Height Estimation and Error Assessment of Inland Water Level Time Series calculated by a Kalman Filter Approach using Multi-Mission Satellite Altimetry

Christian Schwatke, Denise Dettmering, and Eva Boergens
Deutsches Geodätisches Forschungsinstitut der Technischen Universität München (DGFI-TUM), München, Germany,
(christian.schwatke@tum.de)

Abstract

In this poster, we present our methodology for estimating water level time series over lakes, reservoirs, and rivers. Furthermore, an error assessment of the resulting water level time series is demonstrated. For computing the water level time series multi-mission satellite altimetry data is used. The estimation is based on altimeter data from Topex, Jason-1, Jason-2, GFO, ERS-2, Envisat, and Saral/Altika – depending on the location of the water body. According to the extent of the investigated water body 1Hz, high-frequent or retracked altimeter measurements can be used.

Different outlier rejections such as thresholds or Support Vector Regression (SVR) can be used for rejecting outliers. For estimating water level heights a Kalman filter approach applied to the grid nodes of a hexagonal grid covering the water body of interest is implemented. After setting an error limit on the resulting water level heights of each grid node, a weighted average water level per point of time is derived referring to one reference location.

For the estimation of water level height accuracies, at first, the formal errors are computed applying a full error propagation within Kalman filtering. Hereby, the precision of the input measurements are introduced by using the standard deviation of the water level height along the altimeter track.

For validation of the time series, we compare our results with in situ data and external inland altimeter databases from Hydroweb (LEGOS), River and Lakes (ESA-DMU), and Global River and Lakes Monitor (GRLM) by USDA. We yield low RMS differences and very high correlations between absolute water level height time series from altimetry and gauges. Moreover, the comparisons of water level heights are also used for the validation of the error assessment.

More than 250 water level time series were already computed and made public available via the "Database for Hydrological Time Series of Inland Waters" (DAHITI) which is available via http://dahiti.dgfi.tum.de operated by DGFI-TUM.

Database for Hydrological Time Series of Inland Water (DAHITI)

The resulting water level time series over inland water are accessible via the website of the "Database for Hydrological Time Series of Inland Water (DAHITI)" (Schwatke et al., 2014). The DAHITI web-service is operated by the Deutsches Geodätisches Forschungsinstitut der Technischen Universität München (DGFI-TUM) and is available under http://dahiti.dgfi.tum.de. The data holding of DAHITI contains about 250 time series over lakes, rivers and wetlands. The water level time series can be downloaded for free after a short registration process.

http://dahiti.dgfi.tum.de

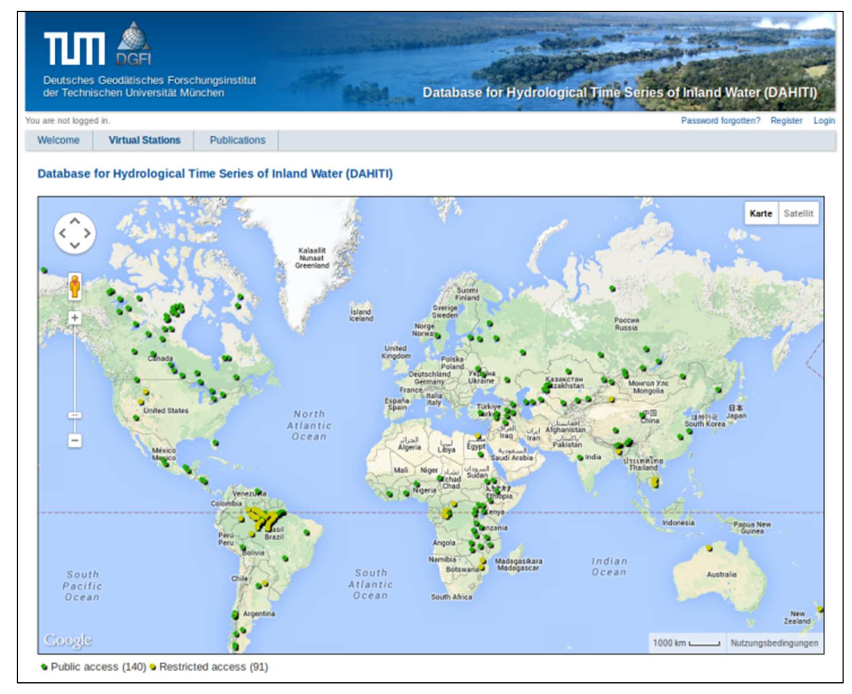

Figure 4: Website of the "Database for Hydrological Time Series of Inland Water" (DAHITI) at DGFI-TUM

