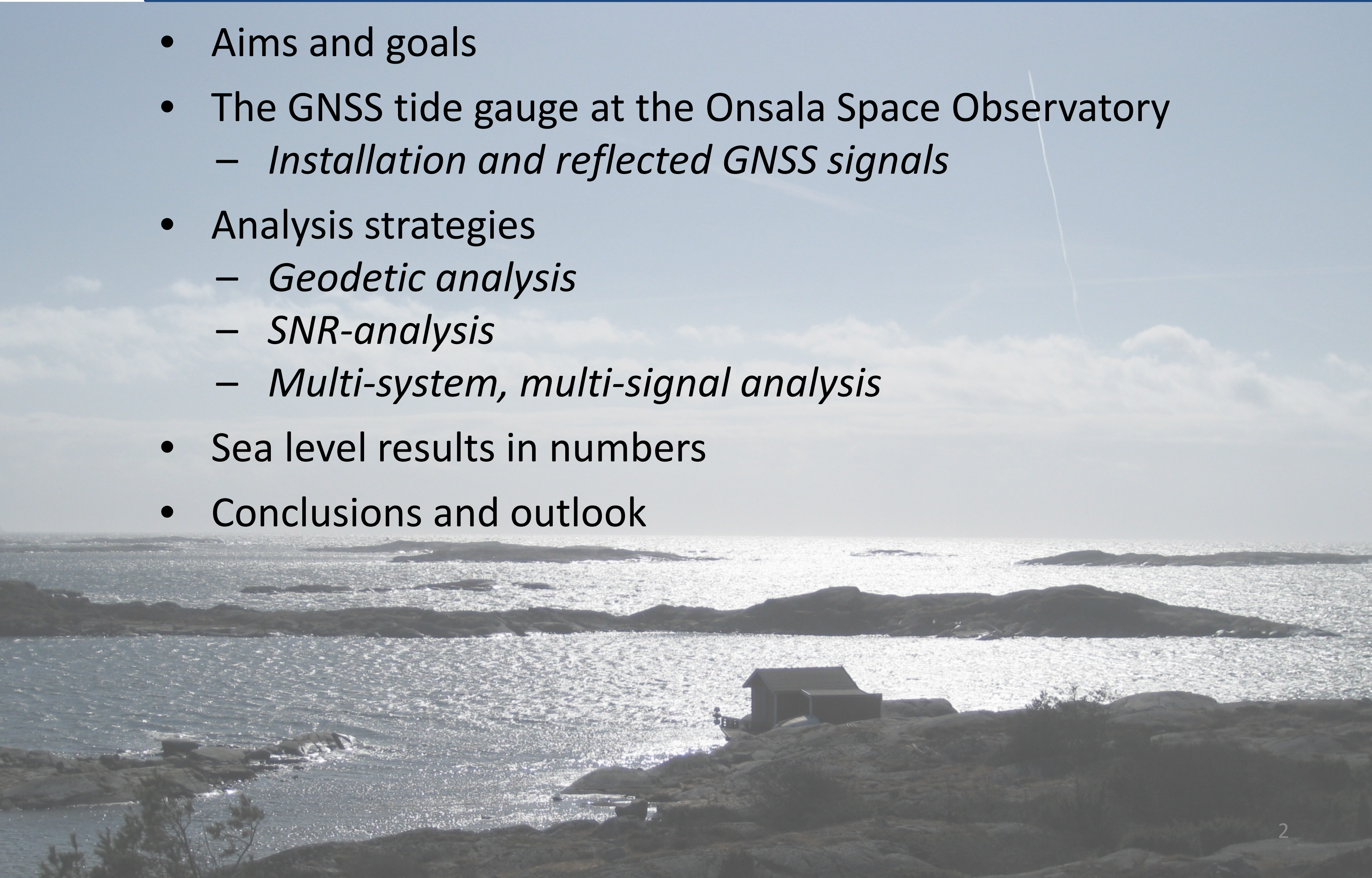
Sea level observations using multi-system GNSS reflectometry

Johan S. Löfgren, *Rüdiger Haas*

Chalmers University of Technology
Department of Earth and Space Sciences,
Onsala Space Observatory, SE-439 42 Onsala, Sweden

