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River Runoff Measurement with SAR Along Track Interferometry

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ABSTRACT

The paper summarizes the need for global space borne river runoff measurements. It reports about an airborne SAR experiment aimed to measure the surface speed of the river Isar. The results from two different SAR techniques, including Along Track Interferometry (ATI) show good correspondence. Finally suggestions for further studies are given.

INTRODUCTION

Rivers have always been vital lines of human communication and development. Already for a long time water level and discharge are observed in order to manage water resources and to minimize the potential dangers emerging from rivers. Today, observational networks of different quality regarding spatial coverage, measurement quality and operational continuity exist world-wide. These networks traditionally operate on local, regional or national scales and are administered by most different organizations (navigation, energy production, water supply and disposal, flood protection, irrigation etc.).
The growing interest on Global Change (climate, environment, demography) has lead to a growing need for discharge data on a global scale:

- Research of climate change requires understanding the closely coupled global water and energy cycles more exactly in order to improve global circulation models (GCMs). Discharge is the only variable in the water cycle where the measurement delivers an integrated value over a large area. In simplified terms, discharge describes the difference between precipitation and evaporation and thus is an essential variable for the calibration of models of these processes.
- Differences in salinity in the oceans due to changing freshwater inflows from rivers and ice-melt potentially influence the global ocean currents significantly.
- Changes in river discharge (and likewise in lake levels) are integrated indicators of changing conditions. Long, continuous discharge time series in global coverage make it possible to identify trends.
- Rivers are essential pathways for the transportation of natural and man-made material flows (sediments, toxic substances). Knowledge of river discharge is the basis for the computation of loads from concentration measurements.
- Along with the rapid growth of world population (2000: 6 billion, UN estimate for 2050: 9 billion people) the fresh water resources are of vital importance. Changes have to be explored and possibly detected, in order to be able to develop mitigation strategies.
- Climate change may influence the frequency and the extent of hydrologic extremes such as floods and droughts. Without a dense global network of continuously recording discharge gauging stations these phenomena cannot be analyzed comprehensively in a global context.

A global river discharge data collection was already demanded in 1980 by the World Metrological Organisation (WMO) within the Global Atmospheric Research Programme (GARP), more specific in the context of the First Global GARP Experiment (FGGE). This initiated the establishment of the Global Runoff Data Centre (http://grdc.bafg.de). Since then, continuous diligent efforts in data acquisition from National Hydrological Services (NHS) all over the world have lead to a database that today holds monthly discharge data at 7200 gauging stations and daily discharge data at 4700 stations. Despite the explicit support of GRDC by WMO, this database does not yet meet all the requirements set by the global research community, with respect to:

- *Topicality:* The maximum number of station discharge records in the GRDC database is available in the years around 1980. The rate of supply of more up-to-date in situ data from NHS is not sufficient to move this peak forward in time in the foreseeable future.
- *Coverage:* The global coverage is not homogeneous, particularly in Africa, Asia and Latin America there are still many gaps, either because there is no measurement or because countries do not make their data available for various reasons, including political restrictions, financial constraints or organisational problems.
- *Continuity:* The continuity of operation of river discharge gauging station networks is frequently at threat, even in industrialised countries. Many National Hydrological Services face significant budget curtailments preventing the extension of existing networks or, even worse, forcing them to abandon the operation of stations, especially in remote, difficult to access areas.
- *Standardization:* Even today, there are still cases where data cannot be provided digitally and if so, typically in heterogeneous formats and often with insufficient documentation (metadata). Standardization as a prerequisite for largely automated data integration procedures in near-real time is missing on a global scale.

Not only for the Third World a remote sensing tool is on demand, also in industrial countries a system which is capable to measure river discharge independently of in situ installations would be beneficial. In a flood event installations often get damaged or destroyed by debris and thus fail to provide a clear picture of the situation in the most important moment. In a flood plain where the water left the original river bed complex flow patterns may exist and a two-dimensional data acquisition is desired. Furthermore, in catastrophic conditions ad-hoc measurements are extremely difficult and dangerous for the staff.
The potential of measuring river discharge from space has been discussed already earlier [1, 2], however, for a long time it seemed that the necessary technology is not available. Therefore, it would be of high interest, if SAR techniques are able to detect surface velocity profiles across the river. The most convincing advantages of SAR are that it operates at high resolution (with the upcoming TerraSAR-X satellite up to 1m), at day and night and during all weather conditions. A radar satellite system dedicated to global discharge measurement would therefore be of great importance.