Data

The data holding for the estimation of water level time series is the **Open Altimeter Database (OpenADB)** (Schwatke et al. 2014a) of the DGFI-TUM. Hereby, satellite altimeter data from all available altimeter missions can be used depending on the data coverage of the investigated inland water body. All altimeter data are cross-calibrated to remove the range bias between the missions to allow the usage of all missions as a single altimeter system.

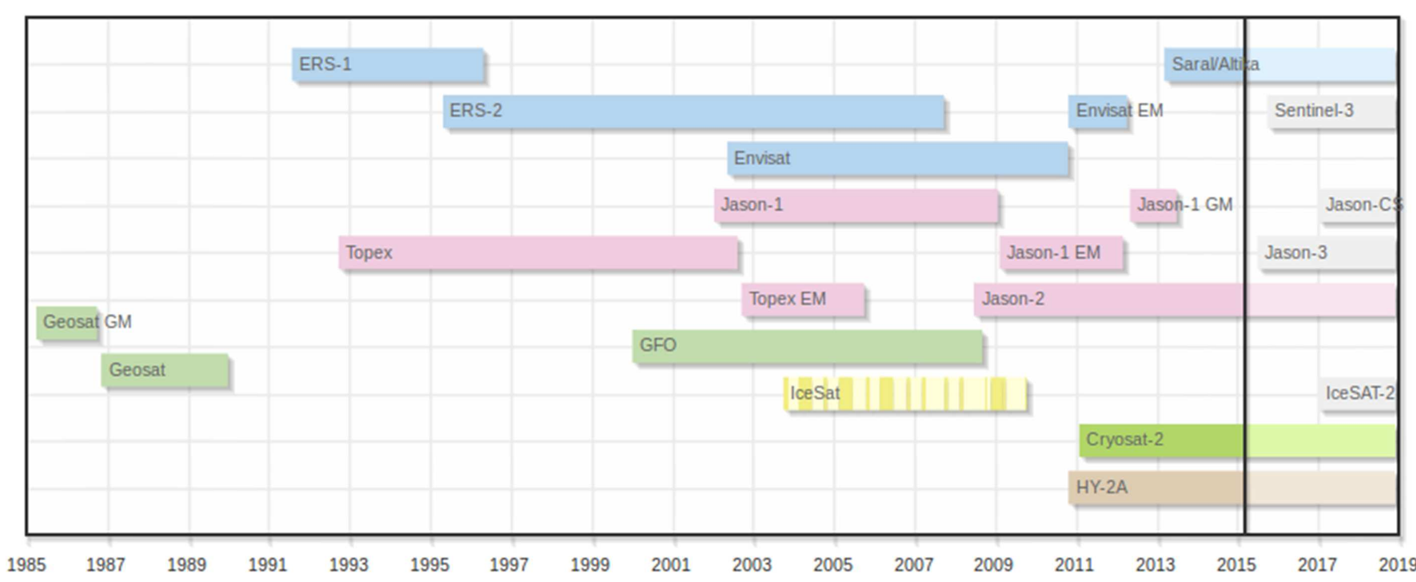

Figure 1: Overview of satellite altimeter missions since 1985

Methodology

The procedure for the estimation of water level time series is divided into three steps: "Preprocessing", "Kalman filtering" and "Postprocessing" which are described as follows.