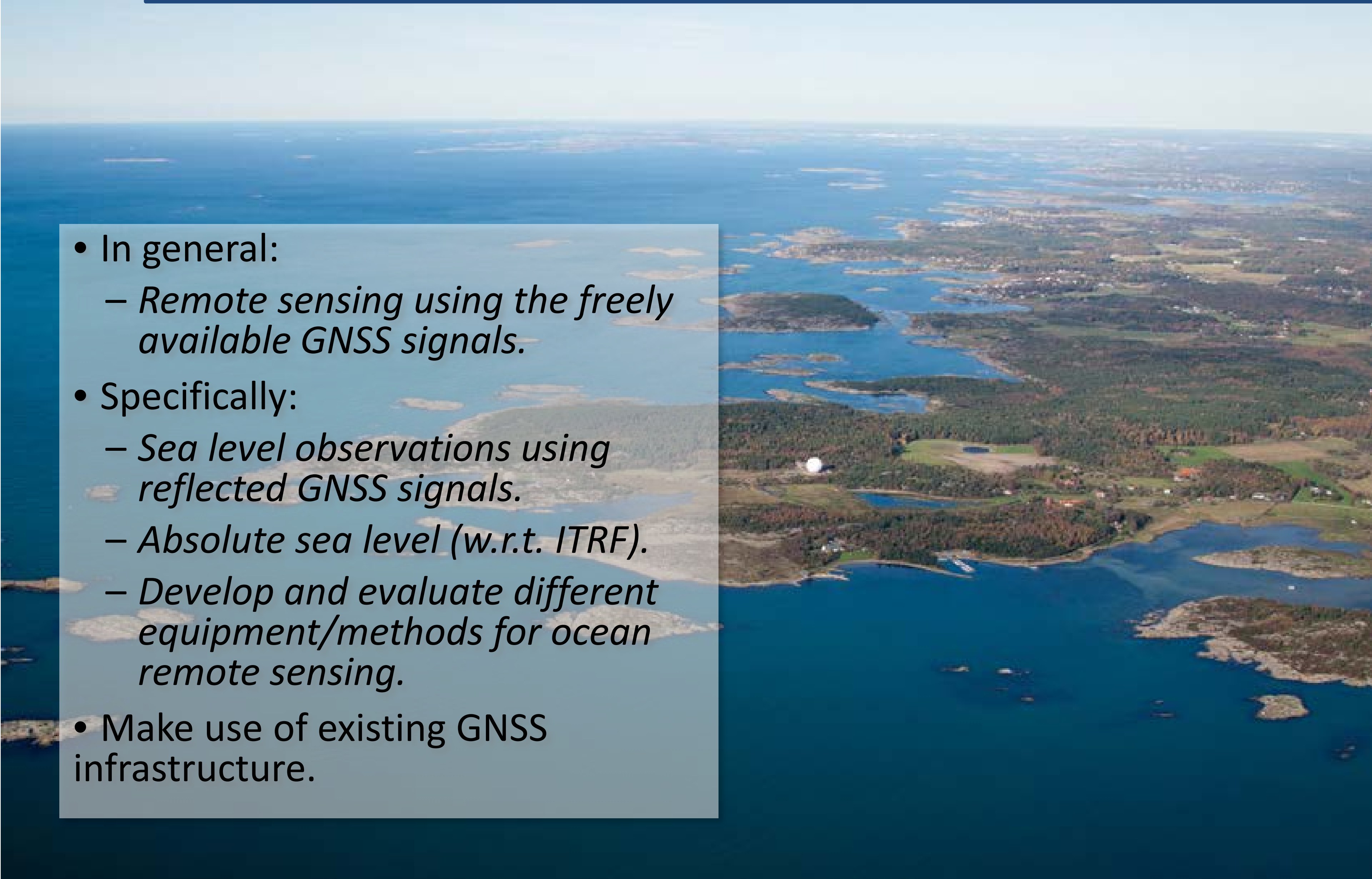
Nordic Geodetic Commission General Assembly, September 1-4 , 2014, Göteborg, Sweden

Outline



- Aims and goals
- The GNSS tide gauge at the Onsala Space Observatory
  - *Installation and reflected GNSS signals*
- Analysis strategies
  - *Geodetic analysis*
  - *SNR-analysis*
  - *Multi-system, multi-signal analysis*
- Sea level results in numbers
- Conclusions and outlook

Aims and goals



- In general:
  - – *Remote sensing using the freely available GNSS signals.*
- Specifically:
  - – *Sea level observations using reflected GNSS signals.*
  - – *Absolute sea level (w.r.t. ITRF).*
  - – *Develop and evaluate different equipment/methods for ocean remote sensing.*
- Make use of existing GNSS infrastructure.

The GNSS tide gauge at Onsala

*Aerial photograph of the Onsala Space Observatory (Chalmers, Onsala rymdobservatorium/ Västkustflyg), the GNSS tide gauge installation (**blue**), and the location of the new radar tide gauge (**red**).*

The GNSS tide gauge at Onsala

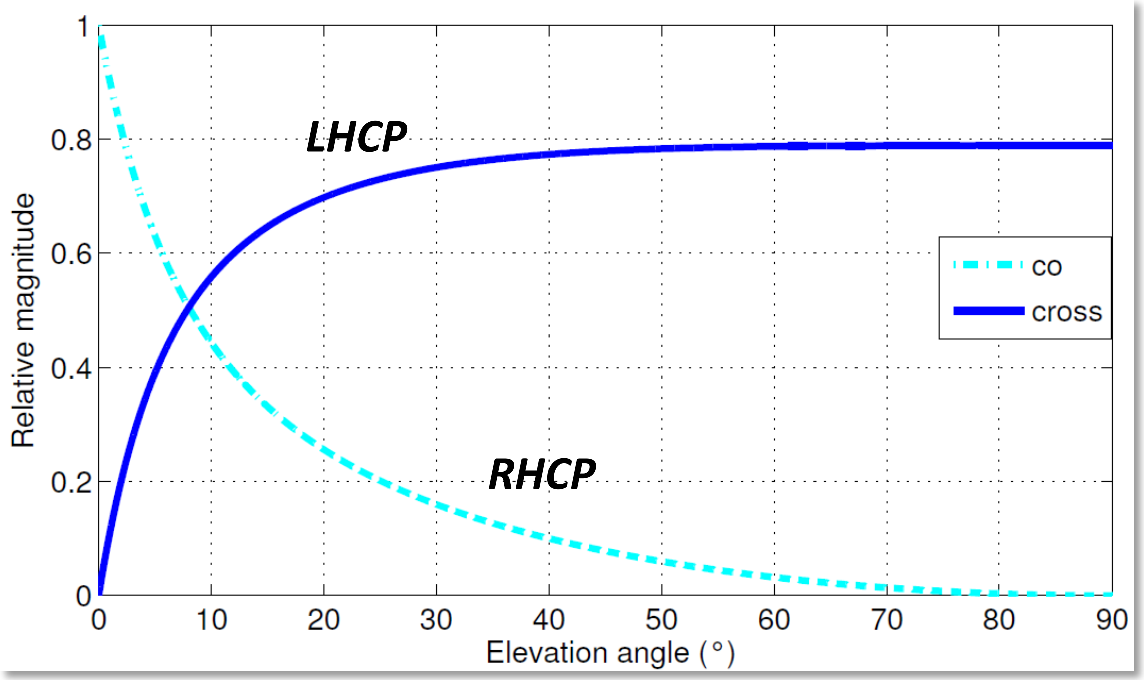
- Two commercial geodetic GNSS antennas:
  - *1 up-looking RHCP.*
  - *1 down-looking LHCP.*
- Mounted, toward the open sea in the south, on a bar extending over the coastline.
  - *Possible to move the bar in 25 cm steps (2-4 m).*
- Each antenna is connected to a commercial geodetic GNSS receiver.
  - *Up to 20 Hz sampling.*
  - *Recording pseudorange, phase, SNR.*
- Co-located with a pressure sensor, pneumatic bubbler, and a radar tide gauge and with SMHI stilling well gauges in 18 and 33 km distance.

