SWOT REFECCT Project

Rehearsal of EFfective Flood Early warning and decision-support system to strengthen Coping Capacity and adapTation in west Africa

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1. Introduction and Objectives

Only for few river worldwide long records of in-situ water height, discharge and other auxiliary data are available to monitor the hydrological processes and constrain the hydrological models.

Water heights are monitored from space since 1991. Conventional Altimetry (CA) has been used to estimate water level variations of lakes, rivers and floodplains. The accuracy for inland water altimetry is few dm and depends on altimeter, lake area and shape, surroundings, and retracking method. Pulse-limited altimetry monitors about 15% of the global lake volume variation and large rivers. A higher temporal and spatial coverage of the altimeter measurements and a better precision of water level estimation are necessary to better monitor the surface water level from space.

The new altimeter generation which employs the Delay-Doppler (DDA), called also SAR altimetry, and the wide-watch techniques gives: (a) higher resolution and improved accuracy of water level and discharge, (b) new additional parameters (e.g. river slope) and (c) sampling sufficient for flood events detection and long term analysis. In SAR mode the spatial and temporal derivatives of water level provide a new observable. On rivers, the accuracy is 10-20 cm with the enhanced unfocused SAR processing SAMOSA+ and SAMOSA++ (Dinardo 2020, Dinardo et al. 2020). SAR waveform and noise floor are different; resolution and accuracy are improved. However, range and corrections are still affected by land contamination.

The mission SWOT (Surface Water and Ocean Topography) will provide critical information on the spatial variability of water surface elevation and allow a better understanding of the interactions between hydrodynamic processes. River Water Discharge (RWD) is another parameter that can be calculated based on water level and water width. It reflects the drainage basin area dynamics and affects environmental conditions like currents and hydrography in coastal waters, it is a function of precipitation and meteorological elements controlling evapotranspiration, geology, relief and vegetation. On longer time scales climate determines the variability. Therefore, the Second Report on the Adequacy of the Global Climate Observing System for Climate (2AR, GCOS) signed the United Nations Framework Convention for Climatic Change (UNFCCC) emphasised the effective data exchange and access in respect of observations of the Essential Climate Variables (ECVs). River discharge is one of these ECVs, which needs to be systematically observed to characterise the state of the global climate system, its variability and vulnerability. For medium size basins (<10,000 km2) RWD is also indirectly estimated from satellite images in the visible and near infrared spectrum (e.g., MODerate-resolution Imaging Spectroradiometer – MODIS) see Tarpanelli et al., 2015. The current state of the art and scientific rationale of the investigation on SWOT contribution in the river is given in the publications of the SWOT Science team projects call 2016-2019, see for river hydrology Chevalier et al. (2017).

The application of the satellite altimetry for estimation of the river discharge has started from the large world rivers: the Ob R. (Kouraev et al., 2004), the Amazon (Zakharova et al., 2006), the Ganges - Brahmaputra R. (Papa et al., 2010). As the accuracy of the water level retrieval has improved, more rivers of smaller size and of challenging fluvial geomorphology were involved. As a rule, smaller rivers have higher variability of water regime, shorter duration of flood events, as well as more complex and irregular fluvial geomorphology. These factors are important not only for the accuracy of the altimetry-retrieved water height measurements, but also for the accuracy of the built/used discharge conversion relations. However, only few European rivers (Po, Severn, Volga, Seine) were subject of these studies. The results show a large range of errors (from 9 to 1000% of RMSE) depending on river and method, which demonstrate the need to extend the number of the exercises. As most European rivers have a good and dense ground monitoring network, their involvement into similar studies will allow the understanding the factors affecting the accuracy of different approaches of discharge retrievals and the evaluation of the role of the different parameters and methods for their approximation.

Our hypothesis is that SWOT and SAR altimetry observations can make an unprecedented progress (1) to monitor the rivers water height and discharge and (2) to study the hydrological processes in ungauged river basins as well as hydrodynamic processes in large rivers. In the project REFECCT (Rehearsal of EFfective Flood Early warning and decision-support system to strengthen Coping Capacity and adapTation in West Africa) this hypothesis is tested.