Preprocessing

- Extraction of altimeter data from OpenADB for the investigated inland water body
- Optional retracking of the altimeter measurements using the Improved Threshold retracker (Hwang et al., 2006) with a threshold of 10%
- Calculation of final normal heights for each measurement by applying geophysical corrections
- Calculation of standard deviations of the heights along each altimeter track based on a moving window (0.5 km for rivers, 1.5 km for lakes)
- User defined outlier detection based on thresholds for the min./max. latitude, min./max. height or max. standard deviation can be applied.
- An additional outlier detection using a linear Support Vector Regression (Smola et al, 2004) can be applied to reject water level heights not representing a flat surface.

Kalman Filtering

- Estimation of a hexagonal computation grid over the inland water body
- Resulting heights and standard deviations from the preprocessing step are used as input data for the Kalman filtering.
- The method of Kalman Filter (Kalman, 1960) is applied. Hereby, water level heights and formal errors for every epoch in which new altimeter measurements are introduced and for every grid node over the water body are computed. The applied Kalman filter approach contains a rigorous error propagation.

Postprocessing

- For every epoch a final water level height and a formal error are estimated
- Finally, a last outlier detection can be applied on the water level time series based on SVR using radial base functions to reject complete epochs.

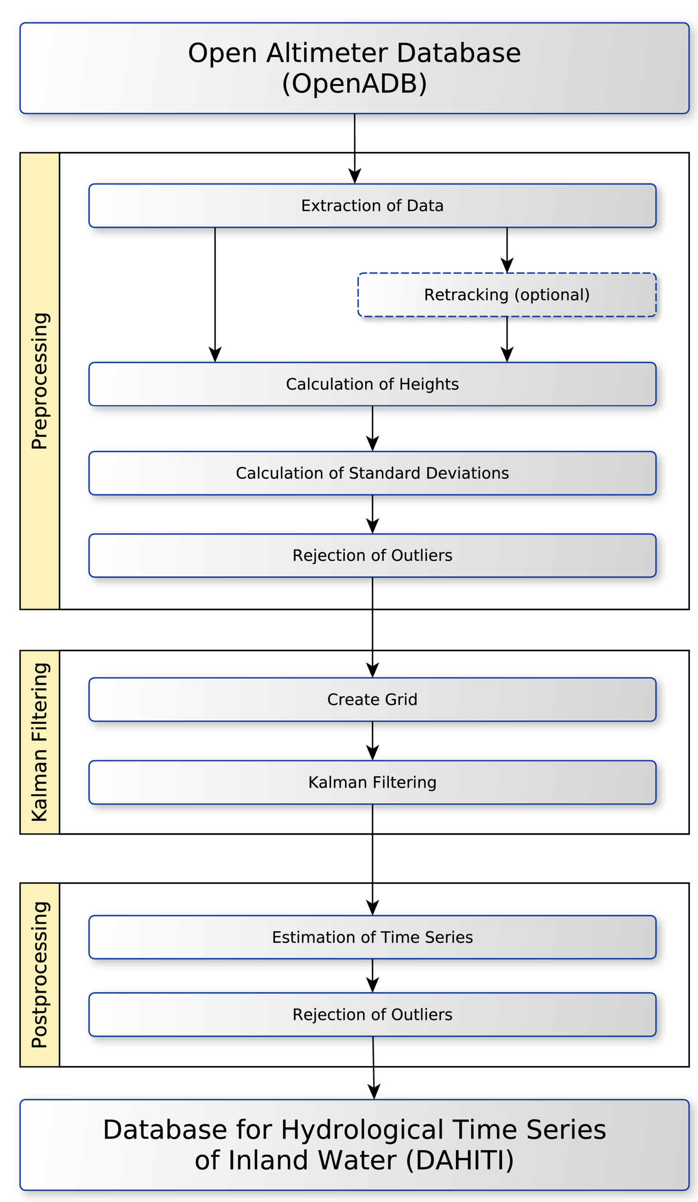

Figure 2: Processing strategy for the computation of water level time series (Schwatke et al., 2015)

Error estimation

The current error estimation of the Kalman filter only yields formal errors which are too optimistic. At the moment, there are no uncertainties of geo-physical corrections or altimeter ranges considered. Furthermore, no correlation between adjacent altimeter measurements are considered. The improvement of the resulting errors are still under investigation.

