FluViSat

Hydrological Flow Measurement
from Satellite Video

Planet Labs PBC

Technical Note on the Opportunities for EO Services

Guy Schuman and Nick Everard

Client Ref: 4000136226/21/I-DT-lr
Version 2
Date 04/12/2022

Title	Technical Note on the Opportunities for EO Services
Client	European Space Agency
Client reference	4000136226/21/I-DT-lr
Disclaimer	The FluViSat Project was carried out under the eo science for society programme of, and funded by, the European Space Agency. The views expressed in this report can in no way be taken to reflect the official opinion of the European Space Agency.
UKCEH reference	D2-4b_WP4_04122022_V2
UKCEH contact details	Prof Harry Dixon Centre for Ecology & Hydrology t: +441491692254 e: harr@ceh.ac.uk
Authors	Guy Schuman and Nick Everard
Project Team	Guy Schuman, Nick Everard, Mark Randall, Sunita Sarkar, Harry Dixon

Contents

1. Purpose

This note provides a technical and commercial assessment of the implications and opportunities for EO data providers, relating to hydrology and wider applications of high-resolution EO video data. It includes recommendations to ESA about the benefits of a next generation Sentinel mission with video capabilities, whether dedicated to hydrology or not, which have been generated from the FluViSat project. This proof-of-concept study showed the potential use of satellite-collected video imagery to accurately determine water flows in rivers using surface velocimetry. Opportunities for improving video capabilities and overcoming limitations experienced during the project are considered, and the potential of SAR and other satellite technologies to improve the method are explored.

2. Summary of project achievements

The FluViSat project builds upon the well-proven method for velocimetry-based measurements from the air (mostly using drones, but also using fixed or mobile cameras) and asked the question as to whether camera sensors on satellites can be used for the same application. The answer was developed by synchronising the collection of river surface flow speeds and other metadata on the ground, with the acquisition of EO video imagery, and comparing the results.

A number of areas of interest (AOIs) were identified by the project team at the start of the project. Sites were chosen which where possible conformed to the following:

- Rivers in excess of 60 metres wide
- Fast flows, generating visible features, and feature displacements large enough to be visible in the satellite imagery
- High flow conditions typically persist for a length of time
- Accessible for making validation measurements with drones and Acoustic Doppler Current Profilers (ADCP)
- Acquisition of EO video is possible
- A gauging station nearby, in case field measurement is not possible

The space asset used for the project was the high resolution SkySat optical satellite constellation operated by Planet Labs PBC. This fleet of satellites was designed for targeted collection at specific times of interest and precisely defined locations. A total of 21 active SkySats allow Planet to capture imagery of any location on earth, anything up to seven times a day, offering the potential for multiple daily observations of the same location.

Satellite image velocimetry derived discharge and channel mean velocity data was validated for five sites across Australia, Japan, Switzerland and the UK. The results from each of the sites were all within the +/-10% bounds that the project had set based on accepted hydrometric practice. In fact, where intercomparisons between field and satellite-derived data were closely synchronised, the results were within 1% of each other.

The FluViSat method was further demonstrated in two use additional cases, the Zambezi and Indus rivers. Surface water velocities derived from the August satellite videos acquired for the Zambezi, below the Victoria Falls, showed expected spatial patterns of water speed, and a reduction in speed over the two dates video was captured. This aligned with the available data from the local monitoring agency. In September 2022, a number of satellite videos were tasked for two locations on the Indus River in Pakistan, to capture the devastating flooding that was taking place. Despite some issues with tasking and stabilisation, the results obtained provide a powerful message that satellite video can be used to measure water flow in remote locations even in extreme conditions.

Demonstrating that space imaging technology can be used for high-repeat, high-accuracy water or flood flow measurements across river landscapes could fundamentally change the way we (as a global community) can monitor and measure important hydrological parameters and manage high impact flood disasters. Remote sensing, especially satellite-based sensing, is particularly valuable for areas in the world that are either not well instrumented or lack instrumentation altogether, or for areas that are difficult to measure in or access, for example in high flow conditions or during flood events.

The next sections will explore further opportunities with existing space assets and discuss new opportunities for satellite-based sensing, but in short, it is clear that the outcomes of this project are already paving the way for a possible game-changing future applications in hydrometry at the global scale.

3. Exploring further opportunities with existing space assets

This section outlines more generally work already done in the area of satellite-based velocimetry measurements, prior to the FluViSat project. The section showcases some noteworthy studies using optical and SAR imaging technologies.

3.1. Optical

Prior to the FluViSat project, two notable studies had been published, which employed high resolution optical imagery from space to estimate flow velocity, with acceptable levels of accuracy.

