Snow Water Equivalent Estimation Using GPS Refractometry

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Method

Study Site

Results

Conclusions

Motivation

- Stored water in snow cover (snow water equivalent) → Flood risk in spring
- Possible to estimate SWE above a buried GPS antenna in snow?

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This work refers mostly to the following publications, which might be used for further reading:

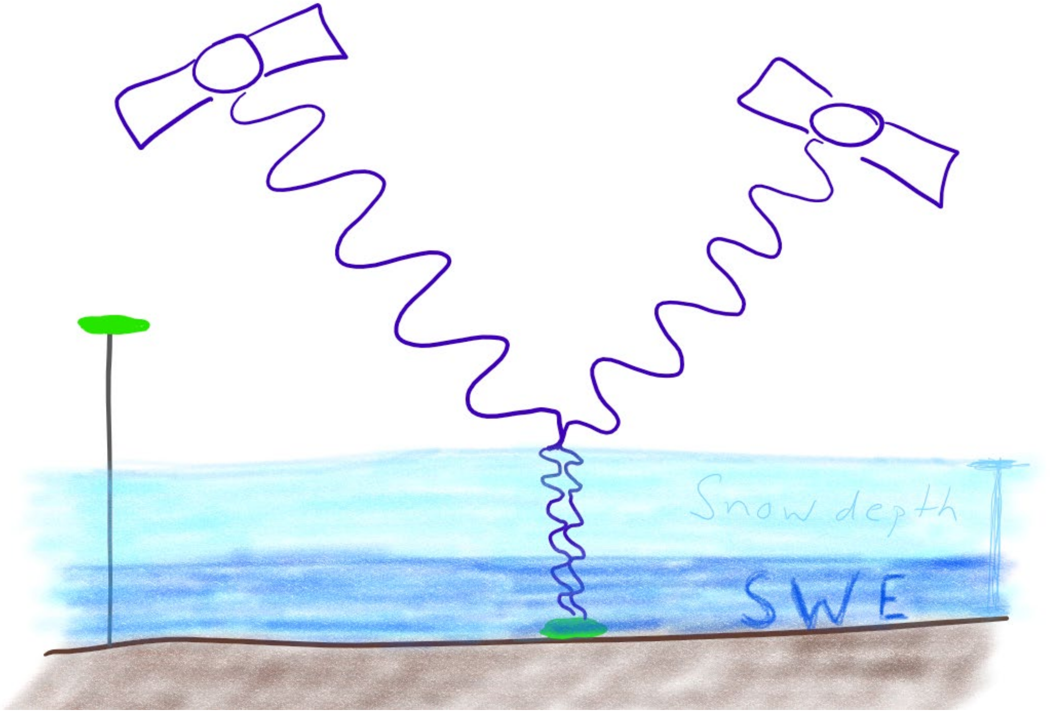
- Steiner, L., M. Meindl, and A. Geiger (2018), Characteristics and Limitations of GPS L1 Observations from Submerged Antennas, Journal of Geodesy.

- Steiner, L., M. Meindl, C. Fierz, and A. Geiger (2018), An assessment of Sub-Snow GPS for Quantification of Snow Water Equivalent, The Cryosphere, vol. 12, pp. 3161 - 3175.

- Steiner, L., M. Meindl, C. Fierz, C. Marty, and A. Geiger, Monitoring Snow Water Equivalent Using Low-Cost GPS Antennas Buried Underneath a Snowpack, Proceedings of the 13th European Conference on Antennas and Propagation, Krakow, Poland, April 2019, in review.

- Steiner, L., W. Li, Y. Zhu, M. Meindl, D. Yang, and A. Geiger, Snow Depth and Snow Water Equivalent Monitoring by Using Reflected and Refracted GPS Signals, Journal of Remote Sensing, 2019, in review.

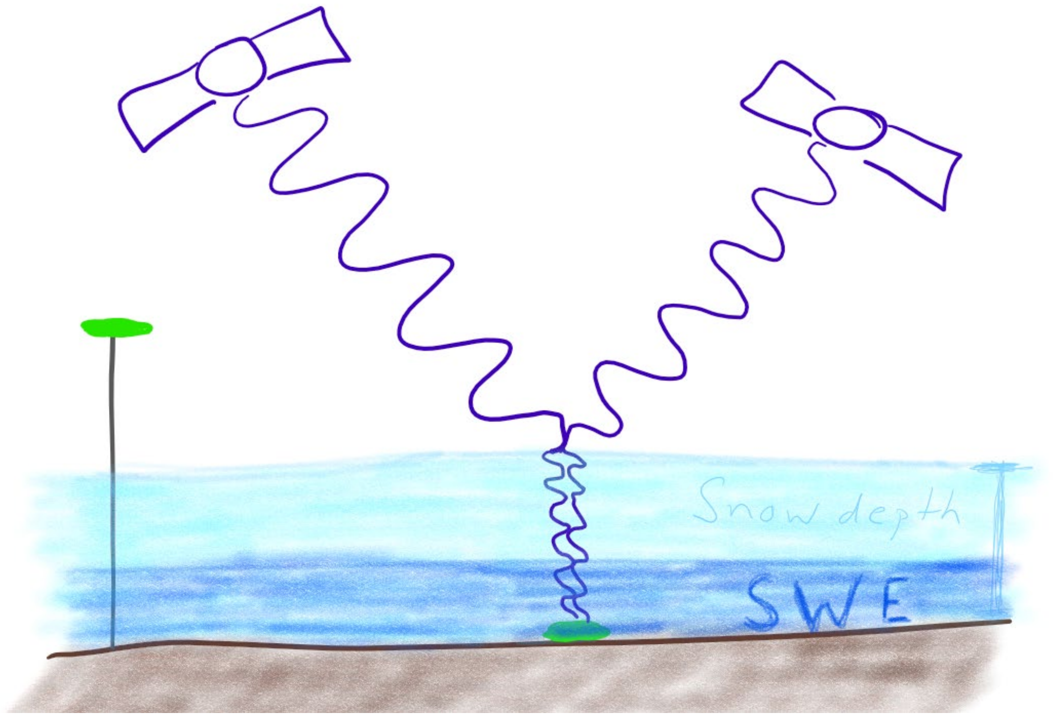
Method – SWE Estimation from Buried GPS Antennas



GPS Refractometry

- Differential GPS to estimate SWE above a buried GPS antenna
- Use of a single layer model to estimate SWE
- GPS signal refraction at the air/snow interface and a decrease in the GPS signal propagation velocity