Results and Validation

For the validation of water levels from DAHITI comparisons with in-situ gauges from the *Agência Nacional de Águas* and the *Canada Wateroffice* are performed. Furthermore, to show the potential of the Kalman filter approach, water level time series from LEGOS (Cretaux et al., 2011), ESA-DMU (Berry et al, 1997) , GRLM (Birkett et al., 2011) are also compared with in-situ data.

The water level time series of Lake Athabasca (7,800 km²) in Canada is presented in detail. Fig. 3 shows the water level time series from DAHITI, LEGOS, ESA-DMU and GRLM compared with in-situ data and shifted to the water level height of DAHITI. Furthermore, The year 2004 is plotted in detail. The comparison between DAHITI and in-situ data shows a very good agreement with RMS differences of 17cm and a correlation coefficient of 0.88. Furthermore, we can increase the temporal resolution and up to 1337 points which are used for the due to the multi-mission approach. The comparison between in-situ data and LEGOS (RMS=33.7cm, R^2=0.79, 272 points), ESA-DMU (RMS=80.5cm, R^2=0.30, 79 points), and GRLM (RMS=55.7cm, R^2=0.27, 76 points) show higher RMS differences and smaller correlation. Fig.3 also clearly show the improvement of the water level time series in parts of ice coverage in winter compared to the other time series from altimetry.

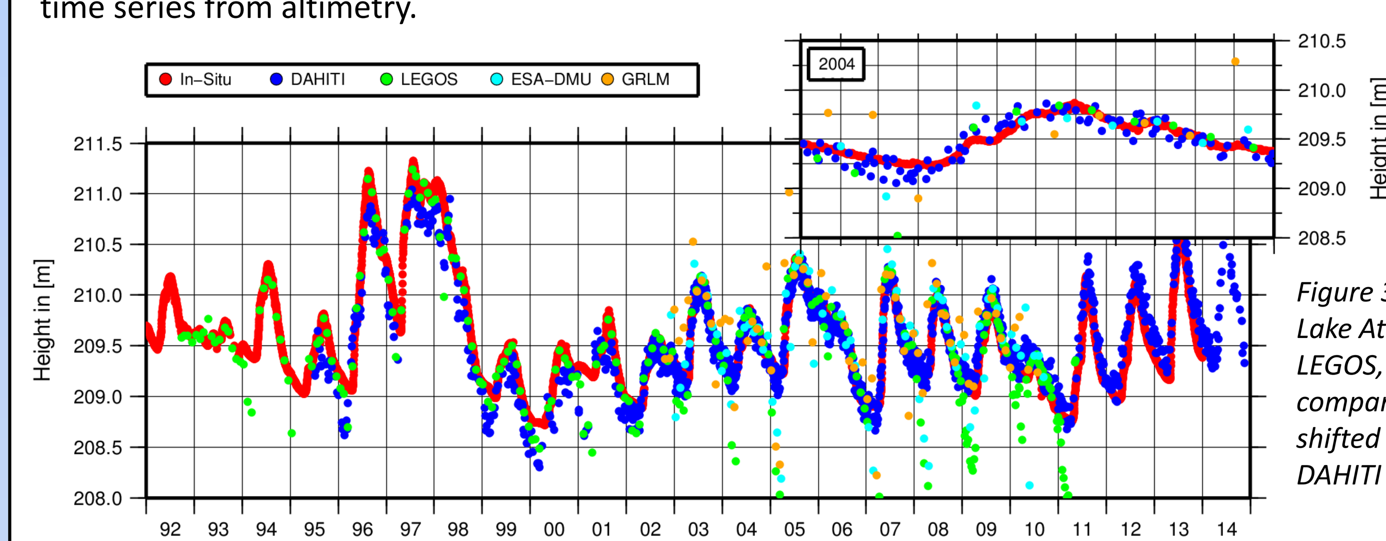

Figure 3: Water level time series of Lake Athabasca from DAHITI, LEGOS, ESA-DMU and GRLM compared with in-situ data and shifted to the water level height of DAHITI (Schwatke et al., 2015)

For a further validation comparisons between DAHITI and in-situ data and time series from other groups for selected lakes in Canada and rivers in the Amazon basin are performed. Table 1 shows the RMS differences, correlation coefficients and number of points used for the.