Primary objective is to assess the capability of SWOT space data to detect river hydraulic characteristics and hydrodynamics processes in a gauged basin scenario with well-known hydrodynamics. The well gauged River Rhine in Germany, is the first Region Of Interest (ROI1) (Figure 1). First we consider the SWOT 1-day phase, with observation at the highest revisiting frequency, and further on the SWOT 21-day phase which covers spatially the complete river.

Secondary objective is to apply SWOT, once the SWOT observations are validated, to measure hydrologic quantities in ungauged African rivers (Mono River basin, Niger River, especially at Niamey and Port Harcourt), our second ROI (ROI2). This works prepares to establish a flood early warning system (FEWS) planned in the project (EFECCT) "EFfective Flood Early warning and decision-support system to strengthen Coping Capacity and adapTation in West Africa" submitted to the Bundesministeriums für Bildung und Forschung (BMBF) WASCAL II – Call for West Africa. (Mono River basin; Niger River, especially at Niamey and Port Harcourt).

The specific objectives of REFECCT are:
(1) understand the SWOT measurements and determine the domain of uncertainty
(2) investigate the hydrodynamic processes and their evolution
(3) investigate the use of SWOT data for analysing regional-to-global-scale responses of river flows to climatic phenomena, e.g. droughts and floods.

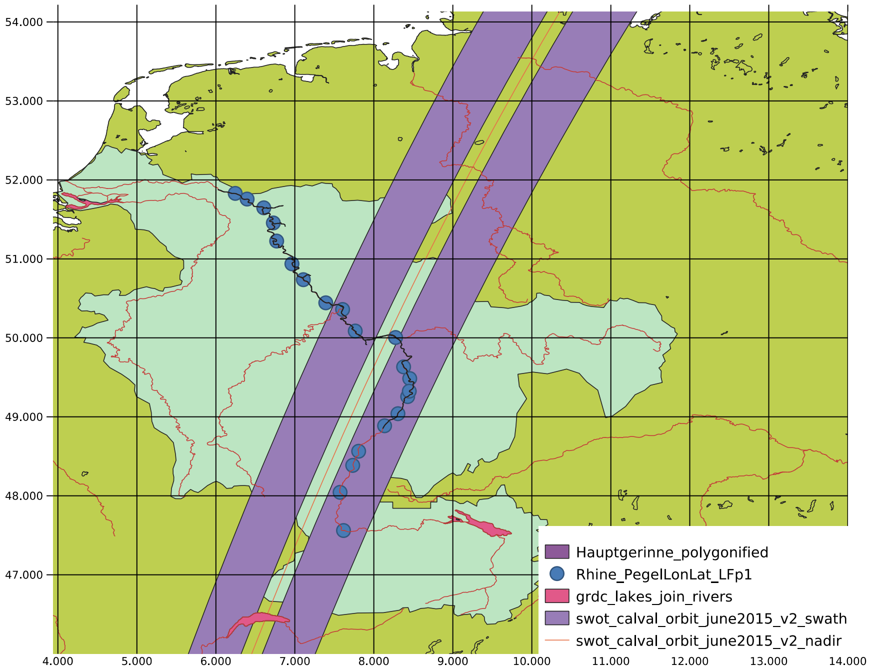

Figure 1. The international River Rhine basin with selected 21 gauges and the SWOT cal/val 1-day ground track

For the cal/val phase of SWOT the technical objectives are:
1) assess SWOT water height uncertainties in rivers

For application to hydrodynamical processes the technical objectives are:
1) estimate discharge from SWOT measurements
2) intercompare algorithms to derive river discharge from SWOT
3) estimate effect of measurement uncertainties on algorithm performance

For the understanding of response of the river system to climatic effects the technical objectives are:
1) study the evolution of the hydrodynamical parameters in time

2. Approach

This project uses standard and new type of observations and model data to investigate the model physical background and to learn on river processes, such as discharge and river flow. The following five open research questions have been identified. The last two are scientific questions.

