Response to Reviewer 2

General Comments

Reviewer Point P 2.1 — This paper presents an interesting study on the use of a camera gauge for long-term measurement of flow velocity and discharge. Its structured and clear approach, coupled with the evaluation of an automatic system over a period of approximately one year, is a noteworthy contribution. Also, the discussion of interpolating and extrapolating surface velocities demonstrates the potential of camera gauges as a viable supplement or maybe even alternative for continuous monitoring in hydrology. However, I think, there are several areas where further elaboration or clarification is needed. The paper focuses primarily on the methodological aspects, and therefore, I think it would be more suitable to be considered as a technical note rather than a research paper. This reclassification would better reflect its contribution.

Reply: Thankyou for the constructive comments. We will seek to implement each of these suggestions in the revised manuscript, and below outline how this will be achieved. With regards to the placement of the article as 'Research article', or 'Technical Note' I will take further advisement on this decision from the Editor. However, from a personal perspective, although the article is indeed technical in nature, we hope that the contribution goes beyond what would be expected of a 'note' and that this could be considered as a 'Research article' contribution.

Reviewer Point P 2.2 — The authors assume stable intrinsic and extrinsic parameters throughout the year-long observation period. This assumption warrants deeper discussion, particularly in light of potential influences like temperature changes (e.g. as shown by Elias et al., 2020) or environmental factors like wind causing camera movement. Would a frequent update of the position/orientation not be needed? What are the expected error ranges if no update occurs? Addressing these issues in more detail is necessary to increase the robustness of the conclusions.

Reply: This point about the assumption of stable intrinsic and extrinsic parameters is an interesting one. Firstly I would like to address the extrinsic parameters (related to the stability of camera orientation):

We agree that a stable frame of reference is critical when deploying camera systems in an automated workflow across prolonged deployment periods. Without the continuous presence of GCPs, we rely on calibrating the extrinsic camera parameters at a single point in time (at the start of the monitoring period). We have performed some analysis on the intra-image stability of the camera orientation between the start (March 2018) and the end (January 2019) of the monitoring period (Figure 1). When we compare clearly visible points (corners of the stage boards located on the far bank), we can identify that the pixel coordinates of the edges are comparable between images (within 1-2px). Using the point cloud survey obtained on-site at the time of camera setup we can estimate that the width of the gauge board is 22cm. Therefore imagery offsets at this distance are likely to be in the order of 1–3cm, which is within the general uncertainty of the registration process. We will incorporate these findings in the revised manuscript, and advocate for assessments such as this as standard practice. Furthermore, we will highlight the benefits of permanent GCP networks in deployments that permit which would enable a time-series of extrinsic parameters to be established. In terms of the stability of image sequences within a single video, the impacts of small frame-to-frame movements may have an impact on the quality of velocimetry reconstructions and we do not seek to quantify this in this article. The role of external environmental conditions (wind, rain) on reconstruction quality is certainly a valid and open question in the field, but this is beyond the scope of the current investigation. Our method of analysing multiple videos for a given flow stage and adopting the median of the 1D velocity estimates for comparison purposes seeks to minimise the effects of external environmental factors which may affect the quality of the velocity field reconstruction for individual videos.