In order to determine the river discharge the river cross section has to be known and the mean flow velocity has to be determined by integration. It has already been demonstrated by several teams that SAR Along Track Interferometry (ATI) can measure surface water flow velocities. The company Aerosensing (today Intermap) reported from successful airborne SAR ATI measurements in the river Weser estuary [3] and with the ATI component on the Shuttle Radar Topography Mission (SRTM) several ocean currents have been mapped [4] . The results were compared with the best available hydrological models for a test site near Brest (P. Flament) and in the Dutch Waddenzee (R.Romeiser) and showed good correspondence [5]. A traffic monitoring project had been started at DLR after it was demonstrated that it is possible to measure even the speed of cars from space with high accuracy using SAR ATI [6].

EXPERIMENT AND SENSOR

An airborne SAR experiment was performed at the river Isar on April, 20th 2004 at 13h 22m on a sunny day with no wind. It was embedded in a larger campaign dedicated to the traffic monitoring project at DLR. For the overall campaign the same sensor, the experimental SAR system "ESAR" of DLR´s Microwaves and Radar Institute has [7] been used.
The X-band radar of the ESAR system has been used in the Along Track Interferometry (ATI) mode. The radar system and SAR processing parameters are provided in the following Table 1.

Table 1. ESAR radar and processing parameter

Sensor velocity	88 m/s
Sensor height above ground	3939 m
Incidence angle	30…53 deg
Antenna distance (ATI-Baseline)	0.87119 m
Radar wavelength	0.0311 m
Polarisation	HH
Processed Doppler bandwidth	200 Hz
Pulse repetition frequency PRF	1000 Hz

The sensor velocity and antenna distance provide an ATI time lag of about 10ms. Because only one antenna was active, the efficient ATI time lag was halved to 5ms [8]. The unambiguous ATI velocity range was +/- 3m/s.

The Test Site and In Situ Measurements

The Bavarian Hydrological Office maintains a dense network of gauging stations at the Bavarian rivers and lakes. The water level at these gauges are automatically measured and transmitted to the central facilities. Here the river runoff is calculated and a Web-Site is updated continuously.

The gauge "Puppling" at the river Isar near the city of Wolfratshausen which is about 25km south of Munich was selected for the experiment. Next to the gauge the Isar runs straight for more than 1km. About 3 km downstream the river from the station the river Isar merges with the river Loisach. Fig. 1 depicts the river network in this area and the location of the Puppling gauge. Here the river Isar is 30m wide and drains an area of 1,730 km². Over the web-site the runoff and the water level is available. Fig 2 provides an example from the 19th and 20th of April 2004, the day before and the day of the experiment (Courtesy http://www.hnd.bayern.de) .

Fig. 1. Location of the test site

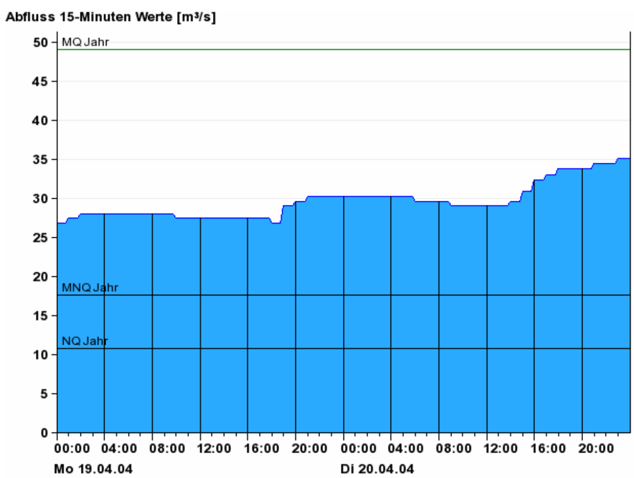

Fig. 2. River runoff at the test site

Beside the regular and automated stage measurements for calibration purposes also surface current measurements have been performed at the Puppling gauge at the day of the experiment. A propeller current meter has been towed across the river with a permanently installed cableway and over 12 locations across the river the surface current has been measured. The following measurement values (Table 2) have been reported from the Bavarian Agency for Hydrology [9].

