Flow Mapping Workshops Background and Update:

- We require flows maps for answering PUNCH science questions
- PUNCH proposal already prescribed tested, published techniques for generating quantitative solar wind speed maps: speed at 4 altitudes between 5 and 80 Rsun at a 6 hour cadence. This is the piece that has to be delivered by the SOC.
- The purpose of the flow mapping workshops is a) to do the best we can (even better than requirement), and b) to find synergies in techniques across Heliophysics.
  - Informal pre-work August 2020
  - First workshop November 2020
  - Second workshop July 2021- Huge THANK YOU!! to PUNCH Associate Investigators Raphael Attie and Bea Gallardo-Lacourt for leading the organization of the July 2021 flow mapping meeting!

PUNCH Flow Tracking WG Objectives

1) **Understand the various methods and characterize their performance on different fronts (small/large scale, close/far from Sun, directionality)**
2) **Work on adapting these methods in preparation for use on PUNCH data.**
3) **Optimize measurement method for model interpretation**

How to do this?

- **Establish benchmark(s) to compare methods**
  - Real heliospheric data: STEREO COR2 deep fields, Aurora, PSP, SoLO, etc.
  - Modeled data
  - Synthetic PUNCH data
  - Non-heliospheric data: Middlebury Optical Flow Benchmark dataset https://vision.middlebury.edu/flow/data/ (both real and synthetic)

Understand how coronal structures become the ambient solar wind

M1. Measure velocity vs latitude (source) and radius (acceleration/advection) on **global** scales

- Nonradial
- Out of plane/ 3D-ish vs. POS
- Multi-LOS features
- Acceleration and variable speed

M2. Measure velocity vs latitude and radius on smaller scales e.g. **shears, gradients, and smaller compression regions**, and relate to density structures and their evolution

- M1 measurements but focused on differences/ranges/outliers
- Small-scale structures: evolution and development
- Inferring anisotropy in small-scale k and flows

M3. with WG2, measure relationship between smaller flows, global flows, **with singular large structures** (CMEs and CIRs)

- Same as above but with a CME/CIR or shock in measurement realm

M4. Characterize **inward** flows and waves

Which methods can meet these measurement goals best? How can we tell?

Several talks showing the state of the art on imagery-based flow tracking techniques in heliophysics

- Optical flows, physics-informed methods, Convolutional Neural Nets (e.g. CNNs & U-Nets)
- Advantages & limitations: particular effort must be done on error estimates.
- Importance of comparing and validating flow measurements against “a ground truth” using numerical simulations and involving in-situ missions: e.g. plasma Flow Tracking Challenge from Vadim Uritsky offers readily available datasets to test many flow tracking algorithms.
- Started drafting guidelines for PUNCH data products related to flow mapping.

Numeral simulations will play a key role in developing reliable plasma flow maps for PUNCH

- Provide a “ground truth” to build benchmarks and compare flow tracking methods
- Examples already or soon to be available like the GAMERA code: MHD-simulated white light images AND flow fields.
- Routine that makes simulated images to look like PUNCH images for realistic estimates of the flow tracking performance
    - baseline to work with, even if the simulation is not as realistic as it could be.
    - Will help assess how much the flow of optically thin brightness pattern correlates with the “true” underlying flow fields.
- Ongoing discussions on the realism of the numerical simulations: any tracking technique evaluated on a simulation may inherit the biases of the numerical simulation. Supervised Deep Learning methods should pay a particular attention to this aspect.

The future of flow tracking cannot just rely on computer vision or supervised Machine Learning

- Inescapable limitations: e.g. aperture problem, wave vs. mass transport ambiguity, simulation biases
- Should focus more on physics-based methods: in the tracking algorithm, can we add an equation that the derived velocities should obey?
- Should Develop e.g. a minimization problem within the tracking algorithm that enforces certain MHD equations to be satisfied?

PUNCH Science Operation Center (SOC) and interaction with PUNCH Flow Trackers

- SOC main focus: deliverability of data, not the integration of software developed by PUNCH users.
- The PUNCH SOC pipeline may support some flow mapping software integration but would require the flow tracking algorithms and their authors to comply with several requirements (language, code structure, data I/O format etc…).
- High data throughput: full cadence & resolution, in compressed form: ~150 GB per day
  => prompts for scalable workflows for many projects, which may discourage or encourage the use of certain programming languages when developing new codes or adapting legacy codes.

Discussions on all of the above continued within the PUNCH Flow Mapping Group at helionauts.org