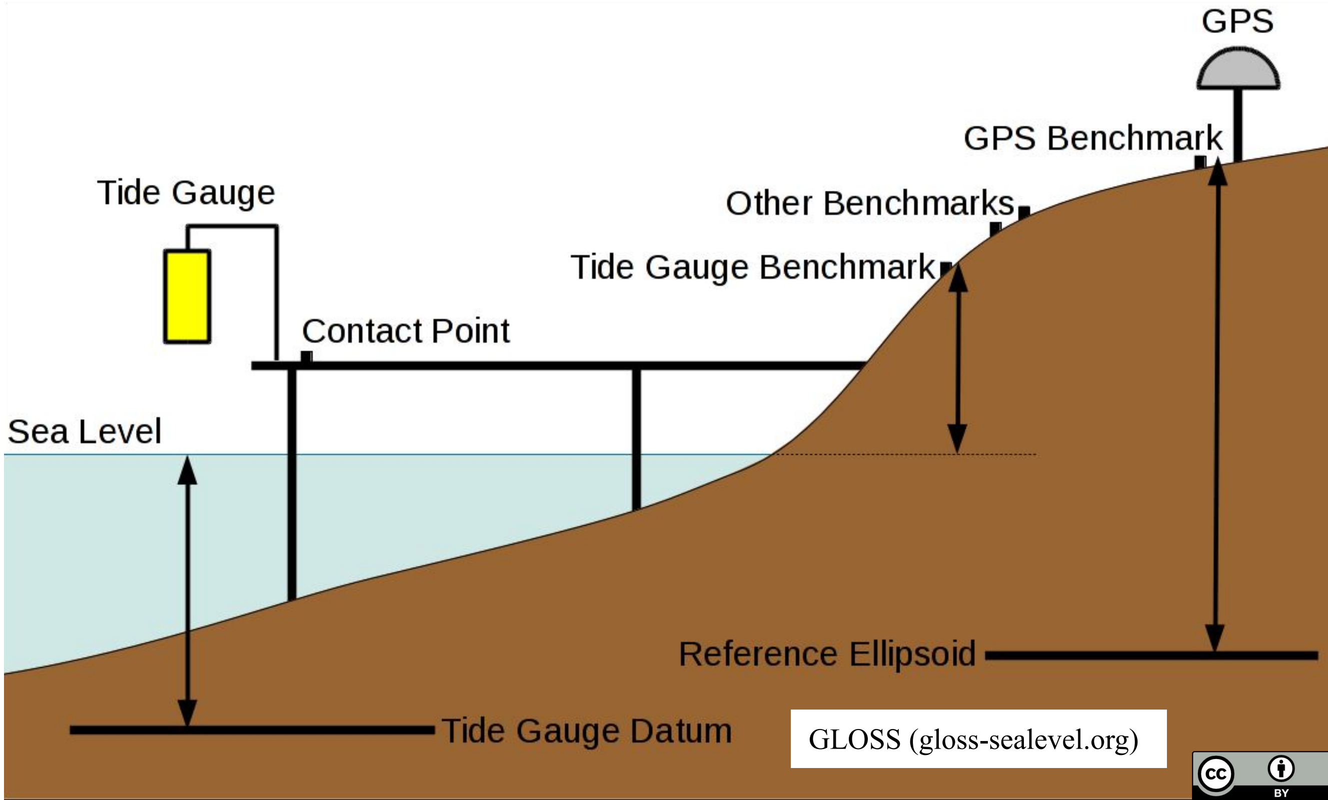
Introduction

Tide gauges have been used for centuries to study tides, survey coastlines and monitor rivers and lakes. Today there is an increased demand for water level measurements for monitoring sea level rise, the global water cycle and validating satellite measurements (e.g., GRACE, satellite altimetry).