Table 2. In-situ measurements

Maximum surface velocity	1.57 m/s
Average surface velocity	1.25 m/s
Average (cross section) velocity	1.12 m/s
Water level (stage)	1.17m
Active cross section	27.96 m²
Run-off	31.423 m^3/s

DATA ANALYSIS

The two channel SAR data have been pre-processed with the standard ESAR SAR processor at DLR´s Microwave and Radar Institute. The interferometric processing of the complex valued image pair has been done with the GENESIS InSAR processor of the Institute for Remote Sensing Technology. This is the same sensor and processing chain which has been used for the traffic monitoring experiment. Only the azimuth processing bandwidth appeared to be different: while for the traffic monitoring the full azimuth bandwidth has been used, only 200Hz have been used for the river measurements. In order to obtain reference data for the car experiment eight different moving objects were equipped with GPS receivers and recorders and their track and velocity had been registered. From the SAR data the velocity of the objects has been determined with measurements of the interferometric phase and of the displacement of a moving object in the SAR image. The latter so called "train off the track" effect causes a displacement of objects in the sensor flight direction ("azimuth") if they are moving towards or away from the sensor. Equation (1) shows how this shift Δ_{az} depends on the following parameters: R the range distance sensor-to-target, v_{los} the target velocity in radar line-of-sight and v_{sensor} the sensor velocity.

$$\Delta az = -R \frac{v_{los}}{v_{sensor}} \qquad [m] \tag{1}$$

The second method to measure the radial velocity component of a moving object is the evaluation of the along track interferometric phase Δ_φ, which depends on this component v_{rad}, the radar wavelength λ and the time lag between the measurement of the front and aft antenna Δ_t (2).

$$\Delta\varphi = 2\pi \frac{v_{rad} \cdot \Delta t}{\lambda} \qquad [rad] \tag{2}$$

A third method which uses the Doppler shift caused by the motion has not been considered here.
Both techniques applied measure only the line of sight (radial) velocity component of the moving object. Corrections have to be applied for the angle between the radar line of sight direction and the track of the moving object. This can be done easily because the direction of roads and rivers is well known or can be derived from the SAR image. When the heading of the moving object comes closer to the flight direction of the sensor the sensitivity is reduced. Therefore, the flight track of an air-borne sensor has to be adapted to the direction of the road or river. In the space-borne case with a fixed satellite orbit inclination not all sections of a winded road or river can be analysed. However, by using ascending and descending orbits this problem might be overcome. In a flood area a two-dimensional current measurement is on demand. In the air-borne case the aircraft would have to fly over the area of interest twice with two different headings.

In the traffic monitoring experiment, the speed measurement has been conducted with 90, 95 and 135 degrees between the flight track and the driving direction. The cars had a good radar backscattering or were fitted with corner reflectors. Their velocities have been computed from the interferometric phase measurements and compared with the GPS measurements. Due to the very good signal to noise ratio (SNR) and signal to clutter ratio (SCR) the RMS error was found to be low as 0,22 m/s taking into account 24 measurements. This is probably the maximum performance which can be achieved with the ESAR ATI system. A river surface has always a much lower radar backscatter and in case of a narrow river the signal of the displaced moving river surface has to compete with the radar backscatter of the river bank. In this case the signal of the river must be high enough in order to dominate the phase of the stationary background clutter signal. This situation relaxes when the river is wide enough and the displaced signal falls again on the river.

Fig. 1a shows the radar amplitude slant range image of the Isar test site near the Puppling gauge with the river Isar in the centre and the river Loisach in the lower left part. Fig. 1b provides the coherence image, where areas with phase changes (due to motion or noise) appear darker. There are "ghost lines" visible above the river Isar and Loisach which are caused by the displaced moving river surface.