- Different analysis strategies:
  - *Geodetic analysis (2 antennas).*
  - *SNR-analysis (1 antenna).*

RHCP – Right Hand Circular Polarization, LHCP – Left Hand Circular Polarization, SNR – Signal-to-Noise Ratio, SMHI – Swedish Meteorological and Hydrological Institute

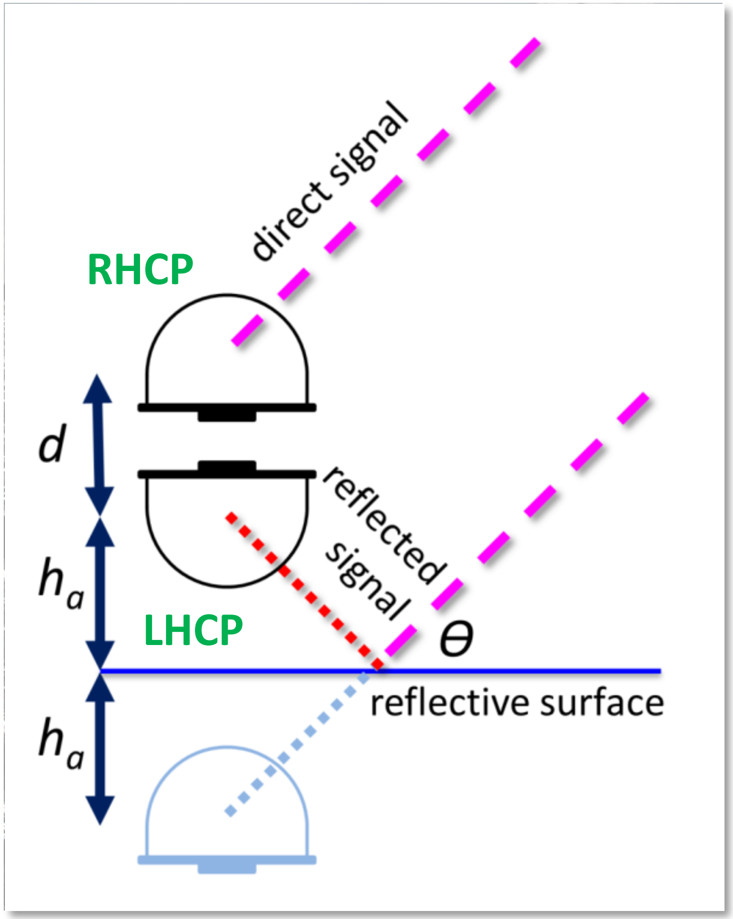
Reflected GNSS Signals

- What happens with the signal polarization after reflection?
- This can be investigated through the Fresnel reflection coefficients:
  - *Dependent on: dielectric constant and conductivity of the medium, wavelength and satellite elevation angle.*
- The GNSS signals are RHCP.
- After reflection, the polarization changes (for most of the reflected signals) to dominantly Left-Hand Circular Polarization.
- The effect on the measurements is also dependent on the antenna gain pattern.



*Magnitude of the circular reflection coefficients for reflection off the sea surface for observations from different elevation angles. If the transmitted signal is RHCP, the co-polarized component (**cyan** dashed line) can be seen as RHCP and the cross-polarized component (**blue** line) can be seen as LHCP.*

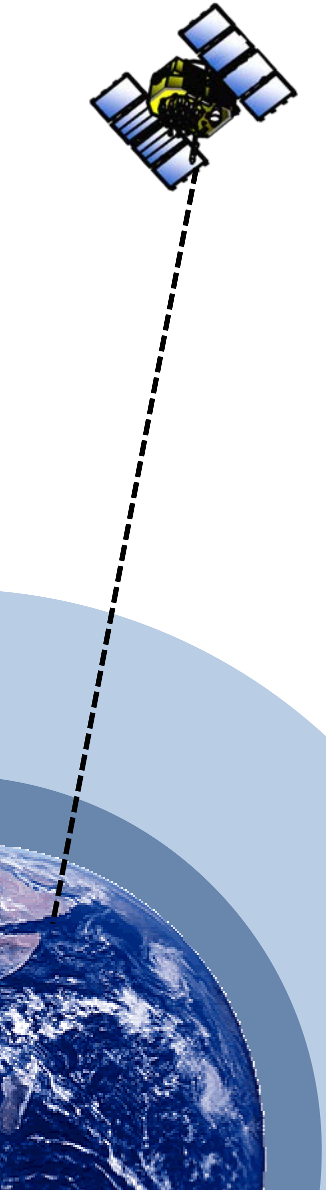
Geodetic analysis

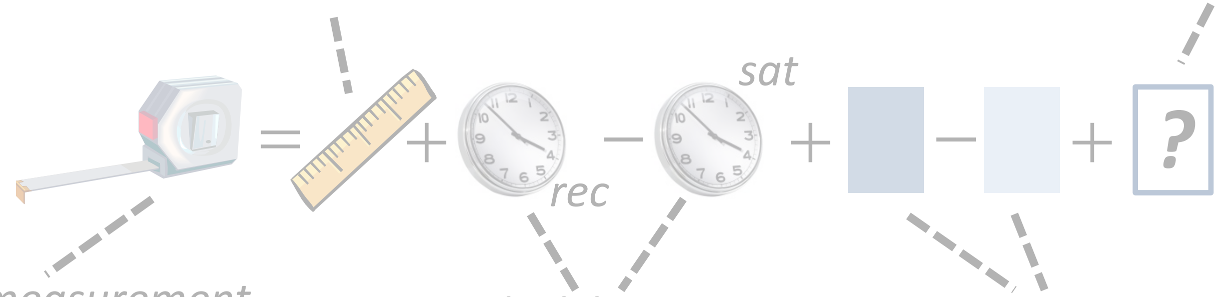


Schematic drawing of the set up for the geodetic analysis method.