Alaska, 1915 (NOAA photo library)

Modern water level sensors

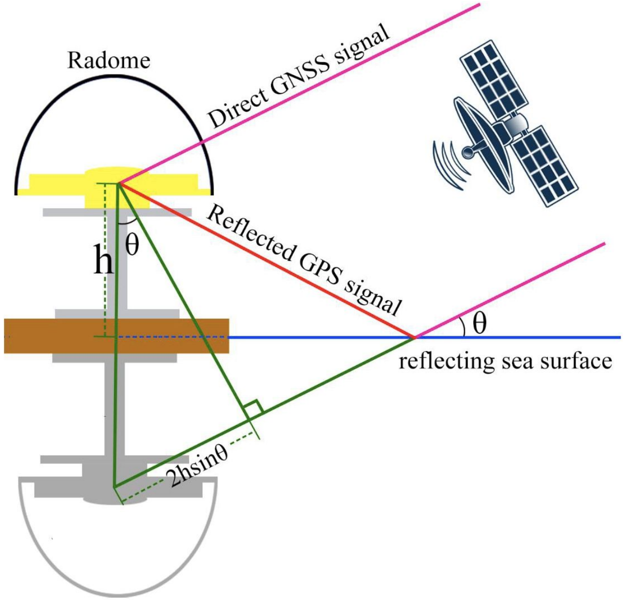
Modern water level sensors may cost several thousand dollars and are often co-located with a GNSS station to monitor land motion, which also may cost several thousand dollars. It can be expensive to install radar or acoustic sensors in remote locations because they require a structure to be built such that they hang directly over the water surface. Consequently, there are few water level sensors in remote regions.



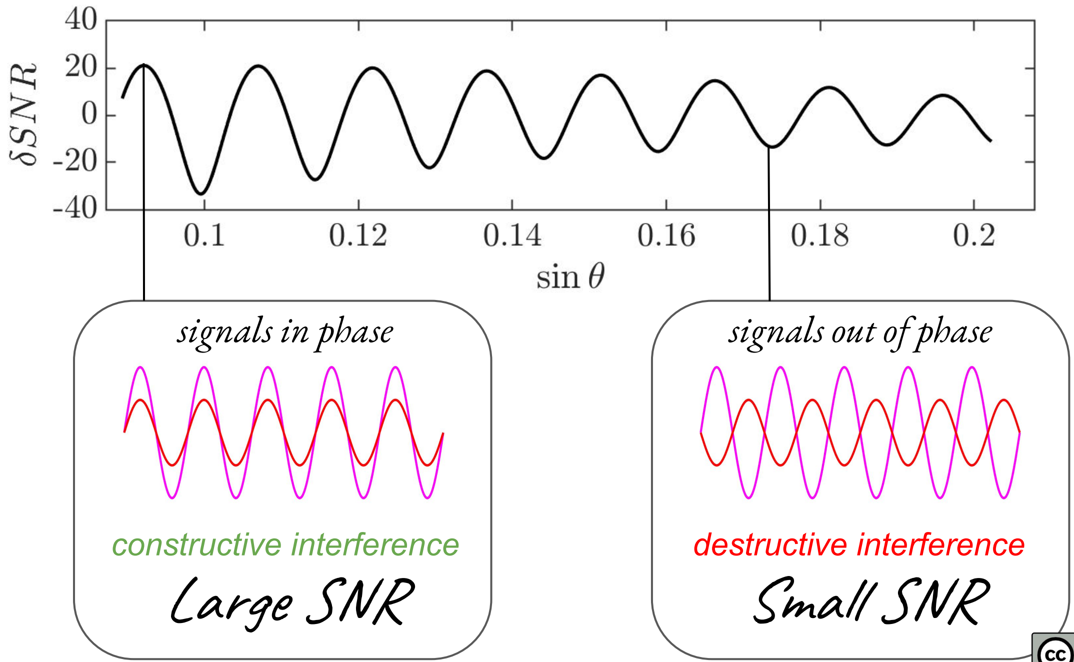
GLOSS (gloss-sealevel.org)

GNSS-R water level measurements

GNSS-Reflectometry is an alternative technique to obtain water level measurements using a coastal GNSS antenna. Microwave signals emitted from a GNSS satellite that reflect off the water surface prior to reaching the antenna interfere with the direct signal, which causes an oscillation in the signal to noise ratio (SNR) data.