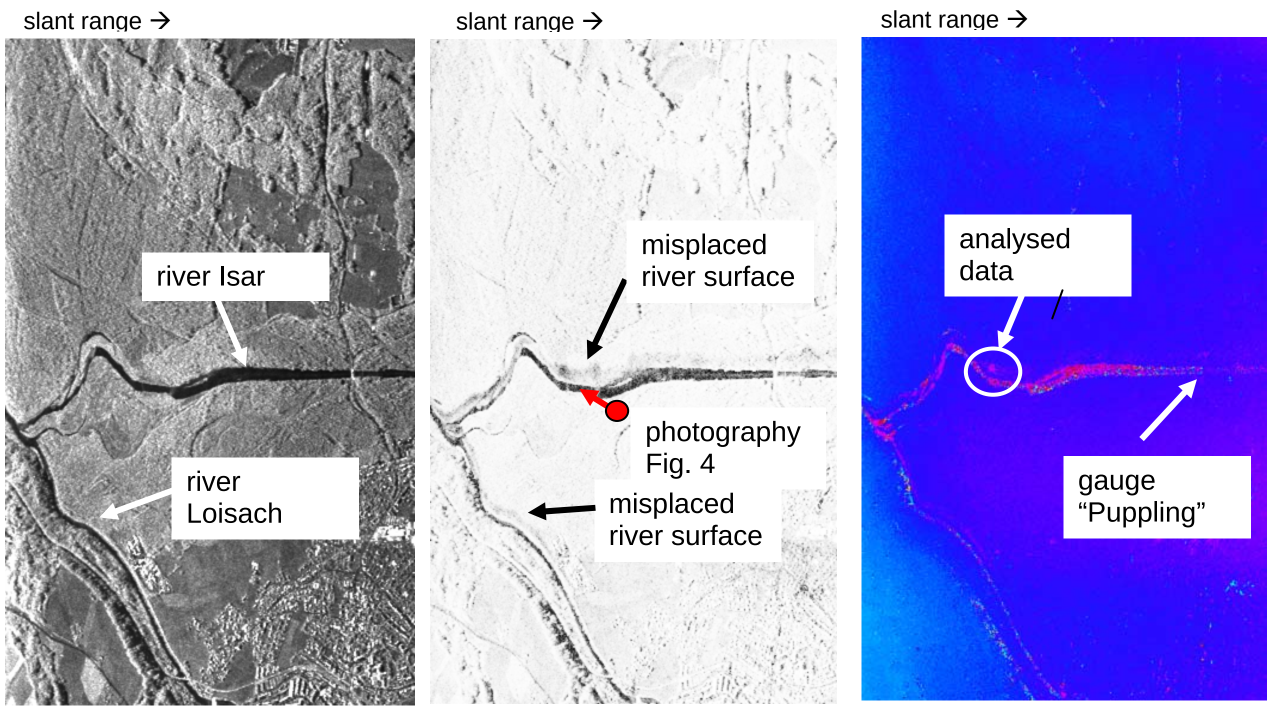

Fig. 3. a) SAR amplitude image b) Coherence image c) Phase image

The interferometric phase image is shown on the right (Fig. 3c). In the ESAR system the two antennas are fixed on the aircraft fuselage in a pure along track formation. Therefore, a phase change can only be generated by motion or by radar noise, but not by topography. Noise appears in shadow areas and in most parts of the river where the river surface has low radar backscattering. Here the surface is too smooth and the signal is reflected away from the sensor. Other surface areas may be too turbulent and will de-correlate and not produce a reliable phase signal. Furthermore we observed spots with relatively high backscattering, but no significant phase. Here the river surface is modulated from rocks in the river bed.

Finally only a few spots along the river generated a significant interferometric phase pattern on the river bank. Unfortunately very close to our reference site at the Puppling gauge no SAR velocity measurements have been possible. The area which has been finally analysed was app. 1500m downstream the Puppling gauge and is marked with a circle in white colour in Fig 3c. Photography of this area (Fig. 4) has been taken from the position and direction indicated in Fig. 3b.

Fig. 4 Photography of the analysed area

In Fig.5 the interferometric phase has been made unambiguous and converted to a ground range velocity from – 2.65 to + 2,65 m/s (taking into account the radar incidence angle). Only a part of the pixels is dominated by displaced motion effects, the major part appears green, which is equivalent to no motion. Here the clutter signal of the river bank was stronger than the signal from the river. Most of the pixels that bear a significant motion phase (blue, negative sign) indicate a flow direction towards the sensor (from right to left). Some pixels appear in red (flow direction away from sensor) which is probably caused by noise.