Target name	Station name	Retracked	Ice Coverage	DAHITI			LEGOS			ESA-DMU			GRLM		
				RMS [cm]	R^2	No	RMS [cm]	R^2	No	RMS [cm]	R^2	No	RMS [cm]	R^2	No
Lake Athabasca	Crackingstone Point[1]	X	X	17.0	0.88	1337	33.7	0.79	272	80.5	0.30	79	55.7	0.27	76
Great Slave Lake	Hay River[1]		X	15.9	0.61	1221	31.2	0.37	246		n.a.			n.a.	
Lake Claire	Prairie Point[1]	X	X	19.9	0.53	141		n.a.		37.9	0.25	70		n.a.	
Lake Winnipeg	George Island[1]		X	14.6	0.81	522	27.7	0.64	257	41.9	0.49	77	30.9	0.56	703
	Gimli[1]		X	24.4	0.49	518	30.0	0.55	264	41.9	0.48	76	35.9	0.42	722
	Pine Dock[1]		X	19.1	0.65	499	28.3	0.63	254	42.7	0.51	74	33.8	0.50	702
Lake Manitoba	Westbourne[1]	X	X	20.0	0.77	318	34.2	0.42	100	34.2	0.42	73	46.0	0.11	71
	Steep Rock[1]	X	X	20.0	0.77	315	36.4	0.40	101	35.5	0.33	75	47.3	0.11	72
Cedar Lake	Oleson Point[1]		X	37.8	0.83	530	76.7	0.20	252	54.8	0.54	78		n.a.	
Lake Winnipegosis	Winnipegosis[1]	X	X	16.2	0.91	426	36.7	0.63	136	34.2	0.61	70		n.a.	
Lake of the Woods	Clearwater Bay[1]	X	X	16.3	0.75	631	44.4	0.58	143	36.6	0.40	77		n.a.	
	Cyclone Island[1]	X	X	15.0	0.78	631	43.4	0.61	143	35.9	0.41	77		n.a.	
	Hanson Bay[1]	X	X	14.7	0.79	631	42.6	0.63	143	36.0	0.40	77		n.a.	
Rio Solimoes	Tefé[2]	X		11.6	1.00	32		n.a.		173.3	0.76	27		n.a.	
	Tefé[2]	X		21.7	0.99	72	53.9	0.98	84		n.a.			n.a.	
	Itepé[2]ua	X		49.9	0.98	39	120.4	0.90	44		n.a.			n.a.	
	Itepéua[2]	X		46.0	0.99	117	61.2	0.97	97		n.a.			n.a.	
Rio Purus	Aruma-Jusante[2]	X		23.3	1.00	16	24.1	1.00	7	318.9	0.61	6		n.a.	
Rio Madeira	Humanitá[2]	X		21.6	1.00	35	45.1	0.99	29	53.2	0.99	28		n.a.	
	Humanitá[2]	X		29.0	1.00	93	50.2	0.99	91		n.a.			n.a.	
	Guajará-Mirim[2]	X		78.4	0.88	44	87.4	0.88	35	134.3	0.77	36		n.a.	
Rio Negro	Porto de Manaus[2]	X		12.7	1.00	74	21.8	1.00	72	67.5	0.96	71		n.a.	
	Moura[2]	X		65.3	0.97	62	70.9	0.96	43		n.a.			n.a.	
	Moura[2]	X		46.0	0.98	42	46.3	0.97	45	44.1	0.98	40		n.a.	