- 2 antennas (RHCP/LHCP) & 2 receivers.
- The reflected signal experience an additional path delay, which changes with changing sea surface.
  - *The LHCP antenna appears to be a virtual antenna below the sea surface.*
  - *The vertical distance between the antennas is proportional to the sea level.*
- Standard geodetic phase analysis (position of the antennas).
- Observations from higher elevations 15^{o}-90^{o} are considered.

Geodetic analysis: model





Geometrical distance

Phase ambiguity

sat

rec

Phase measurement

Clock biases

Atmosphere

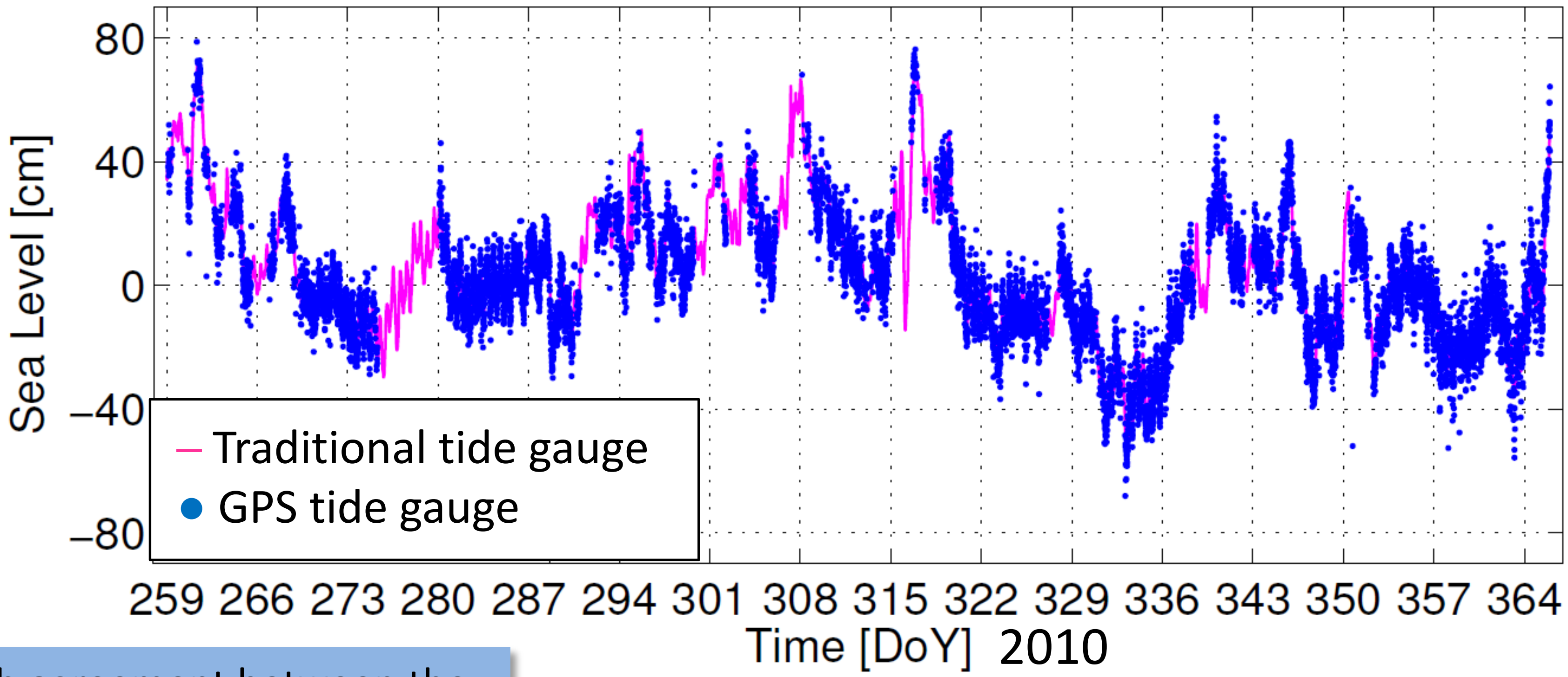
$$\lambda\Phi = \rho + c\left(t_{rec} - t^{sat}\right) + Z - I + \lambda N$$

- Combining observations from both antennas:
  - *Single differences (or double differences).*

$$\lambda\Delta\Phi = \boxed{\Delta\rho} + c\,\Delta t_{rec} + \lambda\Delta N$$

- Solving for the baseline between the 2 antennas:
  - *~~North~~, ~~east~~, and vertical.*