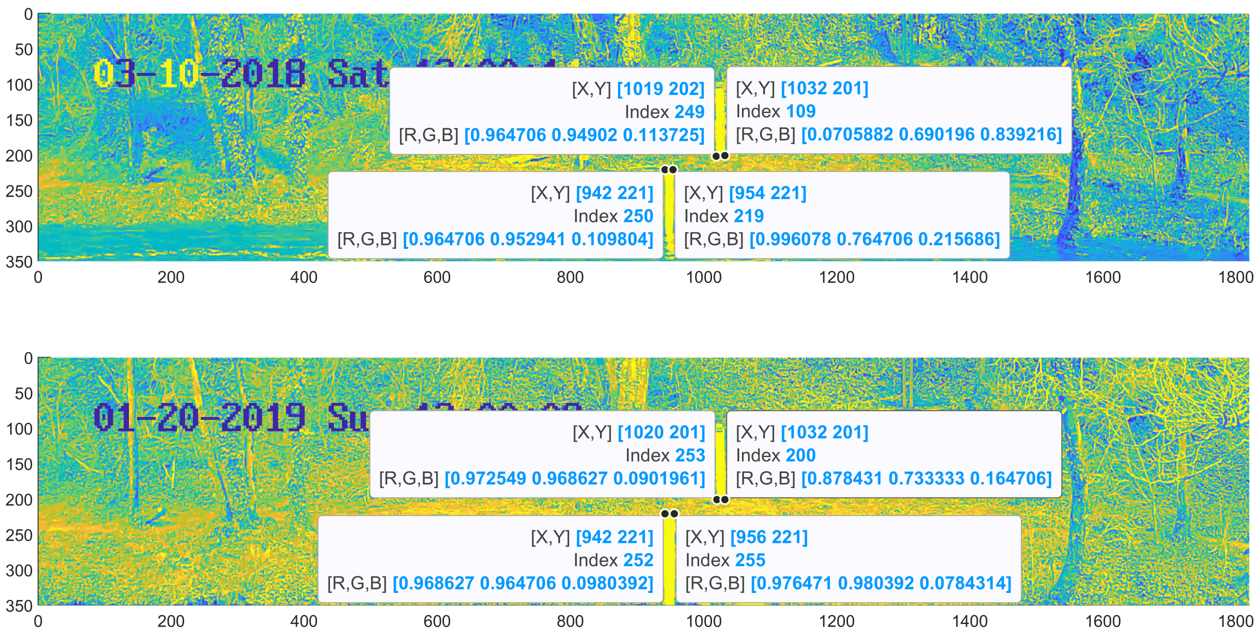

Figure 1: Testing the consistency between images acquired on the first and last day of analysis. Note: the [X,Y] labels within the imagery describe the pixel locations of the stage board edges.

With regards to the stability of intrinsic parameters, this is not something that we have considered in our analysis and as far as I am aware this has not been assessed with reference to the application of image velocimetry. Prior to deployment the camera calibration coefficients were established in a controlled lab setting using a checkerboard, but we have not assessed the influence of external environmental characteristics on this. This is an interesting point and we thank-you for bringing this to our attention. We will provide some discussion around this element in *Section 4.3: Uncertainties in image analysis*.

Reviewer Point P 2.3 — The assumption of stable flow conditions during the calibration period also needs further exploration. I think, it would be beneficial to discuss how this impacts measurement accuracy, particularly over extended periods with potential varying riverbed or cross-sectional conditions. The authors could include further metrics such as standard deviations and deviations from the reference measurements temporally resolved during the observation period to provide more insight of such influences.

Reply: Significant changes to the riverbed and cross-section morphology could indeed have impacts on the Q (and resultant 1-D velocity) estimates that we produce and the potential for this source of error will be highlighted further in *Section 4.3: Uncertainties in image analysis*. In this particular case, whilst there is evidence for significant geomorphic change at this site (in 1979), one of the reasons that this location was selected due to its stable rating curve over the intervening years. Indirectly, the presence of a stable rating curve would provide evidence for the cross-section also being stable. Furthermore, as reported in the research article, our analysis of repeat surveys between 2010 and 2018 indicate that the cross-section has changed by no-more than 5% across the full range of flows experienced. We have since discovered an additional geodetic cross-section survey conducted in October 2020, which further illustrates the stability of the channel cross-section at this location (Figure 2). The differences in profile elevations between 5-10m on the x-axis is a consequence of a new cableway stanchion being built (Figure 3). This was erected after the field experiment was completed. All of the data available to us indicates that morphological change at the location of the field experiment is negligible. However, we do acknowledge that this may be a significant factor for some locations.

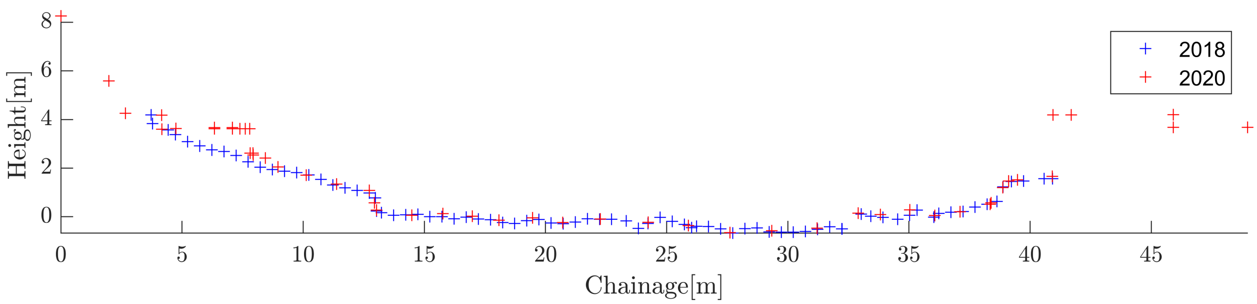

Figure 2: Cross-section survey data at the experimental site acquired in 2018 and 2020.

Figure 3: Image showing the presence of a new cableway stanchion installed in February 2020 (after the end of the field experiment documented here).

Reviewer Point P 2.4 — This study highlights the great potential of camera gauges for long-term, nearly continuous monitoring of hydrometric parameters. However, further discussion of the methodological assumptions and calibration limitations would greatly enhance its applicability.

Reply: Thank-you. We hope that our additional assessment of the stability of extrinsic camera parameters, and time-series analysis helps to allay any concerns about the apparent methodological assumptions that we make in the research article.

Further smaller comments

Reviewer Point P 2.5 — L38-41: The description of the Lucas-Tomasi method should clarify that it is not a stand-alone approach to Particle Tracking Velocimetry (PTV) or Particle Image Velocimetry (PIV). Rather, it is another matching algorithm besides, e.g., NCC or FFT based approaches – however with the advantage of being a least square approach allowing for particle rotation and deformation during tracking, that complements particle detection methods or grid-based strategies.