Table 1: Water level time series of DAHITI for selected lakes and rivers compared with in-situ data and results from LEGOS, ESA-DMU, and GRLM (Source of in-situ data: [1]Canada Wateroffice, [2]Agência Nacional de Águas) (Schwatke et al., 2015)

Discussion/Outlook

- DAHITI provides time series over inland water for hydrological applications
- Comparisons of results from DAHITI with in-situ data over selected lakes and river show a decrease of RMS differences and an increase of the correlation coefficients compared with water level time series from LEGOS, ESA-DMU and GRLM
- The new approach uses a Kalman filter and leads to reliable and high accurate water level time series over inland water
- DAHITI provides formal errors, which represent the temporal variation of errors very well but at the moment, the resulting errors are too optimistic due to the used standard deviation as error for the Kalman filter approach
- In future, the Kalman filter approach can also be used for the prediction of water level time series over inland water

References

- *Berry, P., Jasper, A., and Bracke, H.: **Retracking ERS-1 altimeter waveforms over land for topographic height determination: an expert system approach**, ESA Pub. SP-414, 1, 403–408, 1997*
- *Birkett, C., Reynolds, C., Beckley, B., and Doorn, B.: **From Research to Operations: The USDA Global Reservoir and Lake Monitor**, in: Coastal Altimetry, edited by Vignudelli, S., Kostianoy, A. G., Cipollini, P., and Benveniste, J., pp. 19–50, Springer Berlin Heidelberg, doi:10.1007/978-3-642-12796-0_2, 2011.*
- *Crétaux, J.-F., Jelinski, W., Calmant, S., Kouraev, A., Vuglinski, V., Bergé-Nguyen, M., Gennero, M.-C., Nino, F., Rio, R. A. D., Cazenave, A., and Maisongrande, P.: **SOLS: A lake database to monitor in the Near Real Time water level and storage variations from remote sensing data**, Advances in Space Research, 47, 1497– 1507, doi:10.1016/j.asr.2011.01.004, 2011.*
- *Hwang, C., Guo, J., Deng, X., Hsu, H.-Y., and Liu, Y.: **Coastal gravity anomalies from retracked Geosat/GM altimetry: improvement, limitation and the role of airborne gravity data**, Journal of Geodesy, 80, 204–216, 2006.*
- *Kalman, R. E.: **A New Approach to Linear Filtering and Prediction Problems**, Transactions of the ASME–Journal of Basic Engineering, 82, 35–45, 1960*
- *Schwatke C., Dettmering D., Bosch W., Seitz F.: **Kalman Filter Approach for Estimating Water Level Time Series over Inland Water using Multi-Mission Satellite Altimetry**, Hydrol. Earth Syst. Sci. Discuss., 2015 (submitted)*
- *Schwatke C., Dettmering D., Bosch W., Göttl F., Boergens E.: OpenADB: **An Open Altimeter Database providing high-quality altimeter data and products**. Ocean Surface Topography Science Team Meeting, Lake Constance, Germany, 2014-10-30, 10.13140/2.1.1371.8728 (Poster), 2014a*
- *Schwatke C., Dettmering D., Bosch W., Göttl F., Boergens E.: **Database for Hydrological Time Series of Inland Waters (DAHITI)**. Ocean Surface Topography Science Team Meeting, Lake Constance, Germany, 2014-10-30, 10.13140/2.1.3993.3127 (Poster), 2014b*
- *Smola, A. J. and Schölkopf, B.: **A Tutorial on Support Vector Regression, Statistics and Computing**, 14, 199–222, doi:10.1023/B:STCO.0000035301.49549.88, 2004.*

Acknowledgement

OpenADB data holdings are based on altimetry missions operated by CNES/NASA (TOPEX, Jason-1), ESA (ERS-1/2, Envisat, Cryosat-2), USNavy/NOAA (GFO), CNES/NASA/Eumetsat/NOAA (Jason-2), and ISRO/CNES (Saral). The original data sets are disseminated by AVISO, ESA, NOAA, and PODAAC.
We thank Agência Nacional de Águas and Canada Wateroffice for providing in-situ data.

Mapping Water Bodies from Space 2015, Frascati, Italy, 18-19 March 2015