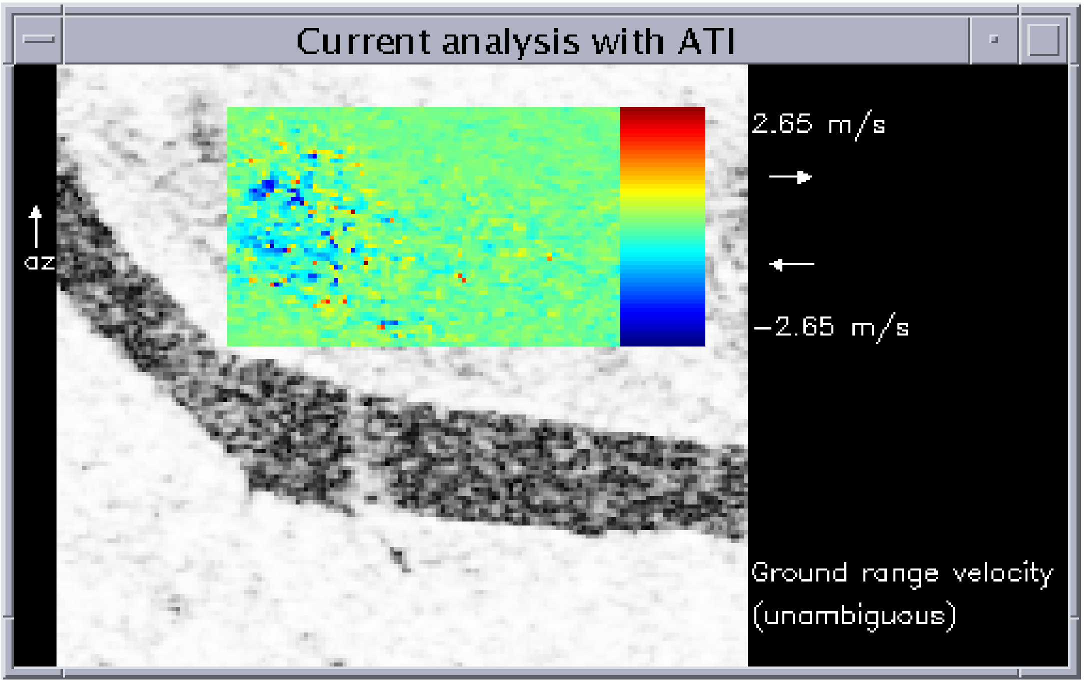

Fig. 5 Evaluation of the ATI phase

In the next step (see Fig 6) a verification of the result has been performed. If the pixel phase values that correspond to the expected velocities are really caused by the river current, they must have been displaced in the SAR image away from the river to the river bank due to the "train-off-the-track" effect. Thus, taking the line of sight velocities that were derived from the phase measurements and converting them to shifts in the azimuth direction by using (2) one should obtain displacement values that, if applied with the opposite sign, should place back those pixels on the river. In deed, while the "static" green pixels stay on the river bank, most of the blue pixels in question overlay with the river, which is a proof that both methods led to the same result. Please note that the velocity scale is a little higher in Fig. 6 than in Fig. 5 since the velocity values have been projected from the ground range direction onto the true river flow direction.