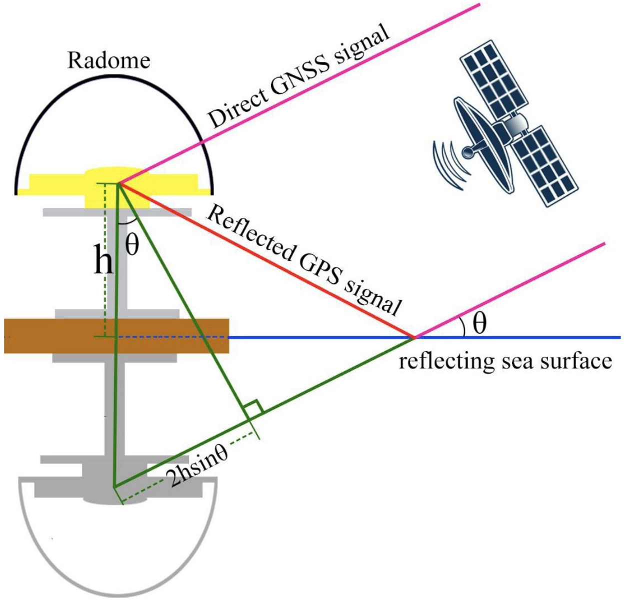


Schematic from Sun (2017)

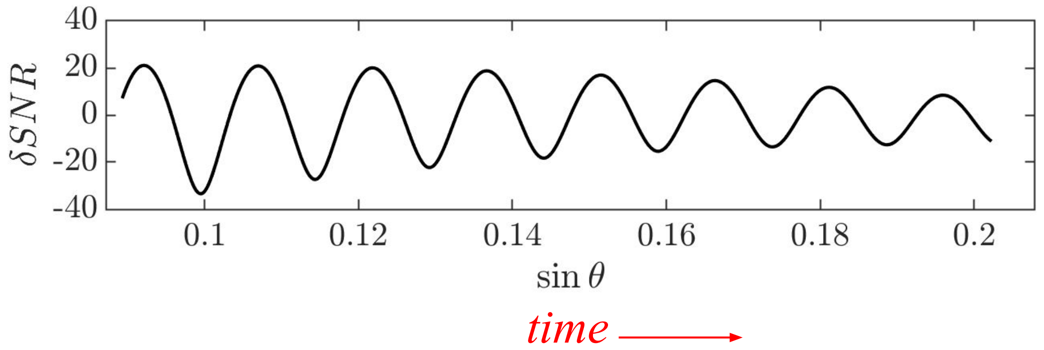


GNSS-R water level measurements

The frequency of the oscillations in the SNR data is approximately linearly related to the height difference between the antenna and the reflecting surface. Therefore, a water level time series can be obtained by performing spectral analysis on the SNR data for every time that a satellite is in the right position.



Schematic from Sun (2017)



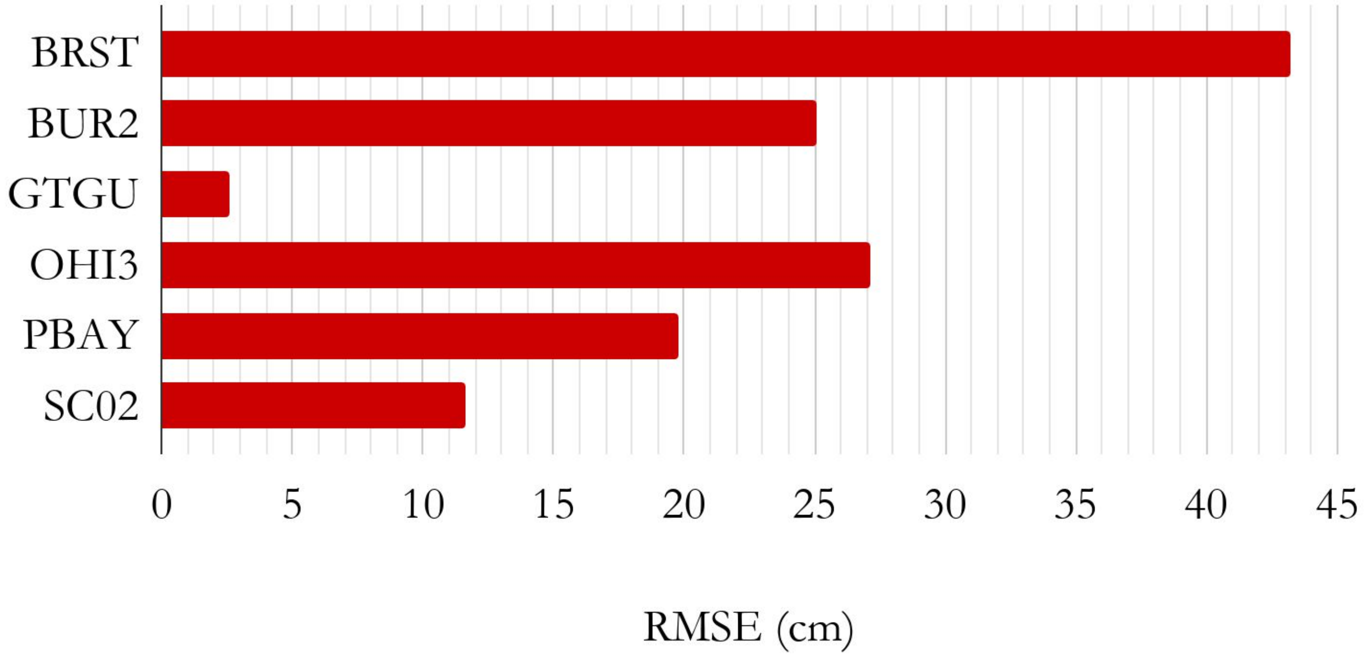
Frequency of oscillation — $f \approx \frac{2h}{\lambda}$