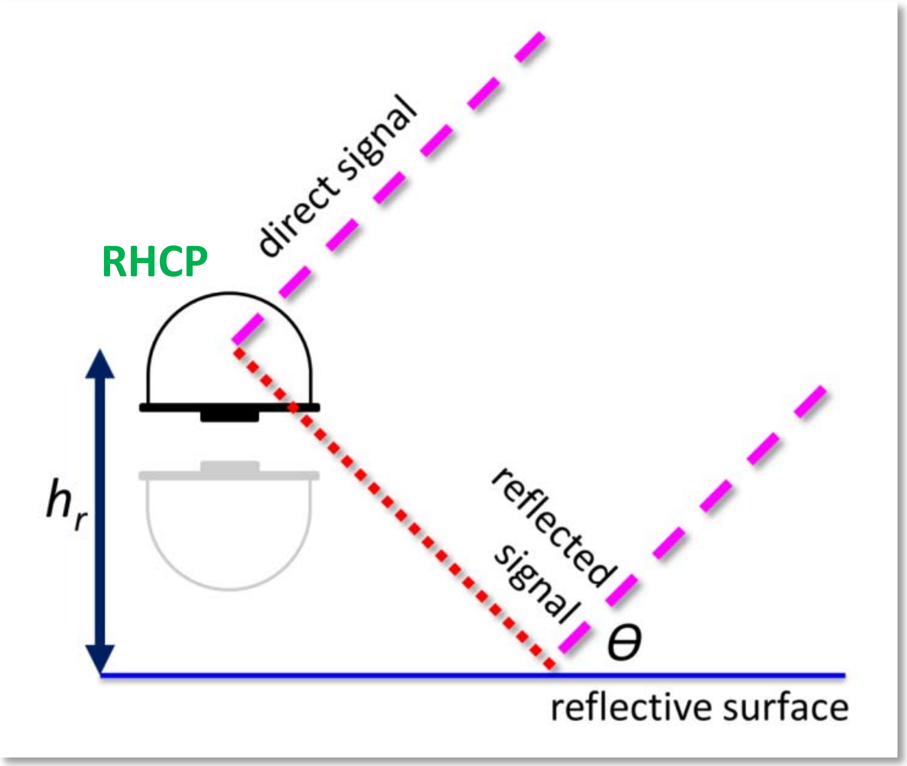
Geodetic analysis: results from Onsala



- High agreement between the GPS-derived sea level and the tide gauge sea level.
  - *Tidal range: 1.2 m*
  - *Correlation coeff. 0.95.*
  - Standard dev. 5.0 cm.

Sea level from the GNSS tide gauge at the Onsala Space Observatory and from a weighted average of the sea level from the SMHI stilling well gauges in Ringhals and Göteborg (18 km south of and 33 km north of Onsala, respectively). A mean is removed from each time series.

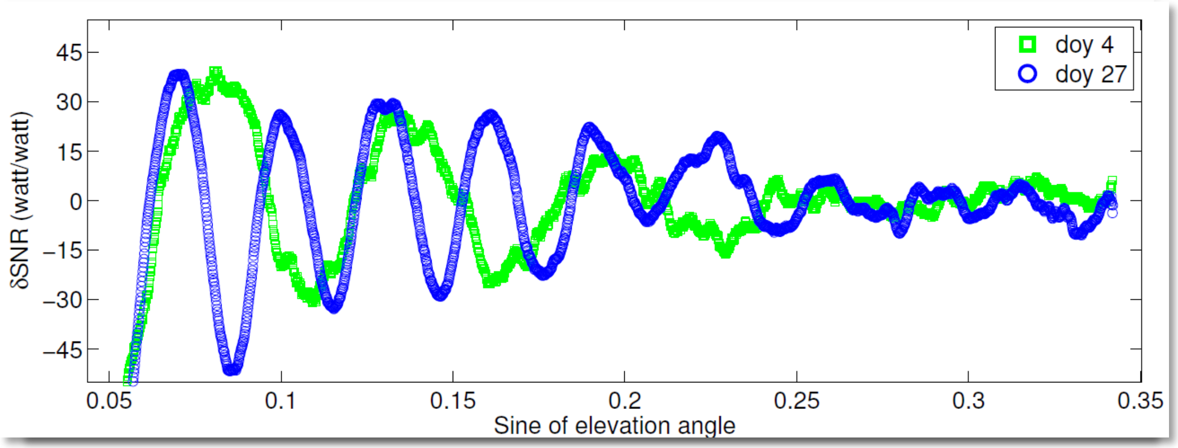
SNR-analysis



Schematic drawing of the set up for the SNR-analysis method.

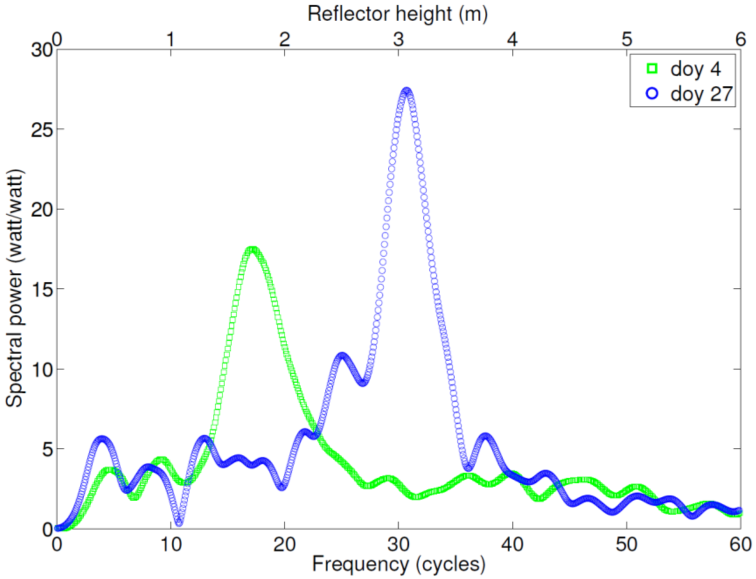
- 1 antenna (RHCP) & 1 receiver.
- The reflected signals (multipath) interfere with the direct signals, causing oscillations in the Signal-to-Noise Ratio (SNR) data.
  - *From the SNR oscillations it is possible to determine the sea level.*
- Standard SNR reflector height analysis.
- Observations from low elevations 0^o-40^o are considered.

SNR-analysis: model



δSNR, i.e., isolation of the SNR oscillations, as a function of sine of satellite elevation angle for a satellite at 2 different days.