(1) How can SAR-altimetry and SWOT-altimetry data be exploited at best in a river? How to improve the SWOT simulators and how to deal with SWOT errors and the huge high resolution data?

(2) Which is the accuracy of the models of the river?

(3) How to reduce the errors in estimating river discharge from the discharge algorithms and which are their effects in the final estimates?

(4) What is the reason of the multiyear and intra-annual hydrodynamic time variability along the river?

(5) What is the impact of climate change and extremes in river floods?

To answer (1) for satellite altimetry, we apply the best state-of-the-art processing to along-track SAR altimetry. To answer (1) for SWOT data, we first use simulated and real SWOT data to understand the SWOT signal. Validation with in-situ and model data allows to assess the improvements and the SWOT measurement error. Measurement error simulated in the SWOT simulators will be reconsidered if necessary. Processing tools for lower level data and point clouds are developed.

To answer (2) two models are compared to in-situ, along-track and SWOT altimetry. In ROI1 we use a hydrodynamic model and a hydrological model, in ROI2 only the second is applied. The one-dimensional hydrodynamic-numerical model SOBEK is based on the solution of the complete Saint-Venant equations, which consist of continuity and momentum equations. SOBEK is developed by Deltares, Delft (NL, http://delftsoftware.wldelft.nl/).
The one-dimensional hydrologic model GRA4J is a Precipitation-Discharge model, which inputs include observed precipitation and other meteorological regional data. Result is the discharge in a selected point. The accuracy of the discharge is ~ 5-15%.

To answer (3) discharge algorithms are selected and outputs are analysed for different running conditions and auxiliary input in the Rhine River.

To answer (4), (5) observation and model results are studied. Various methodologies are used, included statistical techniques and frequency analysis.

We derive the following objectives to address the five open research questions:

(Obj1) Use a multi-sensor approach including SAR (DDA), SAR interferometry (SARin), Satellite Imagery and SWOT data.

(Obj2) Characterize the ability of space-based observations (altimetry and simulated SWOT data) to register the hydro-metro events and their temporal variability (discharge, etc) in ROI1.

(Obj3) Characterize the capacity of (simulated) SWOT to register the spatial variability of the water height in different energetic conditions in the river

(Obj4) Analyse hydrodynamic processes in gauged and ungauged rivers

2.1 Analysis of existing multi-sensor data and models in ROI1 (IGG, BfG, UBochum, DLR)

This first tasks prepares modelling data, in-situ water level and discharge data and other auxiliary data (e.g. GNSS and levelling), river bed hydraulics, water level longitudinal profiles, velocity measurements from the Federal Waterways and Shipping Administration (WVS) handled by Federal Institute of Hydrology (BfG). In addition, morphology of the flood plain is prepared with very high spatial resolution based on lasers scanning measurements. Re-tracking methodologies improve the altimeter datasets. Water/flood masks from multi-sensor satellite data are derived from satellites.
Runs of the SOBEK-River model with measured water level and discharge data as forcing data are performed at BfG for a selected river stretch of the River Rhine. A spatially very detailed joined DTM for the river bed and the flood plain forms the backbone of this model, the resolution of the DTM is 25 metres. Beside simulations for the cal/val period, simulations will cover few years to include strong variabilities in river discharge storing the relevant hydrodynamic output in hourly resolution.
DLR developed an automatic and operational system for near-real time flood extent mapping based on multi-sensor satellite data. The system is mainly based on three fully automatic processing chains for the derivation of the flood extent based on Sentinel-1 and TerraSAR-X Synthetic Aperture Radar (SAR) as well as multi-spectral Sentinel-2 satellite data.