Kääb *et al* (2019) exploited the short time lag between successive PlanetScope cubesat images to track river ice flows on northern rivers as indicators of water surface velocities (Figure 1). The PlanetScope constellation consists of hundreds of optical cubesats that are evenly distributed like strings of pearls on two orbital planes, scanning the Earth’s land surface once per day with an approximate spatial image resolution of 3-m. Successive cubesats on each of the orbital planes, image the Earth’s surface with a nominal time lag of approximately 90-s between them, which produces near-simultaneous image pairs over the across-track overlaps of the cubesat swaths.

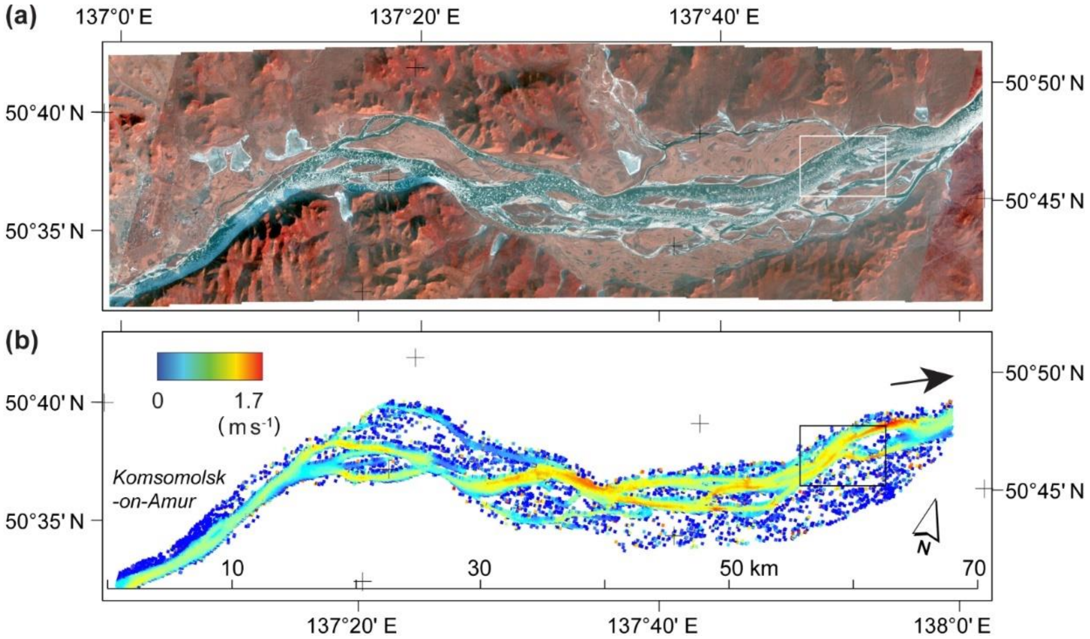

Figure 1 Amur River near the city of Komsomolsk-on-Amur, Siberia (lower left corner). River surface velocities on 1 November 2016 are tracked over a 73 s time lag between overlapping Planet cubesat images. (a) A false colour composite of one of the image strips, and (b) the derived surface speeds. The overall flow direction is from left to right. (Kääb *et al* 2019)

The second notable study in the context of space-based flow measurement is by Legleiter and Kinzel (2021). In an ongoing effort to develop non-contact methods for measuring river discharge, their work evaluated the potential to estimate surface flow velocities from satellite video of a large, sediment-laden river in Alaska via particle image velocimetry (PIV). In this setting, naturally occurring sediment boil vortices produced distinct water surface features that could be tracked from frame to frame as they were advected by the flow, obviating the need to introduce artificial tracer particles. In their paper, they emphasized the need for refining stabilisation, geo-referencing and image preprocessing. Their results confirmed the importance of preprocessing images to enhance contrast and indicated that lower frame rates (e.g., 0.25 Hz) lead to more reliable velocity estimates, because longer capture intervals allow more time for water surface features to translate several pixels between frames, given the relatively coarse spatial resolution of the satellite data.

Figure 2 illustrates that even for the lowest frame rate that yielded the strongest agreement with the ADCP measurements, the dimensional version of the RMSE was 0.5 m/s, indicating that PIV of the satellite video failed to provide precise estimates of surface flow velocity on a point-by-point basis at high spatial resolution.

Although further research and technological development are needed, Legleiter and Kinzel (2021) also argue that measuring surface flow velocities from satellite video could become a viable tool for streamflow monitoring in certain fluvial environments.