$2h$: Height of antenna above the water surface

λ: Wavelength of GNSS signal

Precision of GNSS-R measurements

In previous literature, authors have compared GNSS-R measurements with a colocated water level sensor and found a Root Mean Square error (RMS) between 3-45 cm.

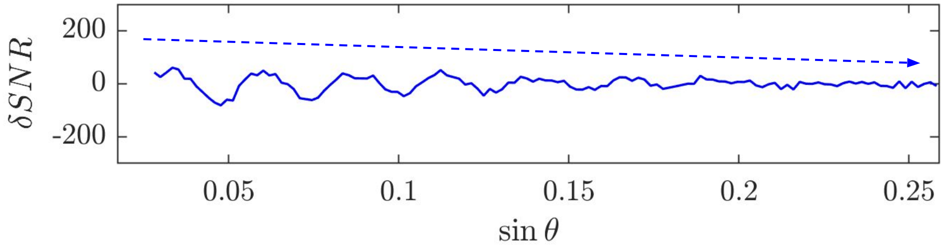


Results from previous studies:
Larson et al. (2017)
Löfgren et al. (2014)
Geremia-Nievinski et al. (2019)
Wang et al. (2017)

Low-cost vs. high-cost GNSS antennas

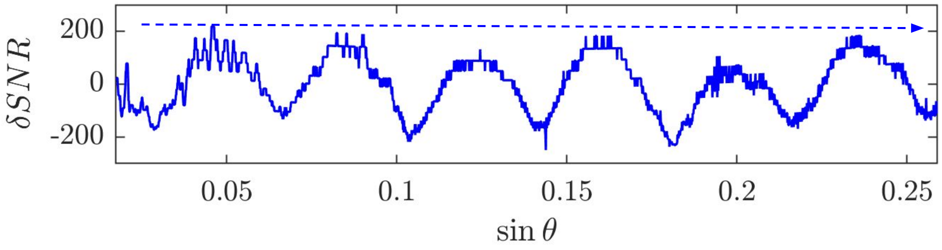
Site GTGU in Sweden

Oscillations damping with increasing elevation



Low-cost antenna

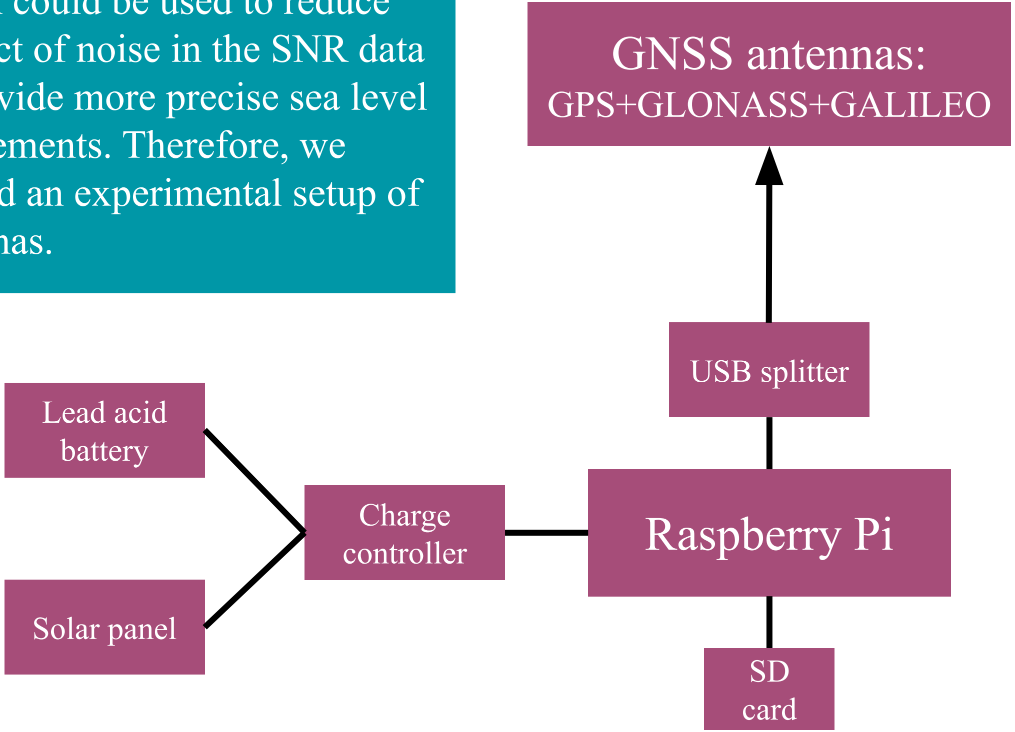
Stronger interference, no damping



