Local Sea Level Derived from Reflected GNSS Signals

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1. MOTIVATION

- Sea-level rise is an indicator of global climate change, e.g., through
  - *melting of large masses of ice in polar and subpolar regions,*
  - *thermal expansion of sea water,*
  - *changes in atmospheric and ocean circulation.*
- Sea-level variations have a large impact on populations in coastal regions and on island, e.g., especially during extreme weather conditions.
  - ➢ *Coastal sea level needs to be monitored.*
- Traditionally, sea level is monitored with coastal tide gauges, i.e., relative to the land where they are established, thus measurements are affected by land surface motion.
  - ➢ *To measure sea-level change due to ocean water volume and other oceanographic changes, all types of land motion need to be known.*
- Land surface motion can be monitored by Global Navigation Satellite Systems (GNSS):
  - ➢ *We develop a new concept to measure both land surface motion and coastal sea level variations:* ***the GNSS-based tide gauge*** *(GNSS-TG).*
  - ➢ *We operate the GNSS-TG prototype since 2010 at the Onsala Space Observatory (OSO), see* ***Figure 1****.*
- Our aim is to:
  - *measure absolute and relative sea-level changes,*
  - *monitor the local sea level on different time scales including in real-time,*
  - *improve regional tide models,*
  - *develop applications using reflected GNSS signals.*

__Figure 1__ – The prototype installation of the GNSS-based tide gauge at the Onsala Space Observatory on the west coast of Sweden. This installation allows to measures both coastal sea-level variations and land surface motion.

2. CONCEPT

- The GNSS-based tide gauge consists of two standard geodetic-type GNSS receivers connected to one antenna each (see **Figure 1**):
  - *one zenith-looking Right-Hand Circular Polarized (RHCP),*
  - *one nadir-looking Left-Hand Circular Polarized (LHCP).*
- The RHCP antenna receives the GNSS-signals directly, whereas the LHCP antenna receives the signals reflected off the sea surface, see **Figure 2**.
- The reflected signals experience an additional path delay.
  - ➢ *The LHCP antenna can be regarded as a virtual antenna located below the sea surface, see* ***Figure 2****.*
- When the sea level changes, the path delay of the reflected signal changes, thus the LHCP antenna will appear to change position.
- Since the height of the LHCP antenna over the sea surface is directly proportional to the sea surface height and the RHCP antenna is directly proportional to the land surface height, the installation monitors:
  - *sea surface height,*
  - *land surface motion,*
  - *sea level independent of land motion.*

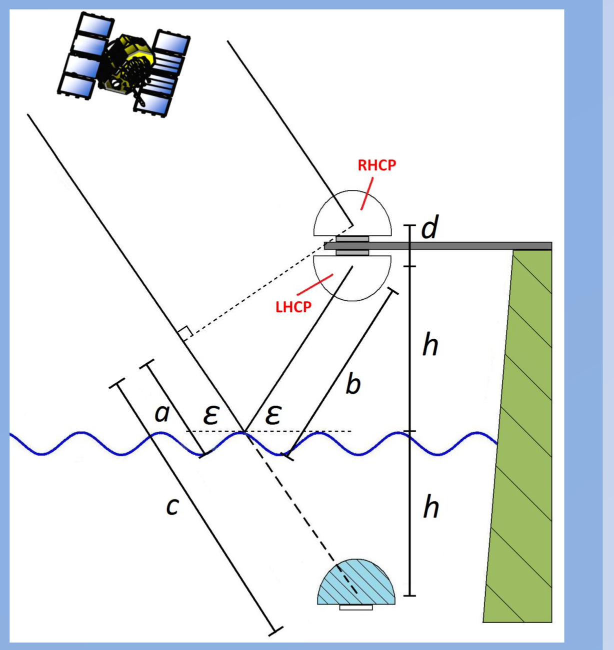

__Figure 2__ – GNSS signals are received directly, with a Right-Hand Circular Polarized (RHCP) antenna, and after reflection off the sea surface, with a Left-Hand Circular Polarized (LHCP) antenna. The reflected signals experience an additional path delay ***a+b=c****. The LHCP antenna appears as a virtual antenna below the sea surface at the same distance* ***h*** *as the actual LHCP antenna is located above the sea surface.*