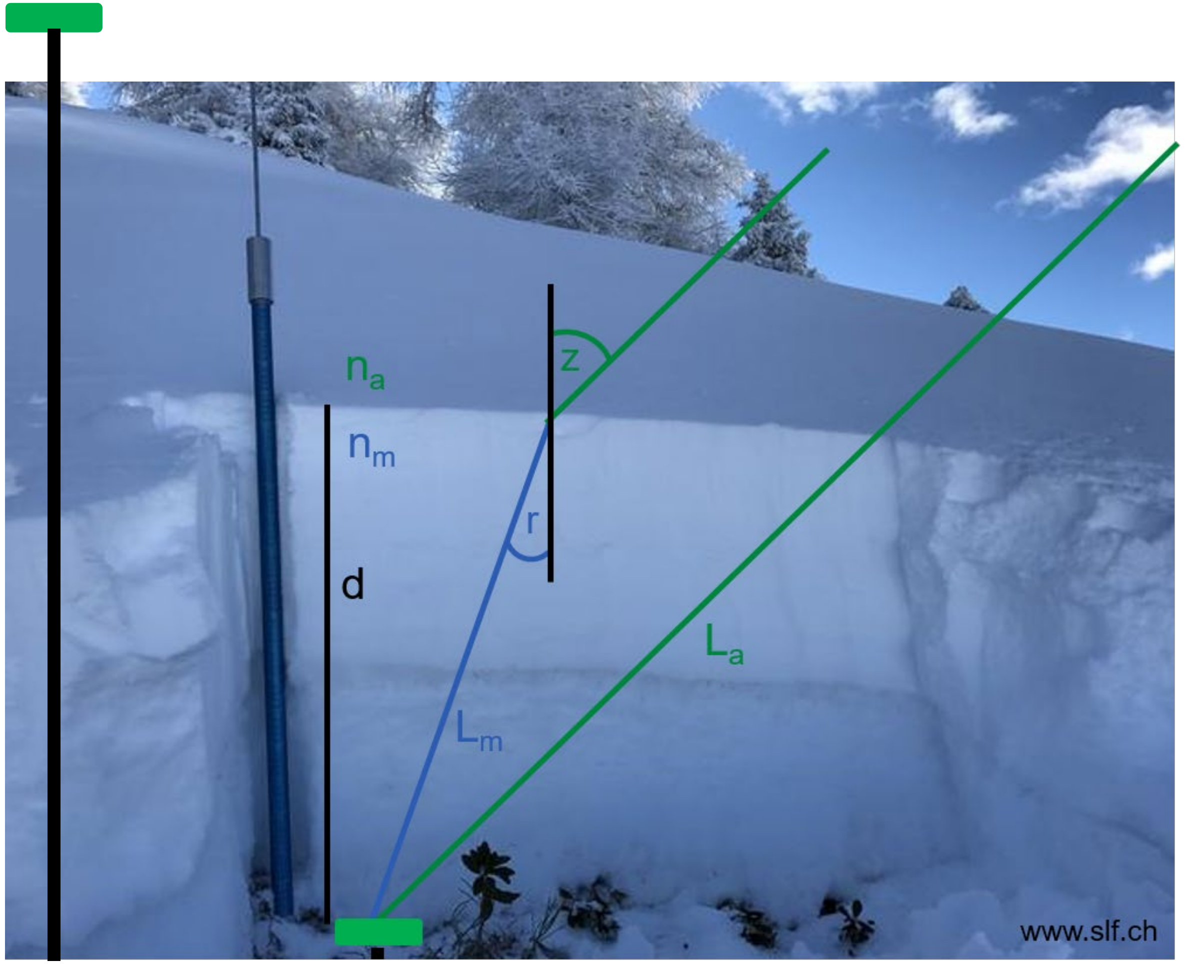
Method – SWE Estimation from Buried GPS Antennas



Research questions:

1. Possible to estimate SWE above buried GPS antenna in snow?
2. How well does it fit to the reference sensors data?
3. Sensitivity to processing parameters?

Method – SWE Estimation based on Single Water Layer Model



Electrical path length in:

- Air: $L_a = c_0 * \Delta t_a$
- Water: $L_w = c_0 * \Delta t_m$

➡ Excess path length δL:

$$\delta L_w = L_w - L_a = d * \underbrace{\left(\sqrt{n_w^2 - \sin^2 z} - \cos z\right)}_{\text{Mapping function F}}$$

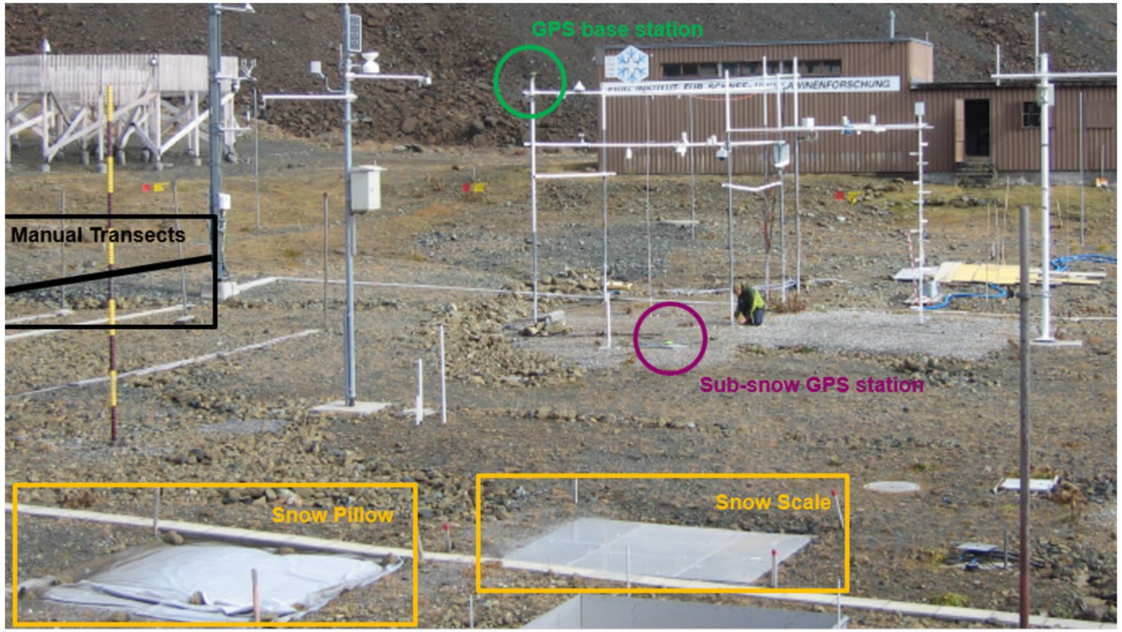
➡ Introduce additional parameter in GPS observation equation and estimate d (SWE):

$$L = \rho + \delta\rho + \boxed{\delta L_w} + \lambda N + \sigma$$

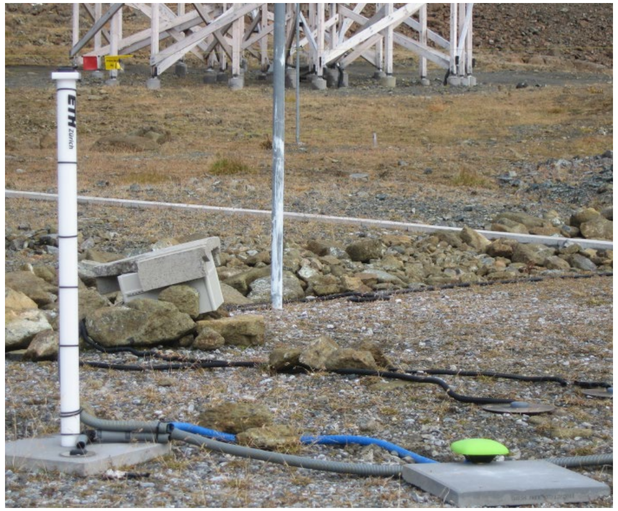
Experimental Study-Site at Weissfluhjoch, Davos, Switzerland