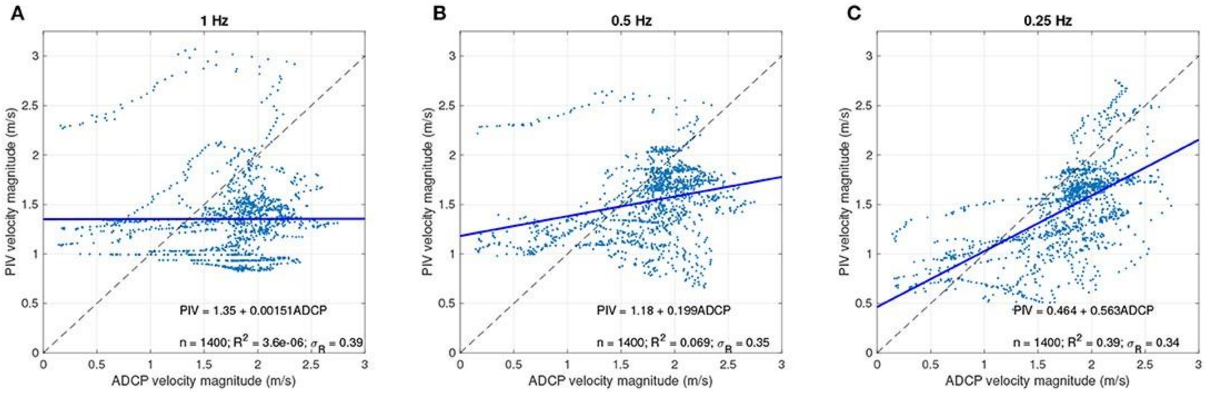

Figure 2 Observed (ADCP) vs. predicted (PIV) regressions for the entire study area (i.e., aggregated over all seven cross sections) for different image frame rates: (A) 1 Hz, (B) 0.5 Hz, and (C) 0.25 Hz. (Legleiter and Kinzel, 2021)

3.2. Synthetic Aperture Radar

Biondi *et al* (2020) propose a novel procedure based on azimuth multichromatic analysis (MCA) and along-track interferometry (ATI) to estimate river surface water-flow velocities exploiting only one synthetic aperture radar (SAR) image. Along-track interferometry (ATI) is a SAR technique which allows for the combination of two or more SAR images of the same scene. Data are acquired from different positions, separated by a physical baseline along the azimuth direction. Then, the phase differences are estimated from all co-registered pixels, which are proportional to the Doppler shifts of the backscattered radar echoes. This feature can be suitably exploited to estimate the surface velocity of water masses.

For estimating flow velocities from SAR ATI, the raw data are first filtered in the Doppler domain in order to create two sub-apertures, which are then refocused, obtaining a couple of single-look complex (SLC) SAR images. It follows that azimuth resolution band of the two SLC images is half of the original resolution. The two SLC SAR images are used to form an interferogram and the phase interference is evaluated to investigate the Doppler behavior exhibited by fixed targets with respect to others sharing the same motion characteristics.

In their paper, Biondi et al. (2020) conducted this study on live airborne full-polarimetric SAR data, and the performance analysis highlights the effectiveness of the proposed approach in providing reliable river surface velocity estimates without the need for multiple passes over the observed scene (Figure 3).

At present, it is rather unclear how SAR ATI would perform on satellite SAR images, coming for instance from the Sentinel-1 constellation, or indeed, any other SAR constellation being able to deliver image data in interferometric mode.

The above point is important, even more so in view of commercial SAR constellations, since some of the currently offered high-resolution commercial SAR constellations are not delivering any interferometric mode data.