2.2 Analysis of simulated SWOT data (IGG)

In the pre-launch phase, SWOT data are simulated from in-situ and model data. In the 1D case, the effect of the revisiting time-interval of SWOT on the restitution of the temporal hydrological variability is studied by sampling water level and discharge time-series according to the frequency of SWOT at the selected locations. Observed and synthetic observations are compared in statistical analyses and multiresolution wavelet approaches.

2D SWOT data are simulated with the CNES LR SWOT hydrology simulator with input model data from the BfG model. The spatial and temporal variability is simulated under different hydrodynamic conditions of discharge and the SWOT capability to reproduce the hydrodynamic variability is studied. The JPL HR SWOT hydrology simulator could be of interest particularly under the right swath (between Bingen and Sankt Goar) due to possible layout effects.

2.3 Understanding SWOT Observations (IGG, BfG, UBochum, DLR)

The third task compares SWOT real data with in-situ, satellites and model data to understand the observed 2D variability in the 1- and 21-day orbits. The water height is calibrated against in-situ data with quantitative metric consisting of water level differences (STDD), bias (mean of differences), correlation. For the SWOT nadir altimeter measurements, the same procedure is applied. The wide swath low level (point clouds) and level 2 products are analysed.

UBochum will support the 1-day cal/val phase for German rivers with the HS Bochum measurement platform. This could be, in principle, used to validate 2D high-resolution river topography underneath the SWOT swath at the time of overpass, and thus generate river slope ground truth. It may be possible to equip the platform further for performing in-situ discharge measurements. However, the above would depend on funding.

BfG will contribute to evaluate and interpret the SWOT results using the hydrodynamical model and in-situ data. Parameters to be evaluated are: water height, discharge and slope. In-situ data from the WSV will be provided for means of comparison. Furthermore, it is planned to extend the BfG-GNSS-network to selected water gauges at the River Rhine to provide a consistent and stable reference. For the cal/val phase, special survey campaigns could be organized in cooperation with the WSV to provide reference results according to the needs of SWOT cal/val characteristics. These could, e.g., be ship-based water level measurements or airborne / UAV laser scanning surveys to provide continuous water level information at specific epochs. The amount of the measurement campaigns would, however, also depend on funding.

2.4 Hydrodynamic processes in a gauged basin (IGG, BfG, DLR)

The forth task investigates hydrodynamical processes in the gauged River Rhine. We investigate different methodologies and the impact of auxiliary datasets on the discharge retrieval accuracy. Various sets of satellite and ground information are needed in empirical and physically-based methods (altimetric water height and water slope, river width, depth, bed roughness parameters, floodplain characteristics). For more accurate discharge estimation, a preliminary analysis of fluvial characteristics of studied river reach is important. We consider three timescales: daily (operational use), monthly (operational and climate application) and annual (climate application). The latter two timescales will address the problem of altimetric temporal sampling. Including monthly and annual discharges in validation routines will demonstrate the performance of the satellites for climate research service. The validation of river discharge product will be done on a multi-criteria basis, including standard statistical scores such as the correlation coefficient, bias, root mean square error and Nash-Sutcliffe efficiency. Changes in amplitude and frequency of extreme heights and discharge are expected to be due to climate change.

2.5 Hydrodynamic processes in ungauged basins (IGG, BfG, DLR)

The methodology applied to the Rhine River in 2.4 to estimate the discharge will be applied to the poorly gauged or ungauged African rivers. The same hydrological model as in River Rhine is used.

3. Analysis and anticipated results

Preliminary work includes use of improved altimetry data in rivers (Schröder et al. 2019). In the Rhine at the Mainz level gauge the standard deviation STDD is 16 cm (Fig. 2).