Permanent differential GPS monitoring system operated since October 2012

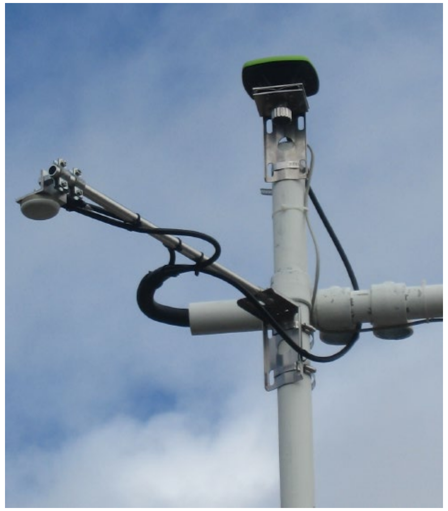
Results are validated to state-of-the-art reference data operated by the WSL Institute for Snow and Avalanche Research (WSL-SLF)



Sub-snow GPS Station



GPS base station



Manual SWE Observation Techniques

Manual: SWE Tube

By density: $SWE = d\,\frac{\rho_{bulk}}{\rho_w}$ with: $\rho_w = 1000\,\frac{kg}{m^3}$

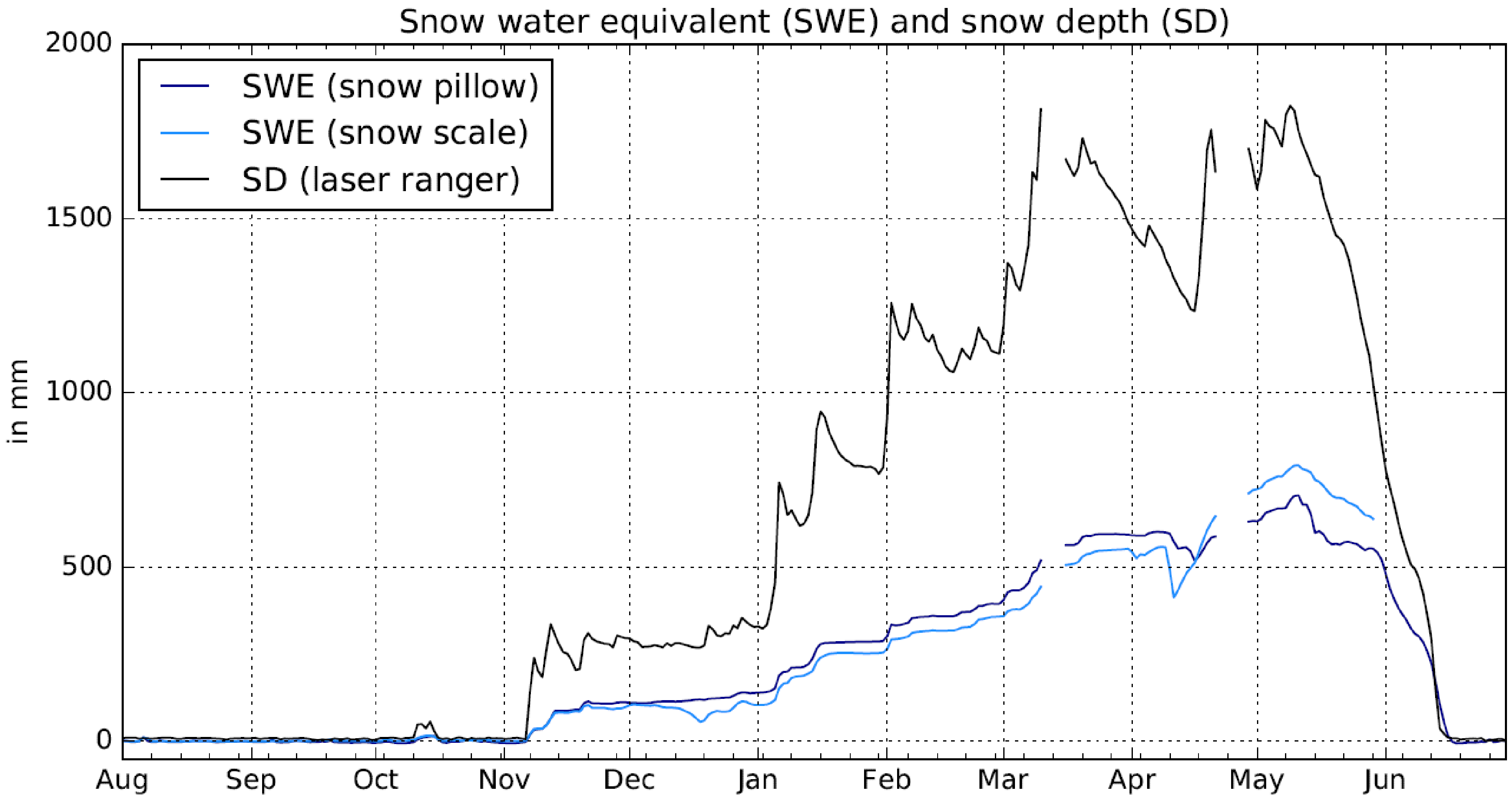
Density cutter

SLF

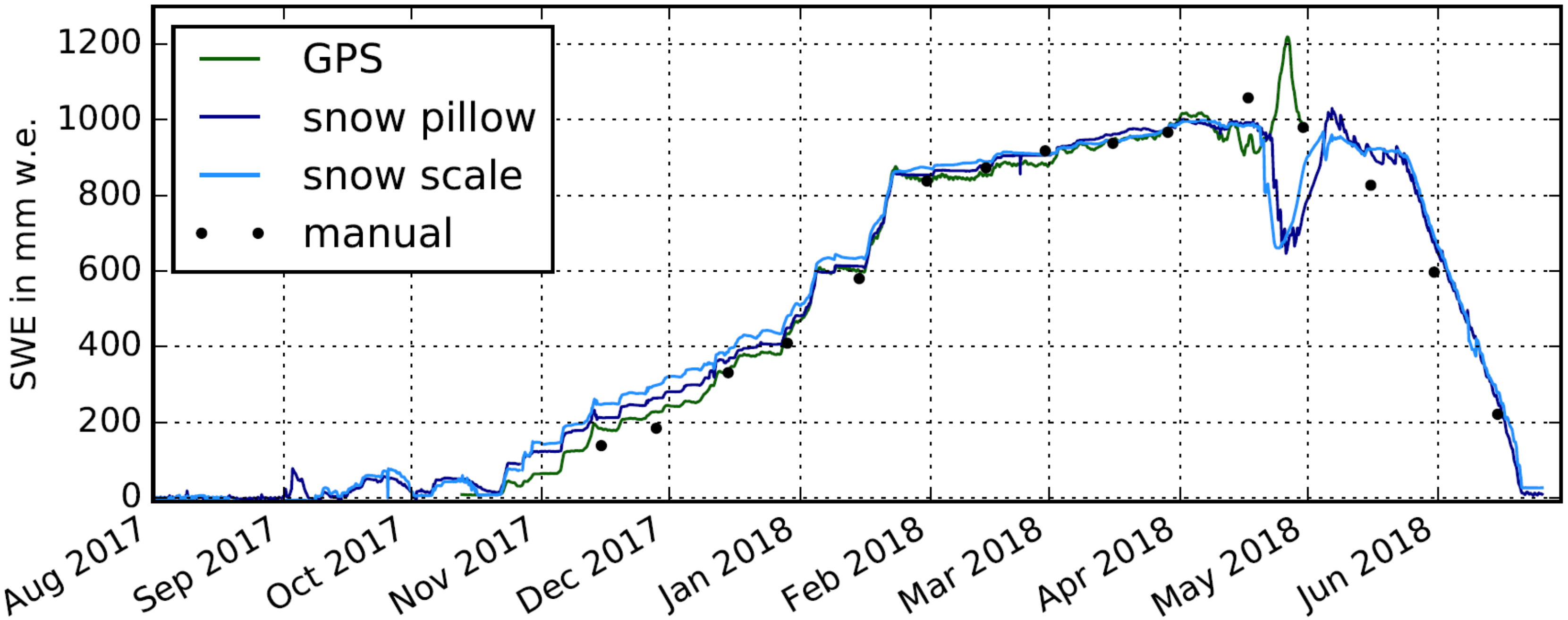
Snow Micro Pen (SMP)