SUMMARY

By receiving GNSS signals that are reflected off the sea surface, together with directly received GNSS signals (using standard geodetic-type receivers), it is possible to monitor the sea level using regular single difference geodetic processing. This is done at the Onsala Space Observatory (OSO), at the west coast of Sweden, with a GNSS-based tide gauge consisting of one zenith-looking antenna (receiving the direct signals), one nadir-looking antenna (receiving the signals that are reflected off the sea surface), and two receivers (connected to one antenna each), see ***2.CONCEPT***. The resulting sea level from the single difference processing (see ***3.DATA ANALYSIS***) is compared with independent data from two stilling well gauges about 18 km south and 33 km north of OSO.

The GNSS-derived sea-level results from our analysis of 7 months of data show a high degree of agreement with the stilling well gauge observations. The root-mean-square agreement is less than 8.7 cm and the correlation coefficients are larger than 0.90 (see ***4.RESULTS***). Furthermore, an ocean tide analysis of the GNSS-derived sea level permits detection of several major tidal components, which show good agreement with the corresponding results from one year of stilling well gauge observations.

We find that the GNSS-based tide gauge gives valuable results for sea level monitoring (see ***5.CONCLUSIONS***) and we are currently evaluating our new and improved GNSS-TG installation. Future plans are to improve the processing techniques and to include multi-GNSS observations (see ***6.OUTLOOK***).