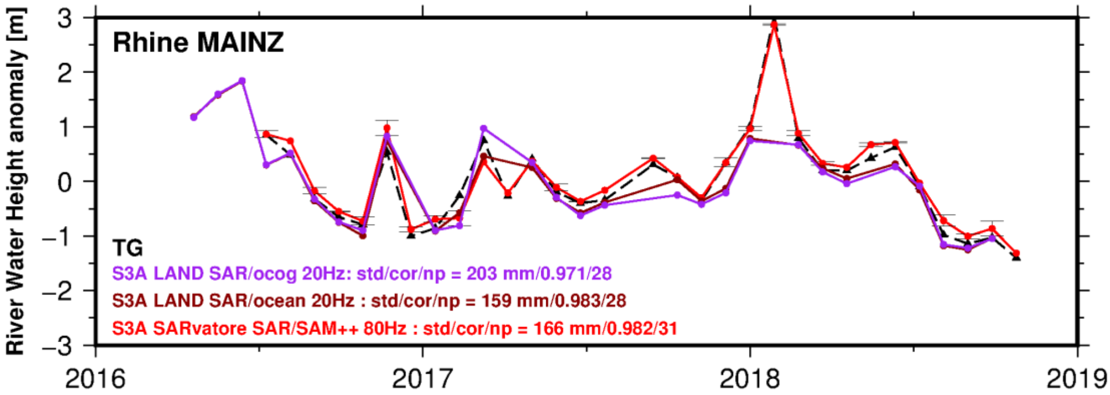

Fig. 2 Water height anomaly of the Mainz tide gauge (black) and of Sentinel-3A altimetry obtained with different processing, the Copernicus Land products with two retrackers and the GPOD SAMOSA++ products (red).

The slope of the River Rhine is derived from the SOBEK-River hydrological model and is shown for different water regimes in Fig. 3. The position of the stations along the river and their height are given in Fig. 4. We have run the CNES LR Hydrology Simulator for the mean water regime given in Fig. 3. Results in Fig. 5 represent the water height output of the simulator after averaging over 1.6 km.

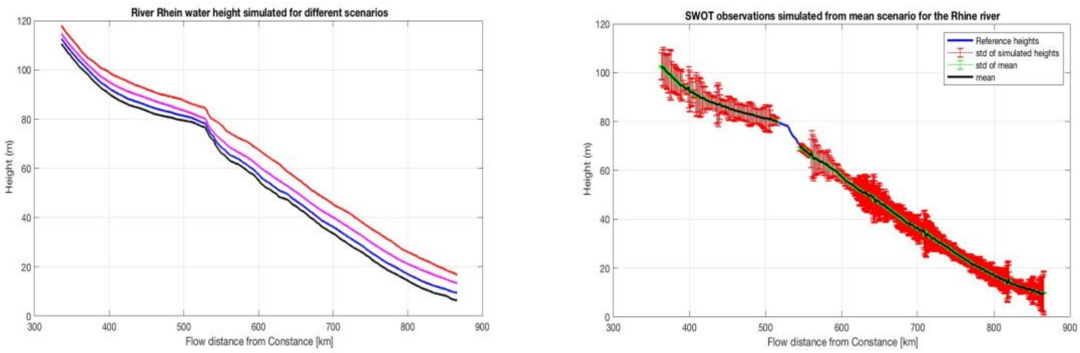

Fig. 3 (left) Slope of the free flowing River Rhine from the SOBEK-River hydrological model for different flow conditions. (right) water heights simulated with the CNES LR SWOT simulator for the section of the Rhine river for the mean SOBEK-River flow conditions