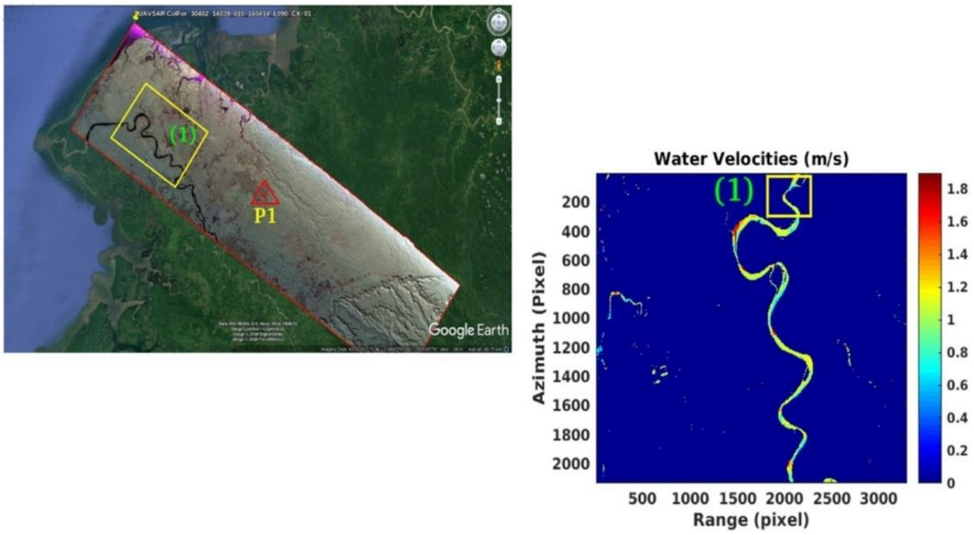

Figure 3 Map of the airborne SAR image (left) used to derive the water velocity measurements shown in the plot on the right. (Biondi *et al 2020*)

4. New opportunities for satellite-based sensing

During the FluViSat project, the team also explored a second closely related and highly innovative satellite velocimetry technique and through this experience have devised a list of possible opportunities and improvements for satellite-based sensing. These are summarized here.

4.1. Still Frame Velocimetry

The ESA Earthnet-supported access to Planet's All Frames data that has taken place in parallel to the FluViSat project, has explored the potential of high-framerate still imagery for the determination of surface water speed. Initial results have demonstrated that the movement of very fast flowing water in large rivers can be detected and quantified using just two frames of still imagery, with a short time separation between them.

Compared to the FluViSat video-based method, still frame velocimetry offers greatly reduced costs for image acquisition and opens up the potential for satellite-based velocimetry to a much larger number of satellite providers, and at a wider range of sites.

As no project funding was available for this exploration of All Frames data, dedicated field-based validation of still frame imagery has not been possible to date.

Comparisons with FluViSat videos results have been possible at some locations, showing very positive results.

Further exploration and refinement of the potential of still frame imagery is recommended and should include:

- Field-based validation of still frame velocimetry
- Exploration of new imagery sources that could potentially greatly improve results by offering improved resolution and a larger image footprint
- Refining image processing methods to improve workflows and sensitivity of technique
- A cost-benefit analysis of still frame versus video velocimetry methods

Furthermore, there is a need to match this new capability to suitable providers of imagery, potential applications, end-users and a community to help drive further development. Efforts should be made to apply the FluViSat and Still Frame Velocimetry methods to high impact flood events, in order to raise awareness and demonstrate the high societal and economic value of the innovation to other sectors such as disaster risk reduction and re-insurance.

4.2. Improving pre-processing and rectification of imagery

Pre-processing and rectification of imagery is vital to enabling satellite-based velocimetry with both video and still-frame imagery. Improved processing techniques and simplified workflows that enable faster processing and improved accuracy of results need to be developed.

4.3. Targeted rapid response application for flood major events

Satellite-based velocimetry has the potential to deliver extremely valuable information during major climate-related emergencies, such as extreme flood events. However, in order for this to work there is a need to develop methods to enable the rapid acquisition of imagery, combined with a streamlined workflow to allow the production and sharing of actionable information during major flood events. This should be conducted in partnership with EO imagery providers and potential customers for improved results.

4.4. Optimizing video acquisition and site selection

It became evident as the project progressed that there were a number of challenges with the quality of the video and the locations where video was possible. This appeared to be linked to factors such as the satellite viewing angle or orientation relative to the sun, or simply the optical quality of the sensors onboard. Further work with imagery providers can help optimize the timing and positioning of satellites to deliver more usable videos for velocimetry measurements. Furthermore, there needs to an improved understanding of site characteristics that are best suited to satellite velocimetry, so that imagery can be obtained for locations where the best results will be achievable (for all forms of river discharge measurement, the location where the measurement is made is of critical importance).

4.5. Building the community

Refinement and uptake of this new hydrometric approach is dependent on building a community of practice that brings together a network of global experts from both the EO and hydrology sectors. This approach has proved successful in previous ‘revolutions’ in hydrometric technologies – for example, the uptake of ADCPs in the 1990s and early 2000s. ADCPs are now the benchmark for field-based measurements.

In addition to this, there is need to actively engage with relevant potential user sectors, such as hazard management agencies, reinsurance companies etc., in order to create a user community and have real-world applications for the technology.

5. Downstream market applications for predicting surface water dynamics

Conventional, field-based streamflow monitoring in remote, inaccessible locations such as Africa, Alaska or Pakistan for instance, or indeed during flood flow conditions, poses logistical challenges. Safety concerns, financial considerations, and a desire to expand water-observing networks make remote sensing an appealing alternative means of collecting hydrological data.