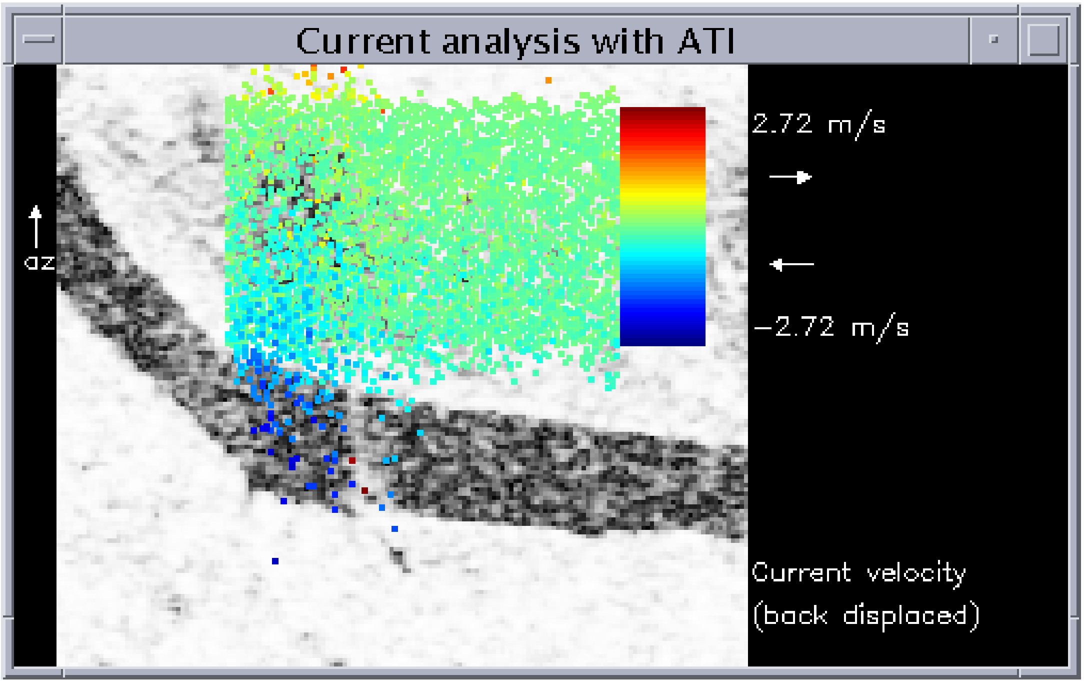

Fig. 6 Back projection of pixels with movement in azimuth direction

In a last step (Fig. 7) only the velocity values of the pixels found over the river (marked with a red square) after placing them back have been considered in a statistic evaluation. As a final result it was found that the mean velocity was 1.50 m/s, the minimum velocity 1.01 m/s and the maximum velocity 2.30 m/s. (Please note that in Fig. 7 the colour bar has been adapted.)