- Assuming a non-moving horizontal reflector, the frequency of the oscillations is constant as a function of sine of elevation.
- This frequency is proportional to the reflector height:
  - *The vertical distance between the antenna phase center and the reflecting surface.*
- The reflector height can be determined by spectral analysis.
  - *And is directly proportional to the sea surface height.*

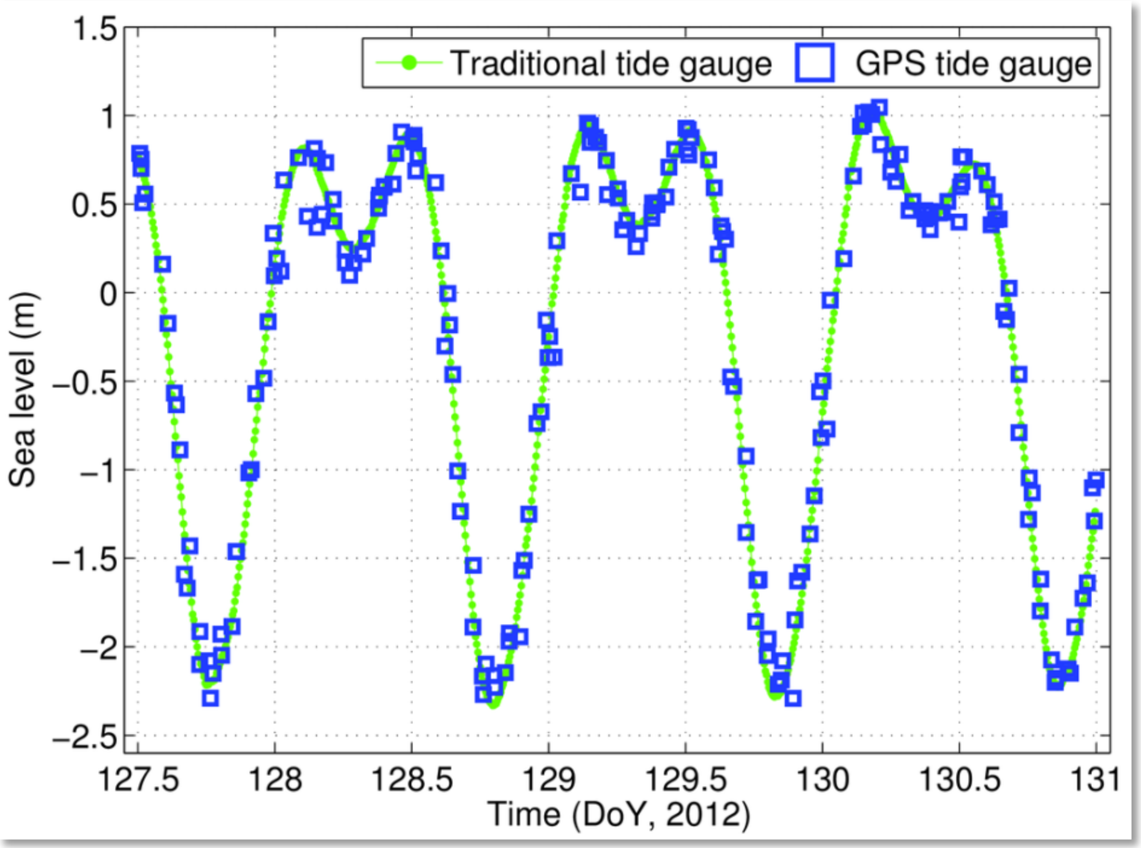


Results from spectral analysis of the δSNR data as a function of frequency and reflector height.

- Using the SNR data from a GNSS station, it is possible to remotely sense:
  - *Sea level height, snow height, soil moisture, vegetation, volcanic ash clouds etc.*
- Record and store SNR data from your GNSS stations!

SNR-analysis: results from SC02

The UNAVCO permanent GNSS station SC02 in Friday Harbor, USA, located close to the ocean.



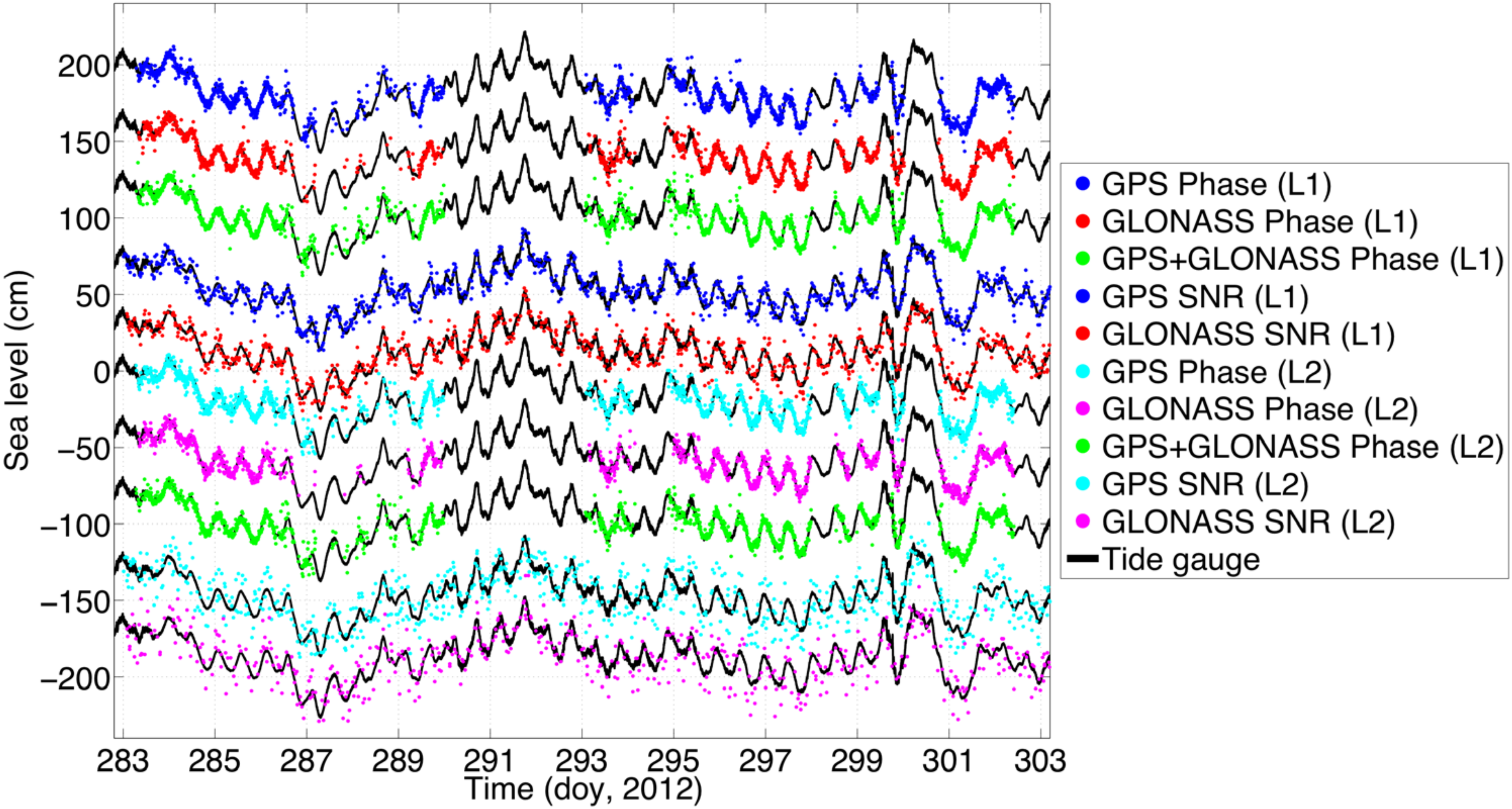
Three days of sea level results from SC02 in Friday Harbor, USA. The GNSS installation is co-located with the traditional tide gauge.