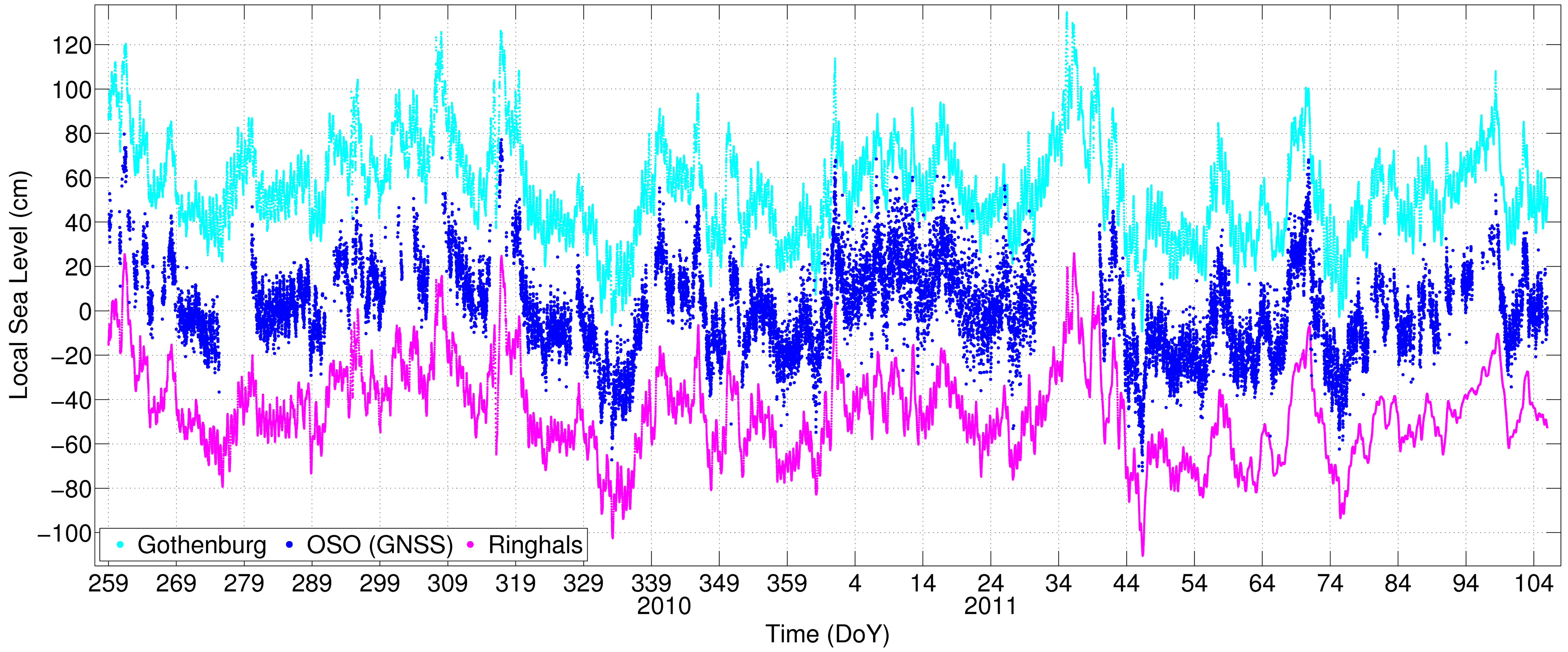

__Figure 3__ – Local sea level in cm from the GNSS-based tide gauge at the Onsala Space Observatory (OSO), centre ***blue****, the stilling well gauge at Gothenburg (approximately 33 km north of OSO), top* ***cyan****, and the stilling well gauge at Ringhals (approximately 18 km south of OSO), bottom* ***magenta****, both operated by the SMHI. To improve visibility, the Gothenburg and Ringhals sea-level observations are presented with an offset of plus and minus 50 cm, respectively. The times series span 7 months of data from September 16, 2010 to April 16, 2011.*

3. DATA ANALYSIS

- Dataset: 7 months of 1 Hz sampled GNSS data (September 16, 2010 - April 16, 2011) from both reflected and direct signals:
  - *the reflected signals have a lower signal-to-noise ratio than the direct signals,*
  - *there are less observations from the nadir-looking antenna than from the zenith-looking antenna (only open sea surface in a southward direction),*
  - *it is a kinematic situation due to a moving sea surface.*
- Processing with an in-house single difference software in MATLAB.
- Solution setup:
  - *20 minutes of data,*
  - *Global Positioning System (GPS) L_1 carrier phase delay observations,*
  - *broadcast satellite ephemerides,*
  - *application of elevation and azimuth mask,*
  - *horizontal baseline fixed to measured values (zero).*
- Least-squares solution with estimation of:
  - *vertical baseline* ***Δv*** *between the antennas (for each 20 minute interval),*
  - *phase ambiguity differences (when necessary),*
  - *receiver clock bias differences (each epoch).*
- Vertical baseline is converted to local sea level by: ***Δv=2h+d***, see **Figure 2**.

4. RESULTS

- Comparison with independent sea-level observations from two stilling well gauges operated by the Swedish Meteorological and Hydrological Institute (SMHI) at Gothenburg (*GOT*) and Ringhals (*RIN*) about 33 km north and 18 km south of OSO, respectively:
  - *show a high degree of agreement with correlation coefficients of 0.90 (OSO-RIN), 0.93 (OSO-GOT), and 0.91 (GOT-RIN) and Root-Mean-Square (RMS) differences of 8.7 cm (OSO-RIN), 7.2 cm (OSO-GOT), and 7.8 cm (GOT-RIN).*
- Gaps in the GNSS time series are attributed to power failure, the receivers' capability of keeping lock on the reflected signals in rough sea conditions, and processing restrictions.
- An ocean tide analysis of the GNSS-derived sea level determined several major tidal components significantly, e.g., M_2, O_1, and M_4.