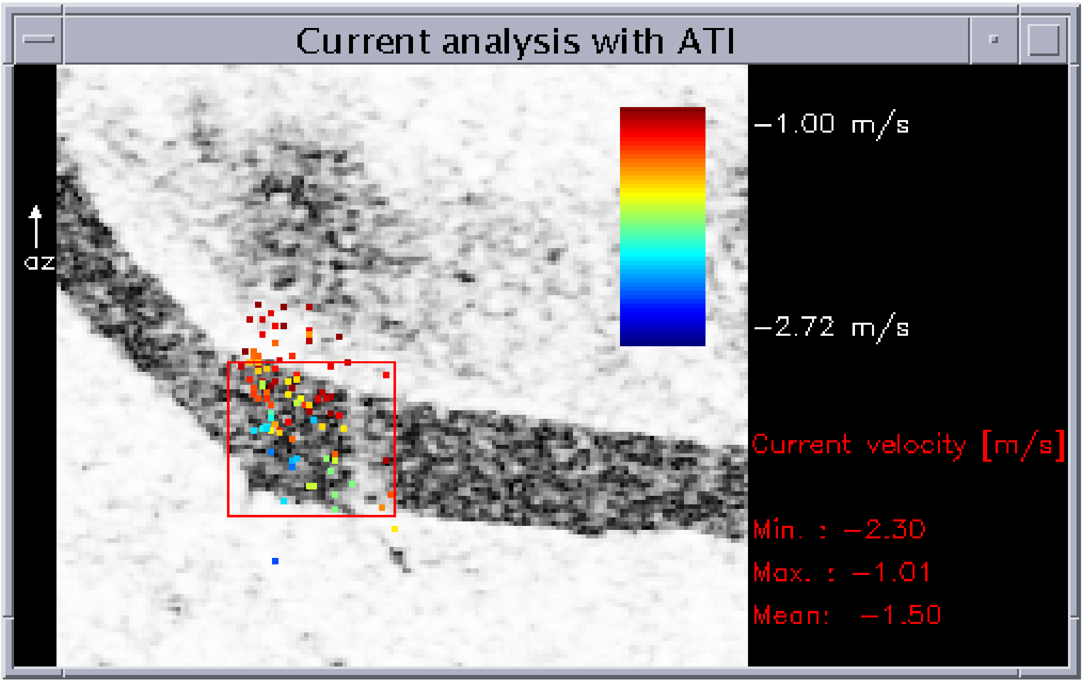

Fig. 7 River surface velocity determination from back projected pixels

CONCLUSION

The radar measurements are double checked with two different methods based on different effects, the along track interferometric phase and the azimuth displacement due to the "train off the track effect" and both lead to an average surface velocity of 1.50 m/s. This has been measured 1500m downstream the river from the Puppling station. Taking into account that the river bed and the fall of the Isar in this region are quite varying we found good correspondence with the reported average surface velocity at the Puppling station of 1.25 m/s. However, the radar measurement has only been possible at certain locations and even here not all pixels could be taken into account.

It has to be kept in mind that this experiment was a first trial of the method and the instrument was not optimized for this purpose. SAR techniques including Along Track Interferometry seem to be interesting tools to measure the surface currents of rivers in remote regions where permanent gauging stations are difficult to maintain. The techniques should work at least with steep radar incidence angles and with rivers wide enough that the displaced energy still falls on the river and not on the river banks. In order to calculate the river run-off in m^3/s the sites would require a sporadic access to update the river cross section and to generate tables with the relationship between stage and surface velocity.

OUTLOOK

In order to further develop this remote sensing application more investigations have to be performed:

- The experiment needs to be repeated with an acquisition of ground truth data exactly at the location of the radar measurement.
- Also larger river than the Isar with a more steady behaviour should be analysed. Furthermore, the test area should be located in the near range part of the radar swath, because the backscatter at steep radar incidence angles is much better than in far range, were the Puppling gauge was located in this experiment.
- It has to be determined which accuracy can be reached with the different SAR techniques and whether the user requirements can be met.
- It needs to be investigated which conditions are required to generate sufficient radar backscatter and stable floating surface structures and where these conditions are likely to be found.
- How must an ideal air-borne and space-borne SAR sensor for this application be designed?
- An alternative or complementary method would be to measure the water level (stage) with across track SAR interferometry. This technique will suffer from the same problem of low radar backscatter over rivers but it has to be investigated weather it may lead to more accurate results for the river run-off.

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REFERENCES

[1] D. Bjerklie, S. Dingman, C. Vorosmarty, C. Bolster, and R. Congalton, "Evaluating the potential for measuring river discharge from space," *Journal of Hydrology*, Vol. 278. pp. 17-38, 2003

[2] C.J. Koblinsky, R.T. Clarke, A.C. Brenner, and H.V. Frey, "Measurement of River Level Variations with Satellite Altimetry," *Water Resources Research*, 29, pp. 1839- 1848, 1993

[3] R. Siegmund, M. Bao, S. Lehner, and R Mayerle, "First Demonstration of Surface Currents Imaged by Hybrid Along- and Cross-Track Interferometric SAR," *IEEE Transactions on Geoscience and Remote Sensing*, 42(3), pp.511-519, March 2004

[4] H. Runge, S. Suchandt, H. Breit, M. Eineder, J. Schulz-Stellenfleth, et al., "Mapping of Tidal Currents with SAR along Track Interferometry," *Proceedings of IGARSS 2004*, Anchorage, USA, IEEE, 2004

[5] R. Romeiser, H. Breit, M. Eineder, H. Runge, P. Flament, et al., "Validation of SRTM Derived Surface Currents off the Dutch Coast by Numerical Circulation Model Results," *Proceedings. of IGARSS 2003*, Toulouse, IEEE, 2003

[6] H. Breit, M. Eineder, J. Holzner, H. Runge, R. Bamler: "Traffic Monitoring using SRTM Along-Track Interferometry,". *Proceedings of IGARSS'03*, Toulouse, France, IEEE, 2003

[7] ESAR airborne SAR description: http://www.dlr.de/hr/institut/abteilungen/sar-technologie/fg/flugzeug-sar

[8] R. Bamler, Ph. Hartl, "Synthetic Aperture Radar Interferometry." *Inverse Problems*, 14, 4, S. R1-R54, 1998

[9] Personal communication with K.H. Frei, *Bayrisches Landesamt für Wasserwirtschaft*, Tel.: + int. (0)89 9214 1578