Geodetic Standard GNSS antennas that have been used in previous GNSS-R literature are expensive and designed to reduce interference from reflected signals.
Whereas, low-cost antennas (commercially available online for 10 USD) are isotropic in their gain pattern and thus better suited for reflectometry, potentially providing a more accessible means to monitor water levels.

Low-cost antenna array: initial design

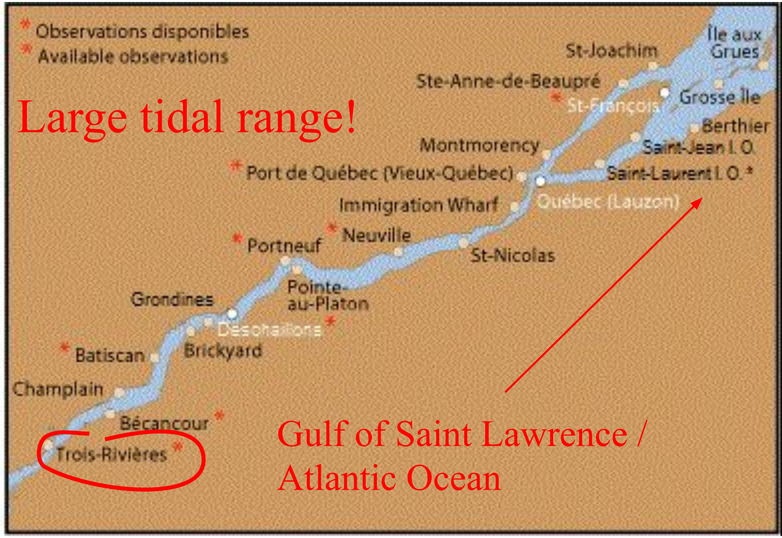
We hypothesize that data from multiple antennas in the same location could be used to reduce the effect of noise in the SNR data and provide more precise sea level measurements. Therefore, we designed an experimental setup of 4 antennas.



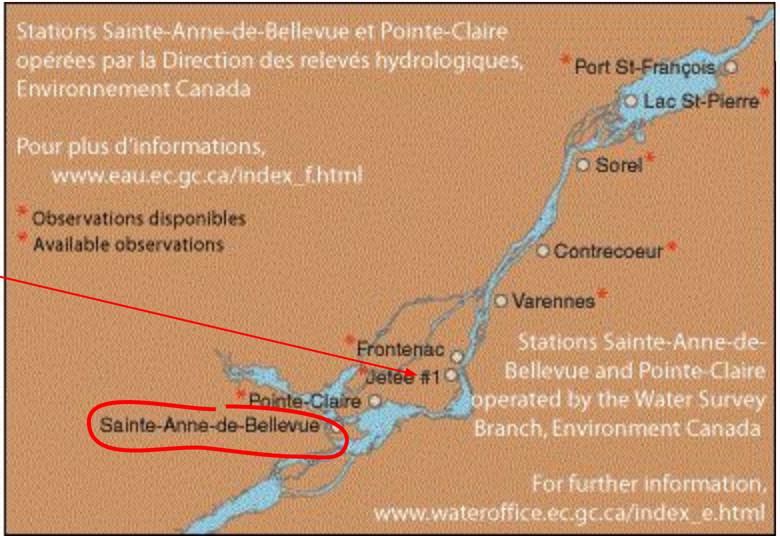
Details on how to build a low-cost sensor are currently being written up into a manuscript by W. Minarik