- High agreement between the GPS-derived sea level and the tide gauge sea level.
  - *Tidal range: 4 m*
  - *Correlation coeff. 0.99.*
  - Standard dev. 9.7 cm.

Multi-system, multi-signal analysis

- Multi-system: **GPS** & **GLONASS**.
- Multi-signal: **L1** & **L2** (not L2C).
- 10 different GNSS solutions
  - *4 **SNR-analysis** solutions:*
    ①SNR GPS (L1), ②SNR GPS (L2),
    ③SNR GLONASS (L1), ④SNR GLONASS (L2)
  - *4 **geodetic analysis** solutions:*
    ⑤Phase GPS (L1), ⑥Phase GPS (L2),
    ⑦Phase GLONASS (L1), ⑧Phase GLONASS (L2)
  - *2 **geodetic analysis combined** solutions*
    ⑨Phase GPS+GLONASS (L1),
    ⑩Phase GPS+GLONASS (L2)
- Comparison to an independent tide gauge, pressure sensor, co-located with the GNSS tide gauge.
  - *Example from one month of data (September 2012).*

GNSS multi-signal analysis: results



One month of sea level results from the GNSS tide gauge at the Onsala Space Observatory. The GNSS installation is co-located with the traditional tide gauge. A bias is added to each time series.

GNSS multi-signal analysis: statistics

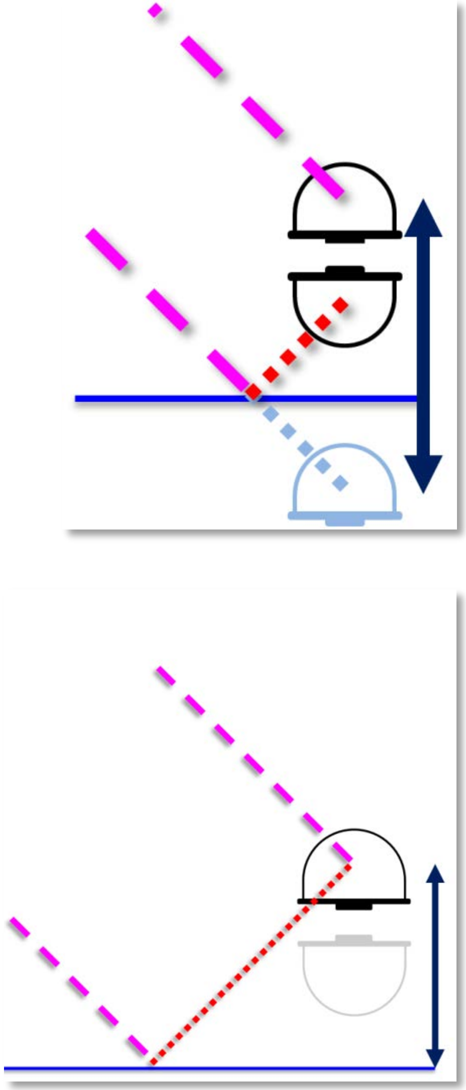
		GPS		**GLONASS**		**GPS+GLONASS**	
		L1	*L2*	*L1*	*L2*	*L1*	*L2*
SNR-analysis [a]	*Solutions (#)*	1516	1229	1254	882		
	Corr. coeff.	0.97	0.86	0.96	0.87		
	STD (cm)	4.0	8.9	4.7	8.9		
Geodetic analysis [b]	*Solutions (#)*	1534	1495	1408	1286	1581	1484
	Corr. coeff.	0.95	0.95	0.96	0.96	0.95	0.96
	STD (cm)	3.5	3.5	3.3	3.2	3.7	3.4

(a) About 49/40 (GPS, L1/L2) and 40/28 (GLONASS, L1/L2) SNR solutions per day.

(b) Phase solutions with 10 min temporal resolution. Fails for wind > 8 m/s.