SLF

Reference Sensor Data – Winter 2016/17

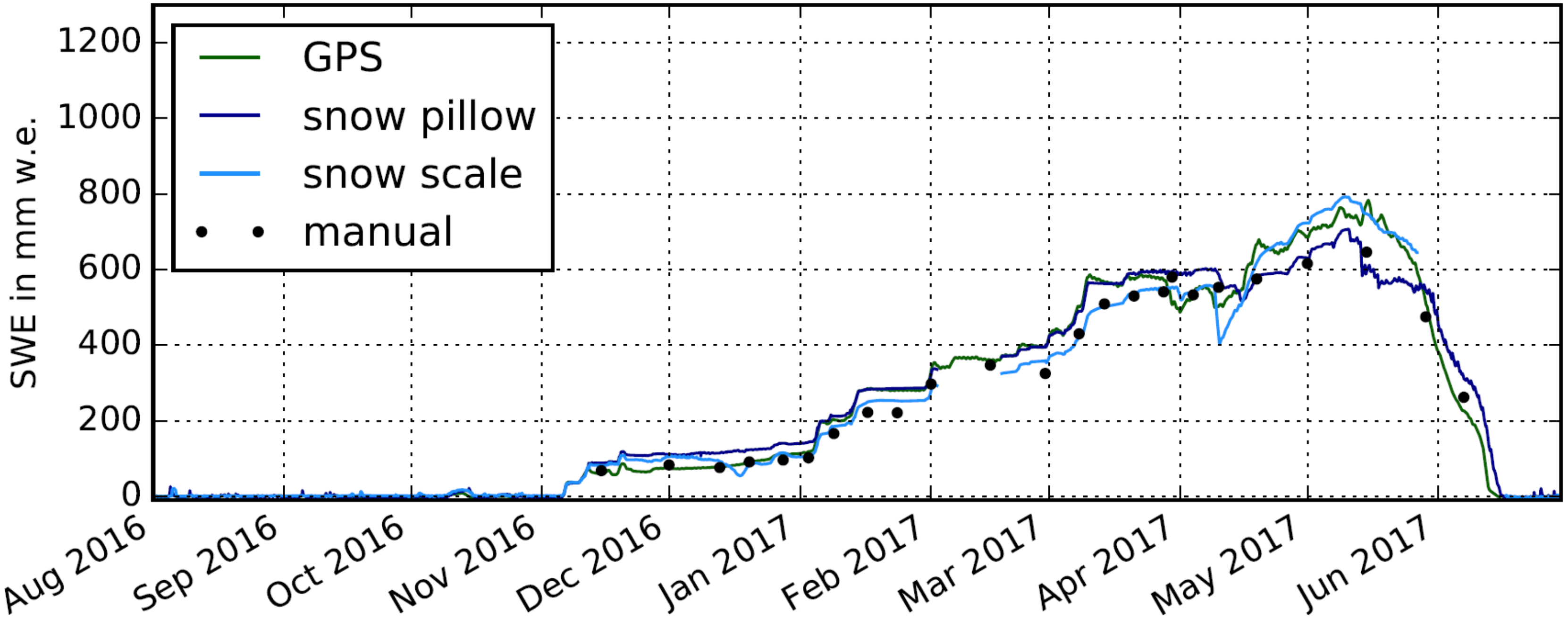


Results – SWE Estimates Wi 17/18 from Leica Sensors



- High correspondence to reference data
- Median relative bias < 10 %
- RMS of SWE estimation ~ 1mm