Reply: Following the comments of Reviewer 1 and Reviewer 2 in relation to this sentence, we have altered this text so that the focus is on optical flow methods generally rather than to a particular algorithm. The text has been revised to read: *These computer vision algorithms e.g. Kande-Lucas-Tomasi algorithm (Lucas and Kanade, 1981; Tomasi and Kanade, 1991; Shi and Tomasi, 1994), automatically identify pixels that are distinct from their neighbours, and these distinct features can be iteratively tracked through a sequence of images.* More specific information regarding the method employed within the current study can be found in *Section 2.5: Image Processing.*

Reviewer Point P 2.6 — L104: Clarify what is meant by a 'distorted camera model'. Do the authors mean a camera model that describes the intrinsic camera parameters including distortion parameters?

Reply: Yes, by distorted camera model we mean a camera model that describes the intrinsic camera parameters including distortion parameters, as opposed a simple pinhole model. In the revised document we will clarify this.

Reviewer Point P 2.7 — L107: The role of location and orientation (iii) in the workflow needs clearer distinction. Are these parameters derived from ground control points (GCPs) via spatial resection? This should be elaborated for better understanding. Is the location/orientation not the consequence from using the GCPs measured in the image and in the object space and then estimating the location/orientation using, e.g., spatial resection?

Reply: Within the KLT-IV software the user may choose to manually fix the camera's position and/or orientation, in which case these parameters will not be allowed to vary in the optimisation process. However, under normal use (and in this particular case), the user would simply provide an estimate of the camera location and orientation. These free parameters would then be optimised with the use of GCPs as you allude to in your comment.

We have sought to clarify this in revised document by stating that *(iii) initial estimates of the location [x, y, z] and orientation of the camera* should be provided. In terms of the specific approach used in the optimisation of the camera model, later on in this section we write that: *the camera location and view direction (yaw, pitch, and roll) was initially estimated using the point-cloud survey. These characteristics were then defined as free parameters and optimized to minimize the square projection error of the GCPs using a modified Levenberg–Marquardt algorithm.*

Reviewer Point P 2.8 — L120: Confirm whether the projection error refers to deviations in object space or image space, i.e., do you indeed mean projection error or rather reprojection error?

Reply: Thank-you for this comment, the method seeks to optimize the camera by projecting the GCP world coordinates to image coordinates and comparing the fit to the GCPs in image space [px]. My understanding is that this would be termed projection error.

Reviewer Point P 2.9 — L163: There is already a study showing that one surface velocity from image velocimetry is enough to get discharge with entropy approach (Bahmanpouri et al., 2022)

Reply: Thank-you for brining this to our attention, we will include reference to this work.

Reviewer Point P 2.10 — L228-232: What is the reason for the deviation?

Reply: Greater error estimates in the near field of the imagery under the highest flow conditions are likely to be a consequence of the water surface deviating from our planar assumption. Due to camera orientation, water surface undulations will have a greater impact on the velocity reconstructions in the near-field than in the far-field of the imagery. In the revised version of the manuscript we will make reference to *Section 4.3*, where we discuss possible uncertainties in the image analysis process.

Reviewer Point P 2.11 — L245: The distribution of the eight reference measurements across different water levels should be clarified. It is critical to evaluate whether these measurements adequately represent the range of conditions encountered at the specific study site. Might it be more important to consider range of water level at which reference available and how well this represents most gauge situations?

Reply: We will provide clarification on this point in the revised manuscript. In the approach that we adopt, the reference observations are randomly selected from the database of flow gauging measurements (spanning 1980–2018). Therefore the random selection of (n) gauging's is conditioned by the frequency distribution of the gauging data. Inevitably, few flow gauging measurements are obtained at the highest flow magnitudes, with the median of the gauged discharge values being 6 $m^3 s^{-1}$. Whilst perhaps ideally, calibration of the index approach would seek to utilise samples from the entire flow range, this is unlikely in a real-world deployment. Therefore, it made sense for us to use the distribution of the actual flow gauging record to inform the sampling protocol.

Reviewer Point P 2.12 — L304: The authors can estimate the error influence theoretically by varying the water level and flow velocities and see how strong changes of estimated velocities are.

Reply: Absolutely, and this is an active area of research for us. We are currently working to see how altering representation of the water surface may be used to refine velocity reconstructions when the assumption of a planar surface is violated. This analysis is currently under way and will be published as a separate research article.

Reviewer Point P 2.13 — References – Note, please do not consider the references as a suggestion to be implemented in the manuscript rather than a proposal to more literature to underline my comments made: Elias, M., et al. (2020): Assessing the influence of temperature changes at the geometric stability of low-cost chip cameras. Sensors, (https://www.mdpi.com/1424-8220/20/3/643) Bahmanpouri, F., et al. (2022): Estimating the Average River Cross-Section Velocity by Observing Only One Surface Velocity Value and Calibrating the Entropic Parameter. Water Resources Research, (https://doi.org/10.1029/2021WR031821)

Reply: Thank-you for providing these references.