Conclusions

- The GNSS tide gauge at the Onsala Space Observatory performs well with various analysis strategies:
  - *SNR-analysis (1 antenna, up).*
  - *Geodetic analysis (2 antennas, up/down).*
- Good agreement to sea level from co-located independent tide gauges using *GPS or GLONASS (L1 or L2) and using GPS+GLONASS (L1 or L2).*
- Results from **geodetic analysis**:
  - *High correlation: > 0.95*
  - *Standard dev. on the order of 3.5 cm (L1 & L2).*
- Results from **SNR-analysis**:
  - *High correlation: > 0.96 (L1).*
  - *Standard dev. order of 4.5 cm (L1).*

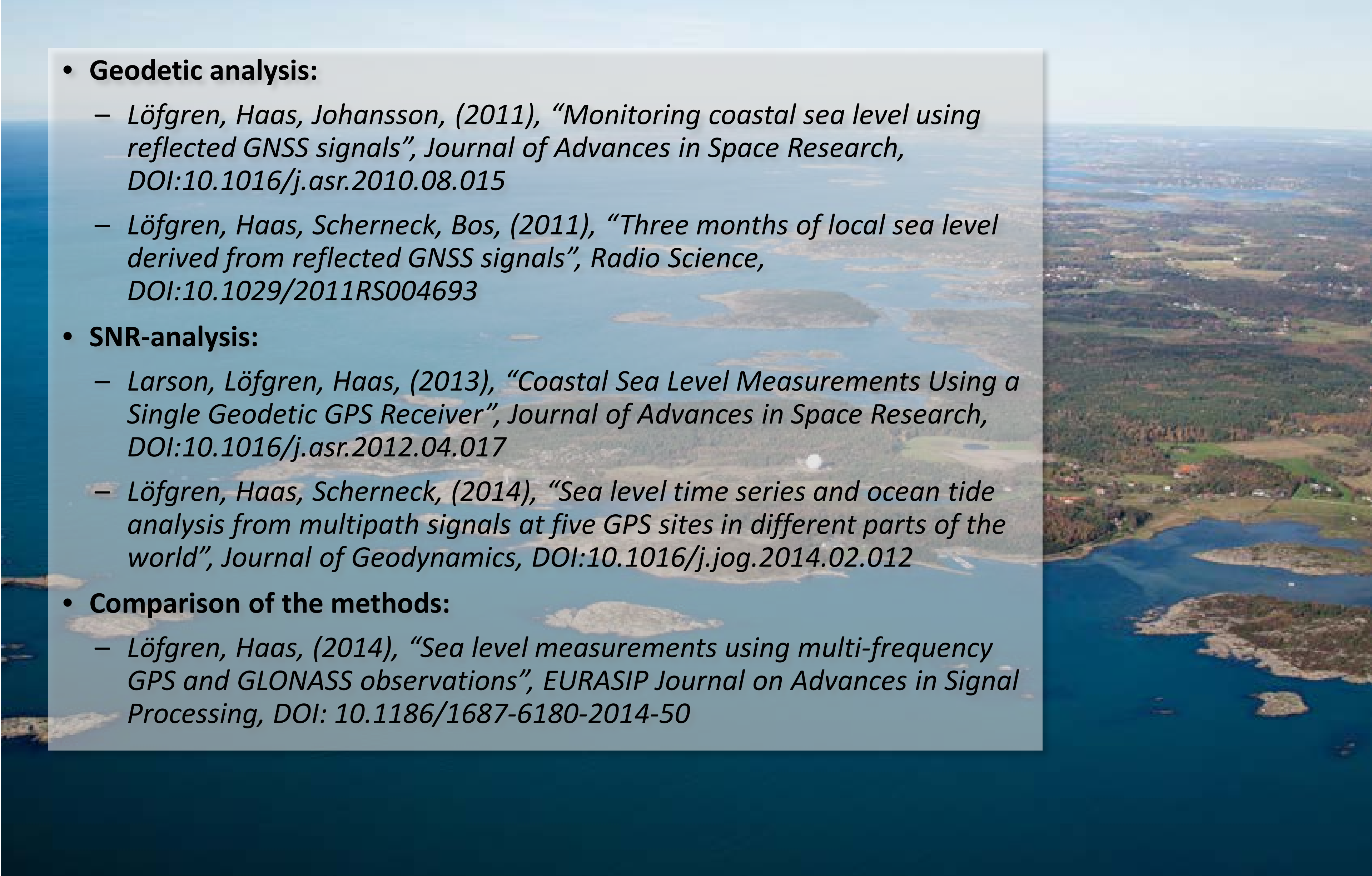


Outlook

- Improving the analysis methods:
  - *Develop the combined phase analysis.*
  - *Real-time SNR- and geodetic analysis.*
  - *Including more GNSS signals (Galileo, Beidou).*
- Absolute comparison between the SNR- and the geodetic analysis results and with the co-located tide gauge.
- Comparison with other GNSS-R systems:
  - *GPS-R system (developed by GFZ).*
  - *GLONASS-R system (developed by Thomas Hobiger).*
- Further comparison and evaluation of the GNSS tide gauges at Onsala with the new co-located radar tide gauge (in collaboration with SMHI).

GFZ – German Research Centre for Geosciences

Thank you for listening!



- **Geodetic analysis:**
  - *Löfgren, Haas, Johansson, (2011), "Monitoring coastal sea level using reflected GNSS signals", Journal of Advances in Space Research, DOI:10.1016/j.asr.2010.08.015*
  - *Löfgren, Haas, Scherneck, Bos, (2011), "Three months of local sea level derived from reflected GNSS signals", Radio Science, DOI:10.1029/2011RS004693*
- **SNR-analysis:**
  - *Larson, Löfgren, Haas, (2013), "Coastal Sea Level Measurements Using a Single Geodetic GPS Receiver", Journal of Advances in Space Research, DOI:10.1016/j.asr.2012.04.017*
  - *Löfgren, Haas, Scherneck, (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, DOI:10.1016/j.jog.2014.02.012*
- **Comparison of the methods:**
  - *Löfgren, Haas, (2014), "Sea level measurements using multi-frequency GPS and GLONASS observations", EURASIP Journal on Advances in Signal Processing, DOI: 10.1186/1687-6180-2014-50*