Results – SWE Estimates Wi 16/17 from Leica Sensors



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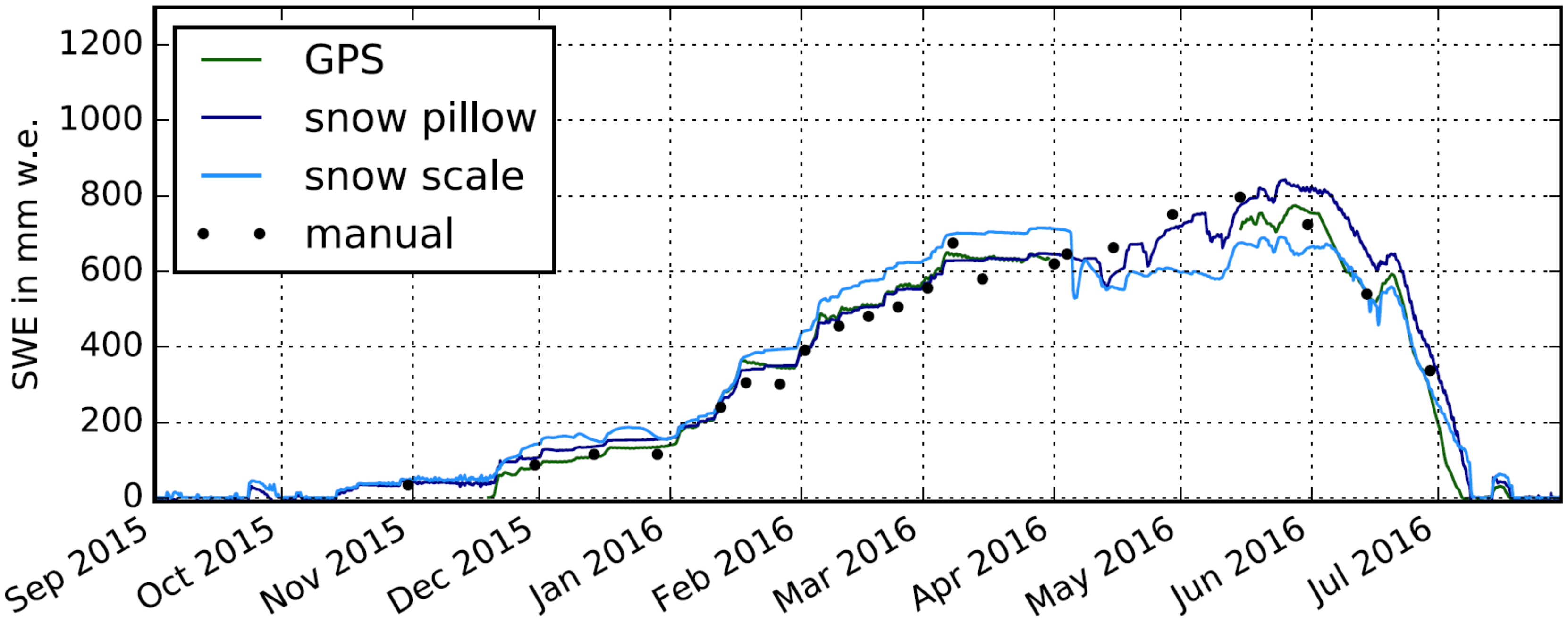
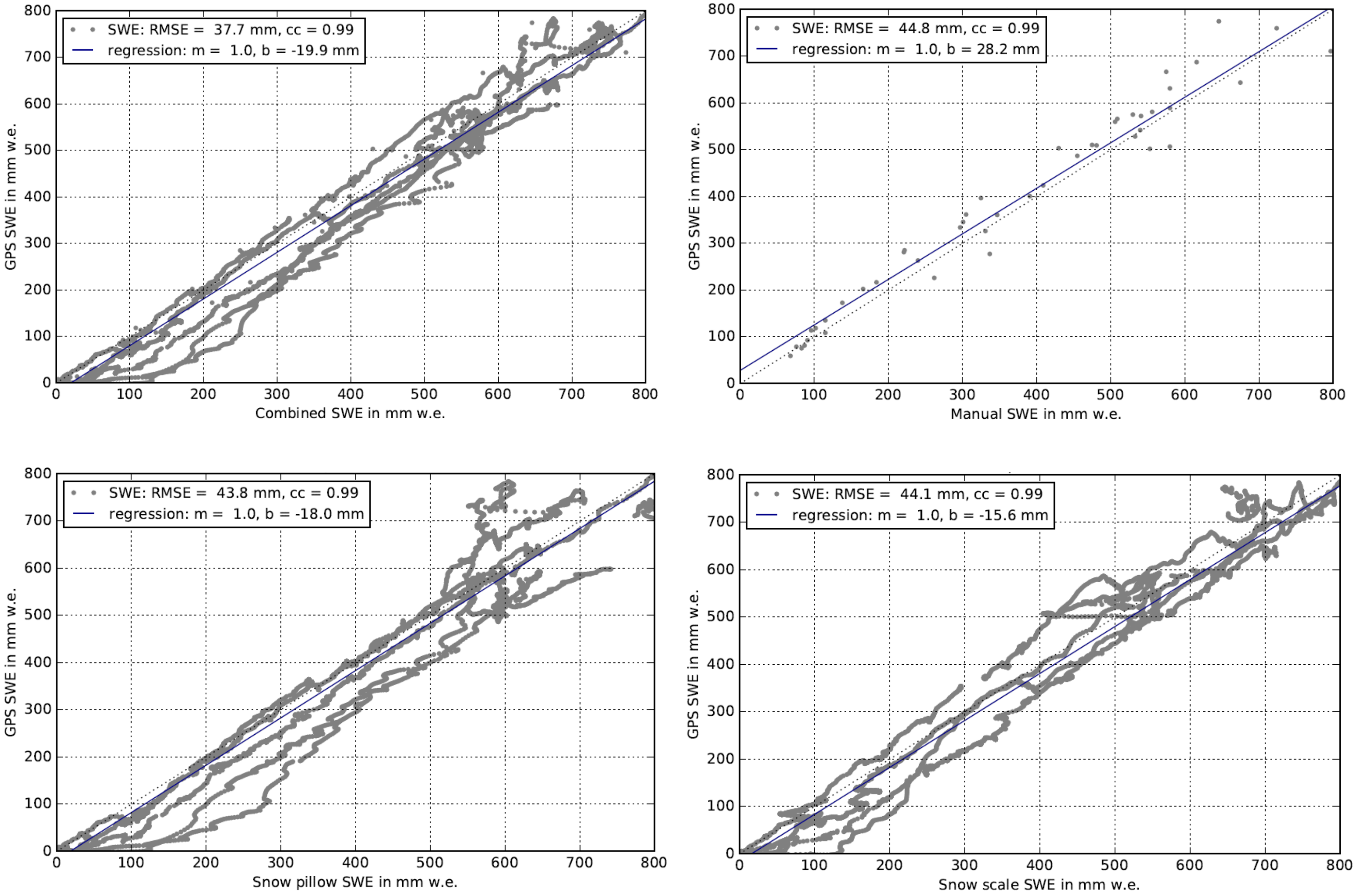


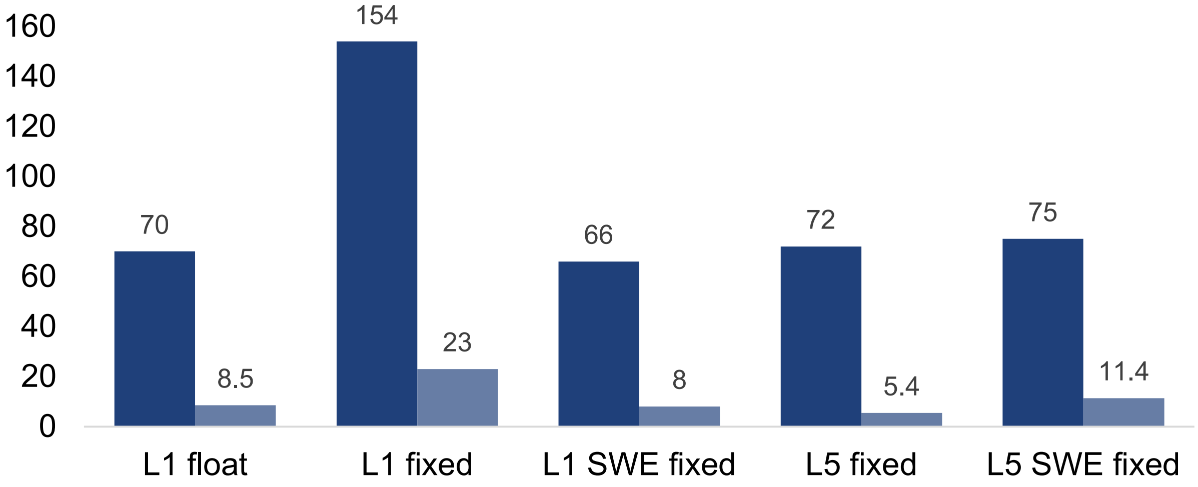
Results – SWE Estimates from Leica Sensors