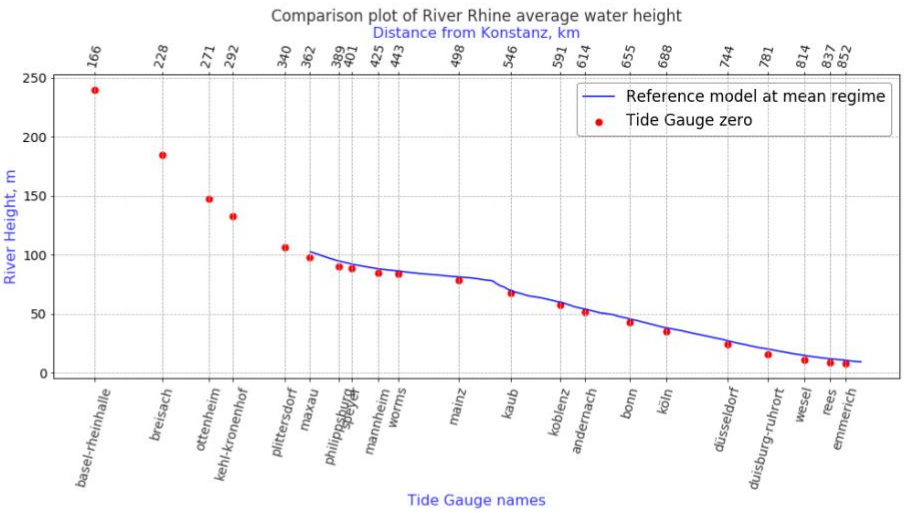

Fig. 4 Location of in-situ gauges along the river with 15 min Water height and Discharge. For gauge Mannheim and Koblenz only water level gauges are available due to backwater effects of larger tributaries. In addition, data of a multitude of water level gauges are available (not shown).

In a first attempt, we have evaluated the discharge for year 2018 for a section 80 km long between the gauge stations Kehl-Kronenhof and Speyer (Fig. 4) using the MetroMan algorithm (Durand et al. 2016). The stations are under the right swat. The input were water level and slope from in-situ data and constant river width extracted from Google Earth (Fig. 3). The discharge obtained is in good agreement with the discharge observed at the same stations (RMSE is 11%). In the further analysis, the hydrodynamic model will provide more precise inputs.

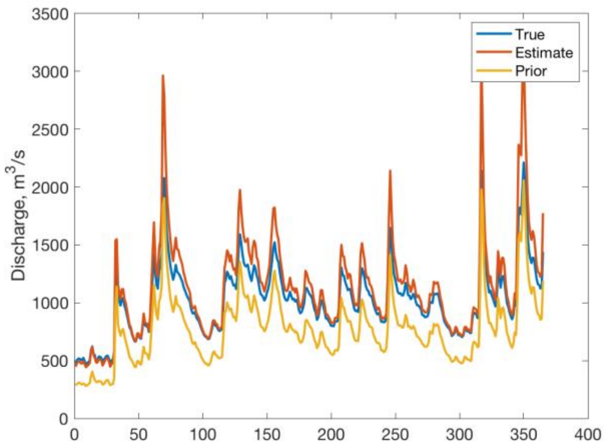

Figure 5. Time-series of discharge evaluated from the MetroMan algorithm using water level and slope from in-situ data and river width from Google Earth

The project REFECCT will assess the quality of the SWOT observations in the river Rhine. The ability to catch the extreme variability will be investigated. Based on that, SWOT will be applied to monitor climate extremes and flood risks in West Africa in the next phase.

We anticipate a contribution to:
1) calibration and validation of SWOT wide swath measurement of water height, discharge, slope, in the 1-day phase
2) calibration and validation of the nadir altimeter at tide gauges collocated with GPS
3) river hydrodynamic (1- and 21-day phase)
4) climate change and extremes (1- and 21-day phase)

The study presents innovative aspects concerning both data and results, which are:
1) Multi-sensor approach for space: Exploitation of the new altimetric high resolution datasets and of SWOT in the Rhine river. We develop and test methodologies which will be useful for state-of-the-art and future applications of altimetry in inland water. The Rhine river is suitable for this scope, due to the in-situ data available and its characteristics
2) Evaluation of limits of temporal and spatial variability recording in rivers
3) Evaluation limits of detecting extremes and water extent
4) Results will be used in another project for the development of a NRT flood early warning system

Finally, although REFECCT is not directly involved in the planned SWOT cal/val activities, results contribute to the cal/val. objectives, since a calibration of the nadir altimeter pointwise at tide gauges collocated with GPS is planned and the intensive analysis foreseen in the 1-day phase is meant to contribute to the understanding of the SWOT measurements.

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