Initial testing

With support from Fisheries and Oceans Canada, we have installed instruments next to pre-existing water level sensors along the Saint Lawrence River in Québec, Canada. We plan to install more this year.



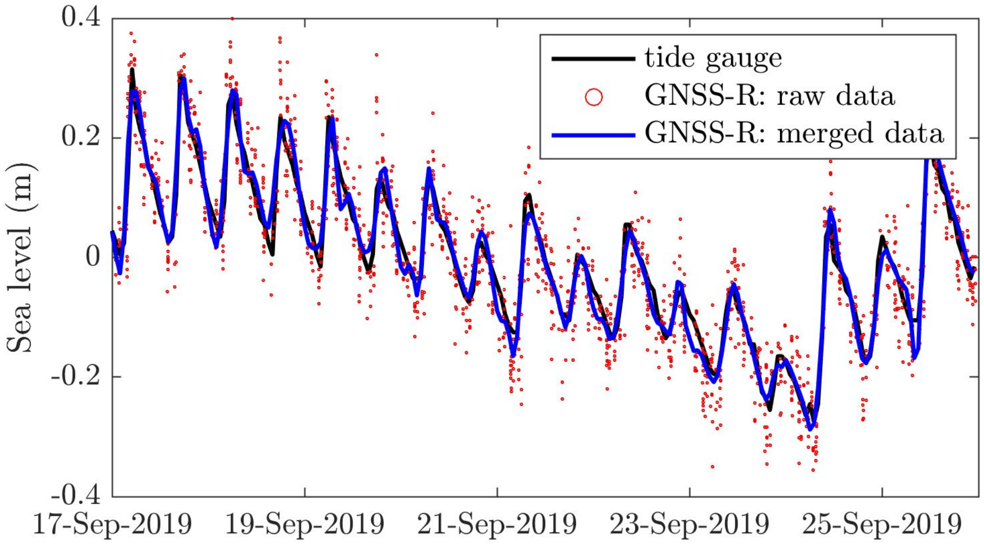
Island of Montréal (where the authors are based)



The Saint Lawrence river is an ideal testing ground for water level sensors due to variable tidal range and seasonality / ice cover.

Initial results: Trois-Rivières

We installed an array of 4 antennas in September 2019 and designed an algorithm based on inverse modelling* to retrieve a water level time series using data from multiple antennas. Comparing 10 days of GNSS-R measurements to the co-located water level sensor, we found an RMS of 4-8 cm using just 1 antenna, compared to an RMS of 2.3 cm when using all 4 antennas. However, the installation was not stable and moved with the wind.



*method adapted from Strandberg et al. (2016)