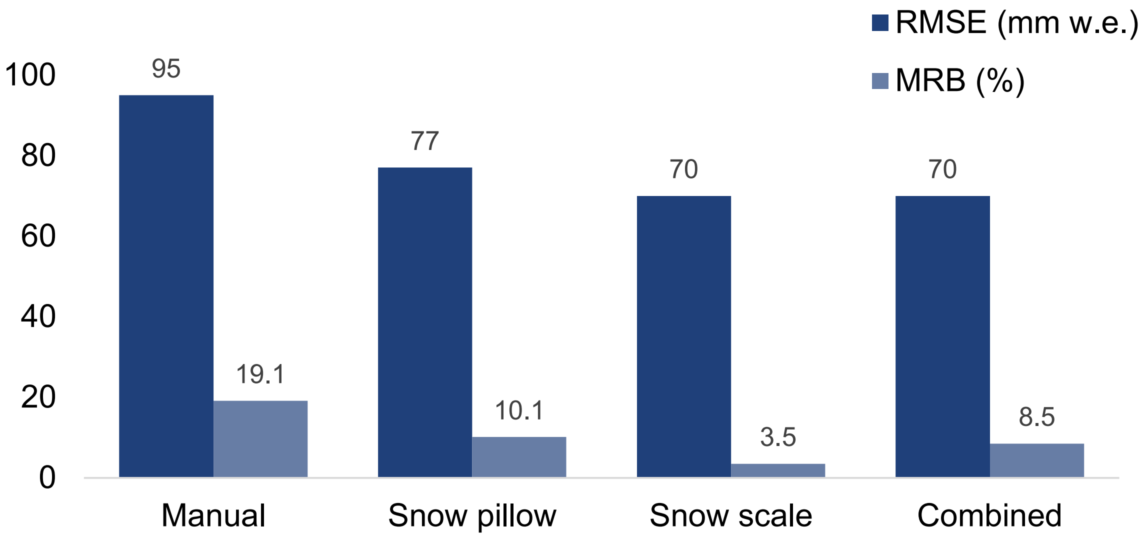


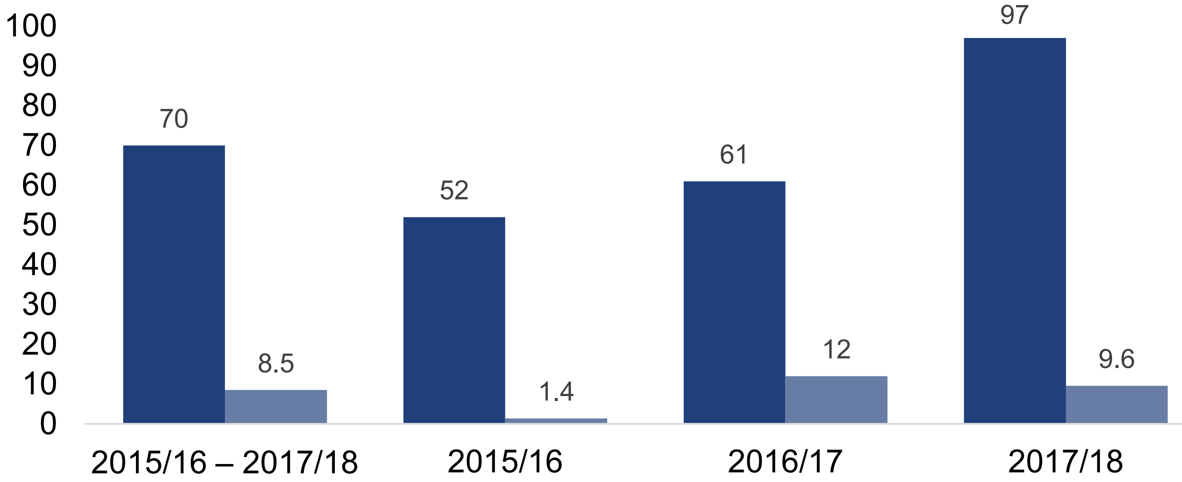
- High correlation to reference data!
- RMS ~ 4cm
- Overestimation compared to manual observations
- Underestimation compared to snow pillow and scale measurements

Results – Sensitivity on Parameters

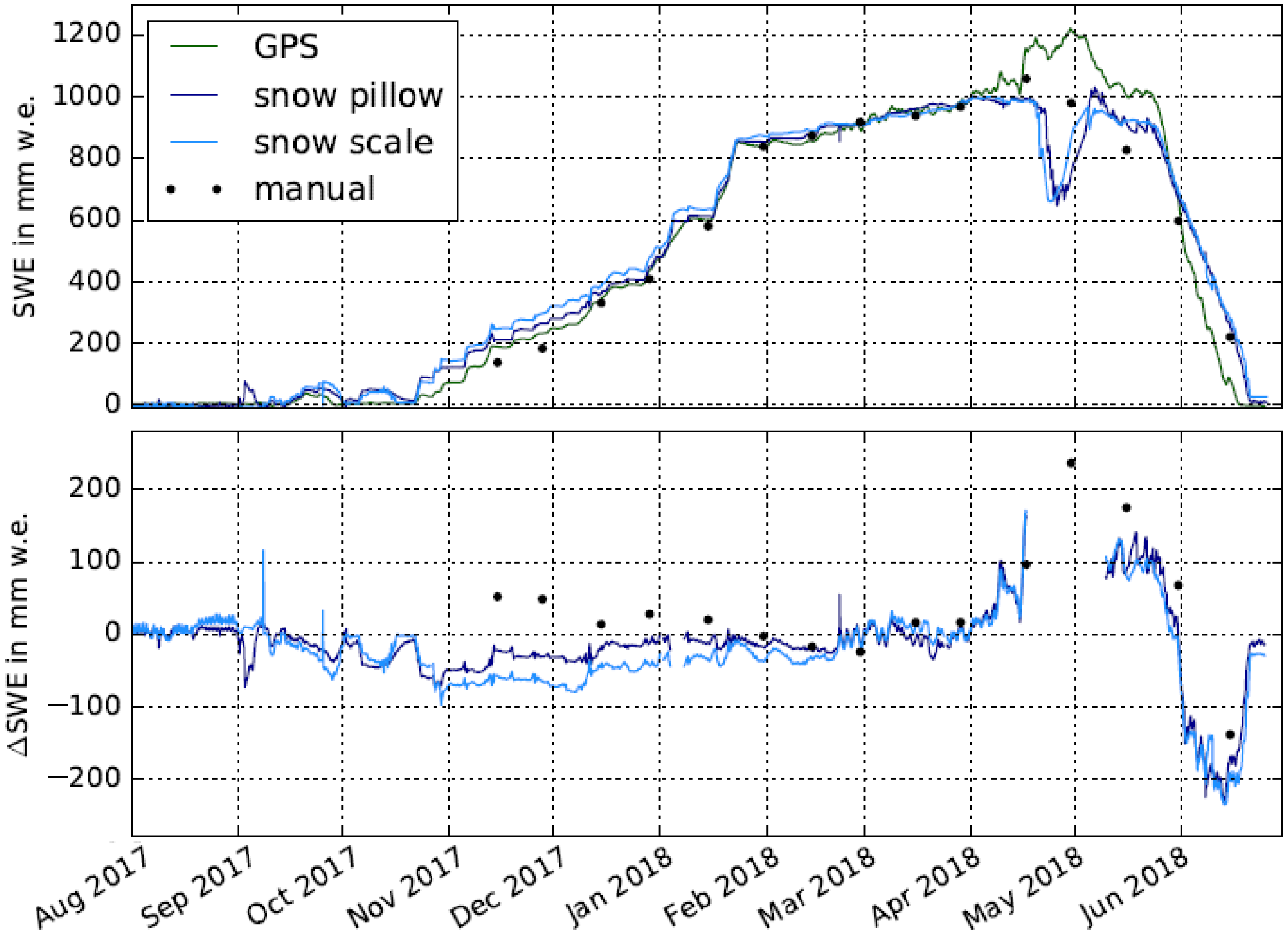
- Best fit to snow scale over all three seasons
- Dependent on season, Wi 15/16 best fit
- Dependent on ambiguity resolution strategies L1 SWE fixed best