A vast amount of literature exists in the area of integrating satellite-derived water extents, flooded areas, and water levels with model predictions of water flow and flooding. Assimilation of those variables into hydrodynamic models has been shown by numerous studies to improve flood predictions. It is therefore clear what satellites can offer in the context of river and flood monitoring.

Prior to the FluViSat project and the isolated single research case studies outlined in the previous sub-section, it had appeared that flow velocity could not readily or operationally be directly observed from space. However, because of the importance of knowing and understanding river flow velocity, this capability has always been at the top of the wish list of everyone interested in measuring and monitoring surface water dynamics.

River and floodplain flow velocity is vital for predicting the magnitude, timing, and likely impacts of flood waves. Scientists and decision-makers use flood wave timing to estimate and issue, as accurately as possible, vital flood alerts. With the exception of some field-based point measurements of velocity or measurements at some river cross-sections, accurate hydrodynamic models are required to simulate spatially and temporally distributed velocity fields of water flow along river channels and across adjacent floodplains.

In contrast to field-based observations, remote sensing technologies, especially satellite sensors, offer the advantage of measuring variables over large spatial coverage and, particularly when used in a constellation, can also deliver the required temporal revisit – in the case of commercial constellations, this can be sub-daily.

River flow velocity is a critical variable for inferring discharge, without a doubt the most important variable to measure in fluvial hydrology. However, for most rivers in the world, discharge data is either not available or not accessible. Therefore, using satellite-based measurements of important linked variables such as water level and velocity, would enormously benefit the global hydrological community. The upcoming measurements of water surface slope and river/lake levels, soon to be provided by the NASA/CNES Surface Water Ocean Topography (SWOT) mission (for more context, see Biancamaria *et al* 2016; scheduled launch date December 2022) provides an exciting new opportunity to explore combining SWOT outputs with satellite-derived flow velocities, to derive discharge.

Finally, flow velocity along with flow depth are the key variables that inform potential damage to flood defences and other important infrastructure assets. As such, there would potentially be great interest in this new method from water resource managers, city planners, (re)insurance sector, and flood model vendor companies in the operational and global production of accurate 2-D flow velocity fields.

6. References

Biancamaria, S, Lettenmaier, DP, Pavelsky, TM. 2016. The SWOT Mission and Its Capabilities for Land Hydrology. *In*: Cazenave, A, Champollion, N, Benveniste, J, Chen, J. (eds) *Remote Sensing and Water Resources*. Space Sciences Series of ISSI, vol 55. Springer, Cham. https://doi.org/10.1007/978-3-319-32449-4_6

Biondi, F, Addabbo, P, Clemente, C, Orlando, D. 2020. Measurements of Surface River Doppler Velocities With Along-Track InSAR Using a Single Antenna. *In* IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing. v13, pp. 987-997. doi: 10.1109/JSTARS.2020.2976529.

Kääb, A, Altena, B, Mascaro, J. 2019. River-ice and water velocities using the Planet optical cubesat constellation. *Hydrol. Earth Syst. Sci*. 23, 4233–4247 https://doi.org/10.5194/hess-23-4233-2019

Legleiter Carl J, Kinzel Paul J. 2021. Surface Flow Velocities From Space: Particle Image Velocimetry of Satellite Video of a Large, Sediment-Laden River, *Frontiers in Water*. 3, https://www.frontiersin.org/articles/10.3389/frwa.2021.652213

Contact

enquiries@ceh.ac.uk

@UK_CEH

ceh.ac.uk

Bangor

UK Centre for Ecology & Hydrology
Environment Centre Wales
Deiniol Road
Bangor
Gwynedd
LL57 2UW

+44 (0)1248 374500

Edinburgh

UK Centre for Ecology & Hydrology
Bush Estate
Penicuik
Midlothian
EH26 0QB

+44 (0)131 4454343

Lancaster

UK Centre for Ecology & Hydrology
Lancaster Environment Centre
Library Avenue
Bailrigg
Lancaster
LA1 4AP

+44 (0)1524 595800

Wallingford (Headquarters)

UK Centre for Ecology & Hydrology
Maclean Building
Benson Lane
Crowmarsh Gifford
Wallingford
Oxfordshire
OX10 8BB

+44 (0)1491 838800

The FluViSat Project was carried out under the eo science for society programme of, and funded by, the European Space Agency.
The views expressed in this report can in no way be taken to reflect the official opinion of the European Space Agency.

UK Centre for
Ecology & Hydrology