Sainte-Anne-de-Bellevue installations

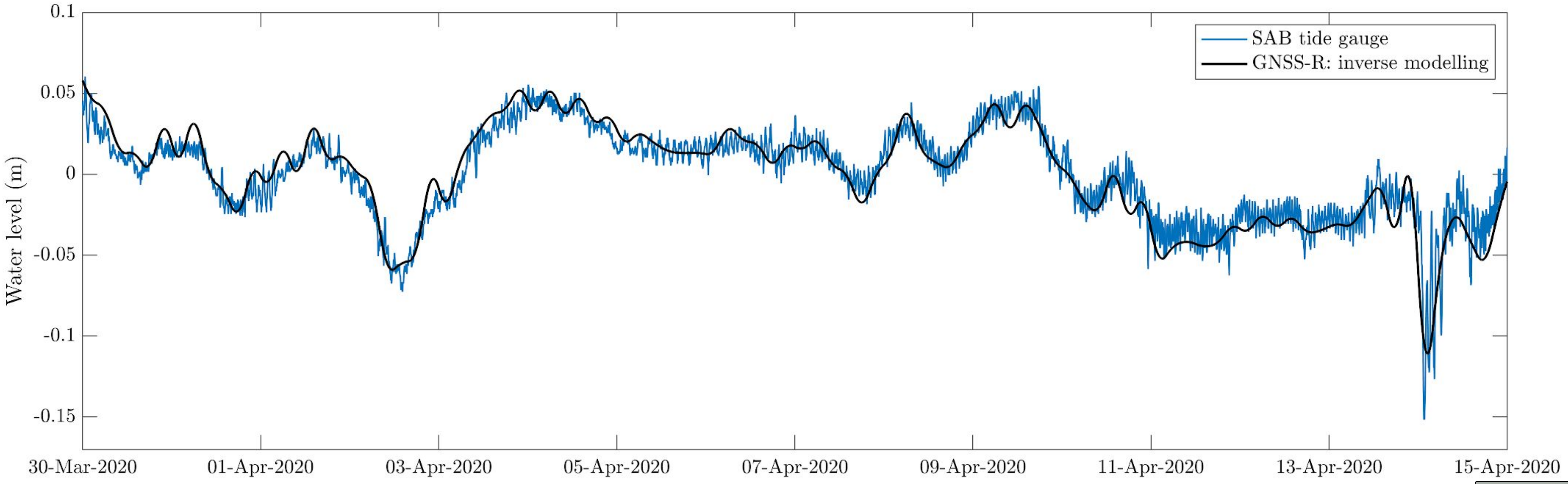
Driven by promising initial results from Trois-Rivières, we built a second array of four antennas and installed both arrays during winter at Sainte-Anne-de-Bellevue.

The key goals of this field work were:

1. To investigate how the placement of antennas affects the precision of water level measurements
2. To collect more data to improve and refine algorithms
3. To assess the ability to monitor the river whilst it is frozen during winter

Sainte-Anne-de-Bellevue: results so far

We have a continuous data set over a 3 month period that captures the annual snowmelt (Feb-Apr). When the lake at Sainte-Anne-de-Bellevue is frozen, the GNSS-R measurements capture a combination of snowfall and changes in the lake level. The data below is showing water level measurements using all four antennas for the first two week period after the lake became ice free. The RMS with a water level sensor 500 m away from our installation is 1.0 cm.



Conclusions

1. Low-cost GNSS-R antennas potentially provide a more accessible means to obtain precise water level measurements

2. Initial results show that multiple antennas in the same locations can be used to provide more precise sea level measurements

3. We found an RMS of 1 cm comparing GNSS-R measurements from 4 antennas with a water level sensor 500 m away over a two week period

4. We are currently working on manuscripts with details on how to build low-cost GNSS-R stations, algorithms for retrieving water level measurements using multiple antennas and our results so far

Contact: david.purnell@mail.mcgill.ca

References

Geremia-Nievinski, Felipe & Hobiger, T. & Haas, Rüdiger & Liu, W & Strandberg, Joakim & Tabibi, S & Vey, Sibylle & Wickert, Jens & Williams, Simon. (2019). SNR-based GNSS reflectometry for coastal sea-level altimetry – Results from the first IAG inter-comparison campaign.

Larson, Kristine & Ray, Richard & Williams, Simon. (2017). A 10-year comparison of water levels measured with a geodetic GPS receiver versus a conventional tide gauge. Journal of Atmospheric and Oceanic Technology. 34. 10.1175/JTECH-D-16-0101.1.

Löfgren, Johan & Haas, Rüdiger & Scherneck, Hans-Georg. (2014). Sea level time series and ocean tide analysis from multipath signals at five GPS sites in different parts of the world. Journal of Geodynamics. 80. 10.1016/j.jog.2014.02.012.

Strandberg, Joakim & Hobiger, Thomas & Haas, Rüdiger. (2016). Improving GNSS-R sea level determination through inverse modeling of SNR data. Radio Science. 10.1002/2016RS006057.

Sun, Jian. (2017). Ground-Based GNSS-Reflectometry Sea Level and Lake Ice Thickness Measurements. The Ohio State University. http://rave.ohiolink.edu/etdc/view?acc_num=osu1500992792329906

Wang, Xiaolei & Zhang, Qin & Zhang, Shuangcheng. (2018). Water levels measured with SNR using wavelet decomposition and Lomb–Scargle periodogram. GPS Solutions. 22. 10.1007/s10291-017-0684-8.