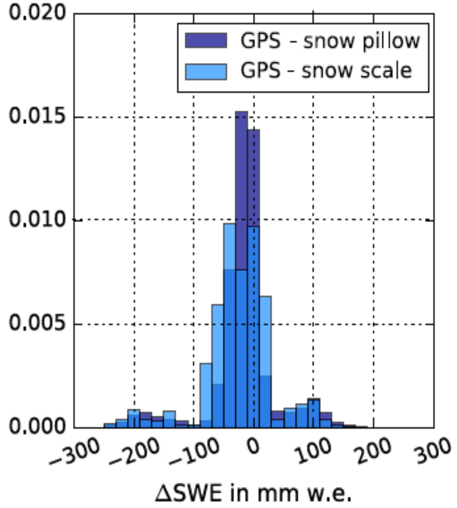


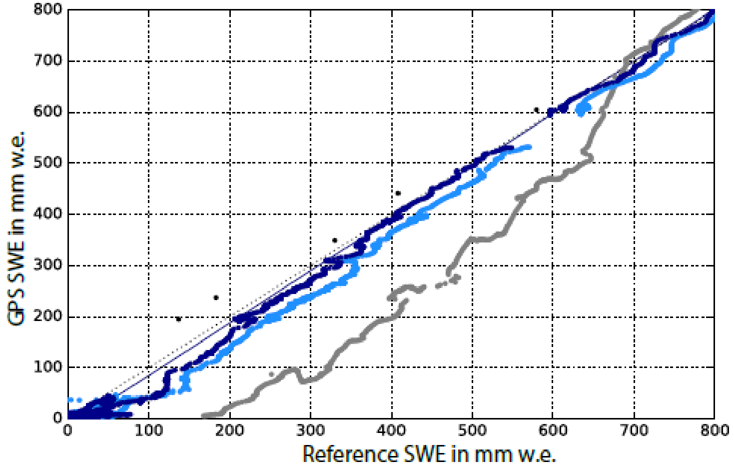




Results – SWE Estimates from U-blox Sensors

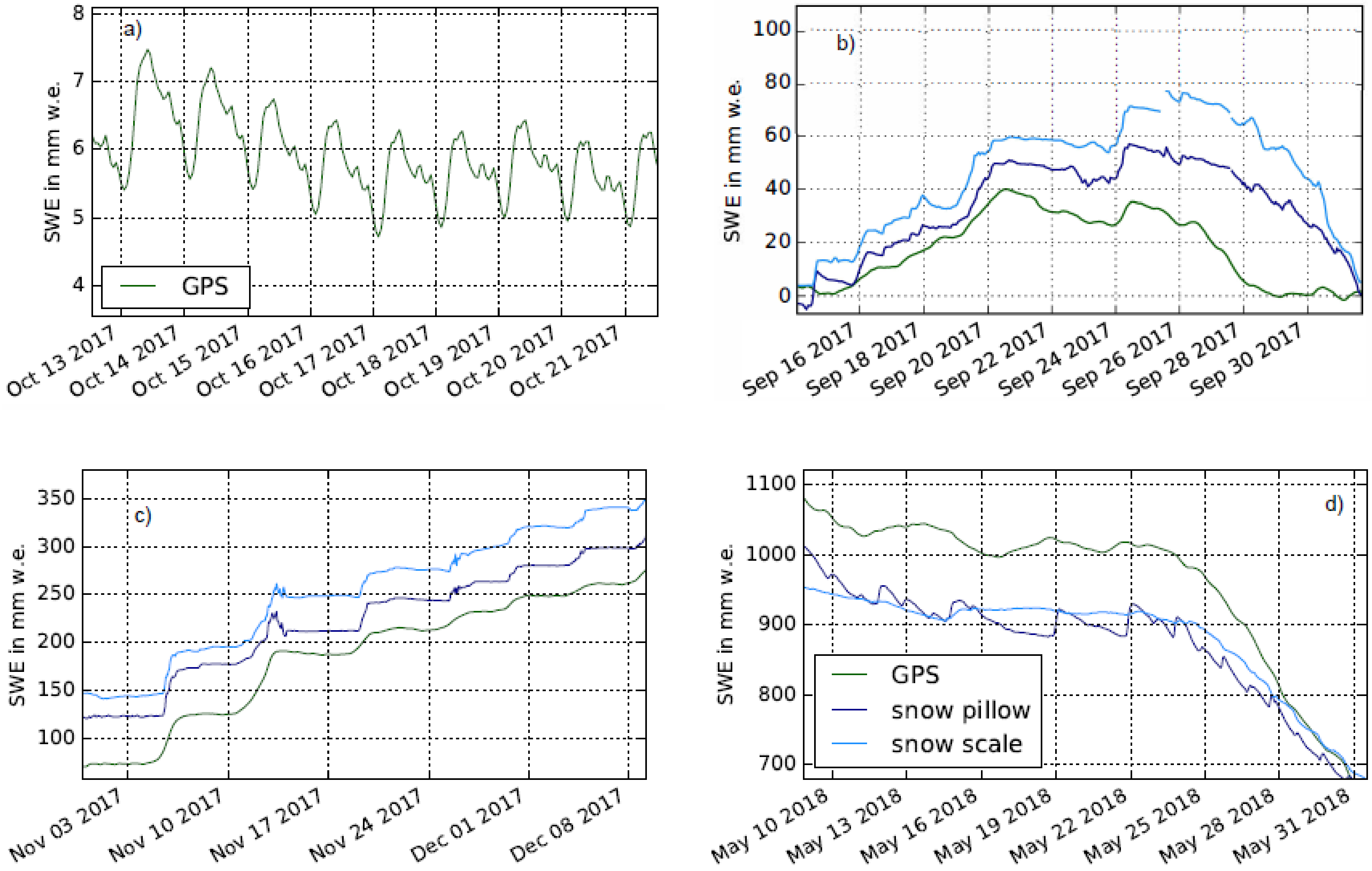






- Overestimation in beginning of melt season

Results – SWE Estimates from U-blox Sensors



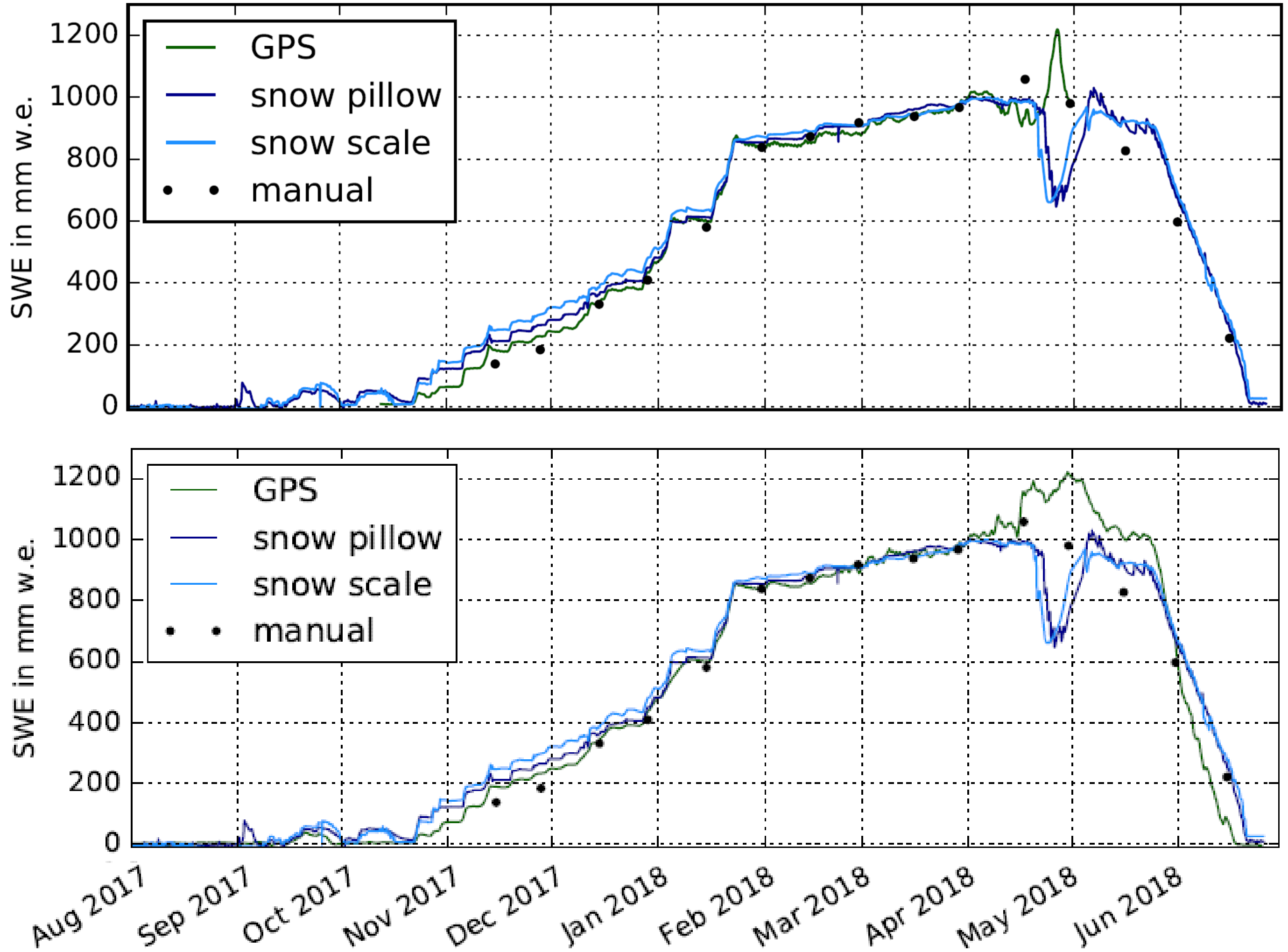
a) Multipath signal

b) Early season snow fall and melt event

c) Snowpack evolution

d) Start of melting season

Results – Wi 17/18, geodetic vs. low-cost

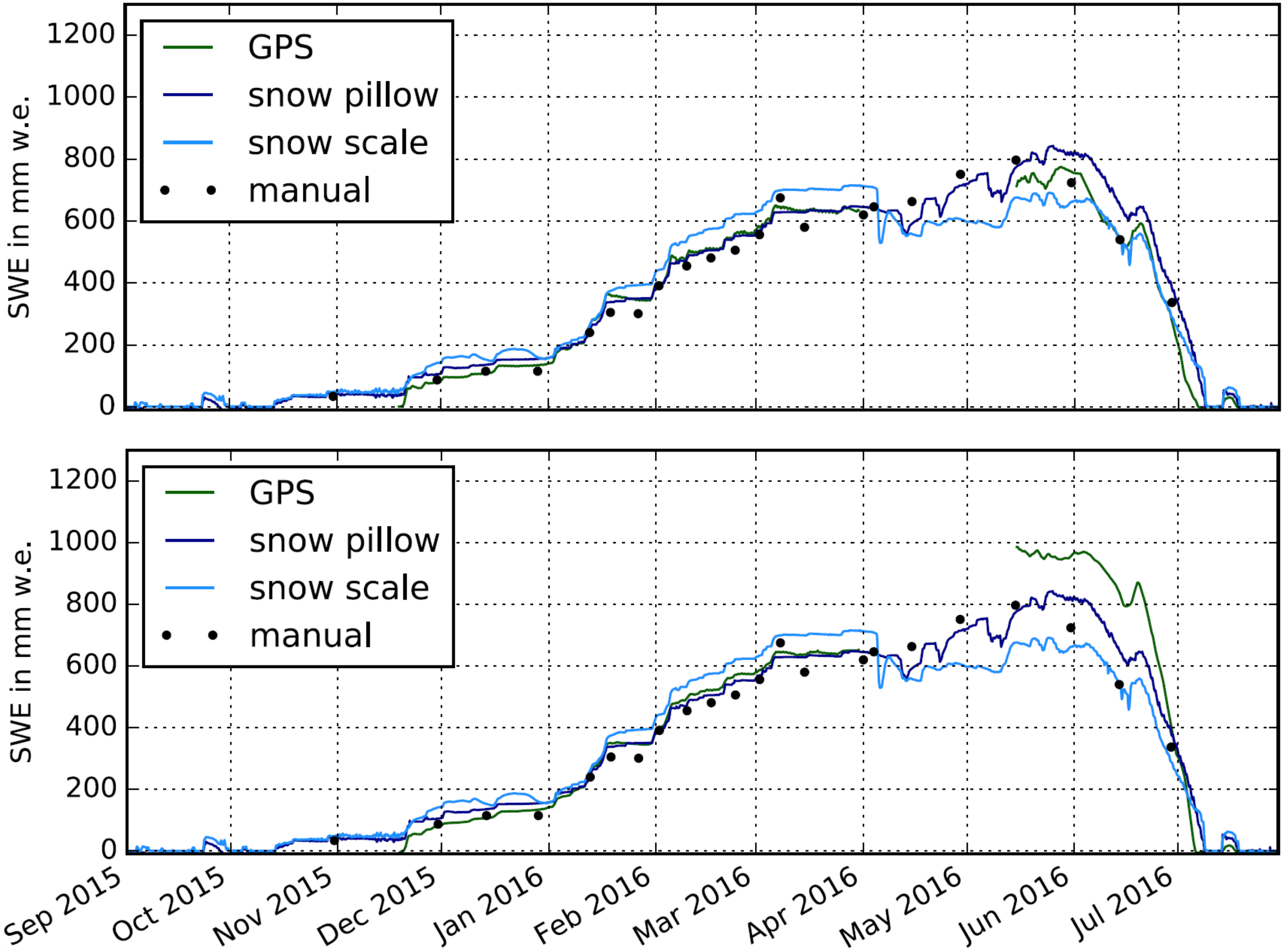


Leica

U-blox

- Good fit in dry snow season!

Results – Wi 15/16, geodetic vs. low-cost



Leica

U-blox

- Good fit in dry snow season!
- Overestimatin in wet snow season for u-blox!

Conclusions

- **Sub-snow GPS is a promising method for point-wise SWE estimation**
- The snowpack is not disturbed due to automated, continuous, self-sustainable observation method. Remote (online) access possible and few maintenance required.
- Accuracy of SWE estimation based on submerged GPS antennas is comparable to state-of-the-art SWE estimations
- **High dependence on GPS processing**
- Low-cost equipment allows to estimate SWE, however not as accurate as using geodetic sensors at the moment
  → Improvement of low-cost GPS data processing for SWE estimation

Outlook

- Effect of a longer baseline for SWE estimation?

  → Possible to separate SWE from tropospheric delay?

- Effect of multi-GNSS on SWE estimation?

- Possible to get SWE distribution from a buried antenna?

Questions?