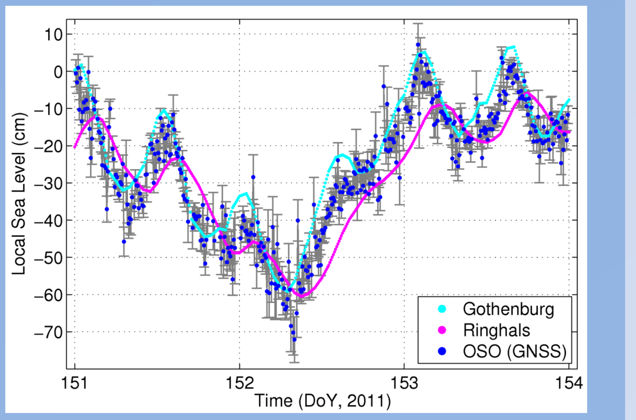

__Figure 4__ – A zoom-in to the time series in ***Figure 3****. Error bars for the GNSS solutions (10 times the formal error) are shown in* ***grey****. A mean is removed from each time series.*

- Comparisons with tidal components from one year (2010) of stilling well gauge data show good agreement in amplitude and phase, see **Figure 5**.
- The tidal components were compared to a Regional Tide Model (RTM):
  - *reasonable agreement for diurnal and semi-diurnal components,*
  - *the model shows limitations for long-period signals (not shown here).*

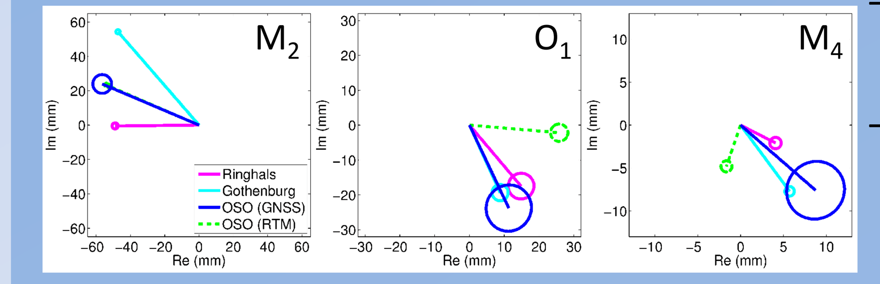

__Figure 5__ – Tidal components for M_2, O_1, and M_4 from Ringhals, ***magenta****, Gothenburg,* ***cyan****, OSO (GNSS),* ***blue****, and OSO (RTM), dotted* ***green****.*

5. CONCLUSIONS

- The GNSS-derived sea level from the Onsala Space Observatory (OSO) resembles well the independently observed sea level from the two stilling well gauges at Gothenburg (GOT) and Ringhals (RIN), 33 km north and 18 km south of OSO, respectively:
  - *the RMS agreements are 7.2 cm (OSO-GOT), 8.7 cm (OSO-RIN), and 7.8 cm (GOT-RIN),*
  - *the correlation coefficients are larger than 0.90.*
- From ocean tide analysis, several major tidal components are determined significantly and show good agreement with results derived from one year of stilling well gauge data.
- A regional tide model shows good agreement for diurnal and semi-diurnal components.

6. OUTLOOK

- We have recently completed a new and improved GNSS-TG installation at OSO. The improvements are:
  - *a larger open water surface resulting in more observations,*
  - *possibility of controlled antenna height changes in steps of 25 cm (range of 2-4 m),*
  - *independent sea-level measurements from a co-located pressure sensor gauge.*
- For the future, we are improving the data processing scheme by:
  - *implementing double difference processing,*
  - *better handling of phase centre variations, cycle slips, and phase ambiguities,*
  - *inclusion of multi-GNSS observations, e.g., GLONASS, Galileo, and COMPASS.*

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FOR ADDITIONAL INFORMATION SEE:

- ➢ ***Löfgren J.S., Haas R., Scherneck H.-G., Bos M.S. (2011) Three months of local sea level derived from reflected GNSS signals, Radio Sci., 46, RS0C05, doi:10.1029/ 2011RS004693.***
- ➢ ***Löfgren J.S., Haas R., Johansson J.M. (2011) Monitoring coastal sea level using reflected GNSS signals, J. Adv. Space Res., 47 (2), 213-220, doi:10.1016/ j.asr.2010.08.015.***
- ➢ ***Löfgren J.S., Haas R., Johansson J.M. (2010) High-rate local sea level monitoring with a GNSS-based tide gauge, Proceedings of the 2010 IEEE International Geoscience and Remote Sensing Symposium 2010, 3616-3619, ISBN/ISSN: 978-1-4244-9566-5.***