Velocity Field Analysis for Edge Turbulence Imaging

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Abstract

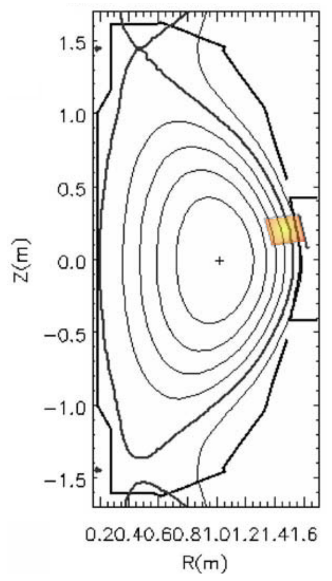
The Gas Puff Imaging (GPI) diagnostic is used to observe and record the propagation of turbulent perturbations of the plasma density and temperature in the edge regions of NSTX. These turbulent perturbations, or "blobs", form elongated filaments in the direction of the local magnetic field and are quickly ejected from the confined plasma. The Hybrid Optical Flow Velocimetry (HOP-V) code was developed for extracting time-resolved 2-D velocity maps from turbulence imaging diagnostics, including the NSTX GPI instrument. Combining optical flow and local pattern matching techniques, HOP-V derives "dense" velocity fields at the full temporal resolution and a fraction of the spatial resolution of the underlying image frames. We believe that these derived fields closely correlate to the bulk fluid flow of the NSTX plasma. The code has been validated for a variety of artificial test patterns of convective flow, including highly sheared cases. Recent work includes statistical analysis of a large number of NSTX shots in both L-mode and H-mode, with an investigation into a wide variety of flow properties. Furthermore, a new linearized approach for estimating dense solenoidal (divergence-free) optical flow fields has been developed. Recent results and outstanding questions from our research will be presented in this poster.

Gas Puff Imaging (GPI) Diagnostic in NSTX

Neutral Helium is injected into NSTX:

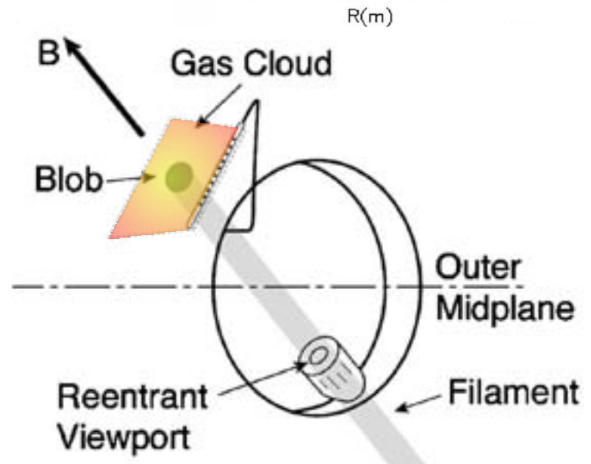
- Gas manifold puffs a minute amount of neutral gas in a sheet perpendicular to local field lines
- Neutral gas shows characteristic spectral line emission due to interaction with plasma electrons (e^-)
- DEGAS 2 neutral transport model shows *He I* spectral line intensity varies with local plasma e^- density and temperature:

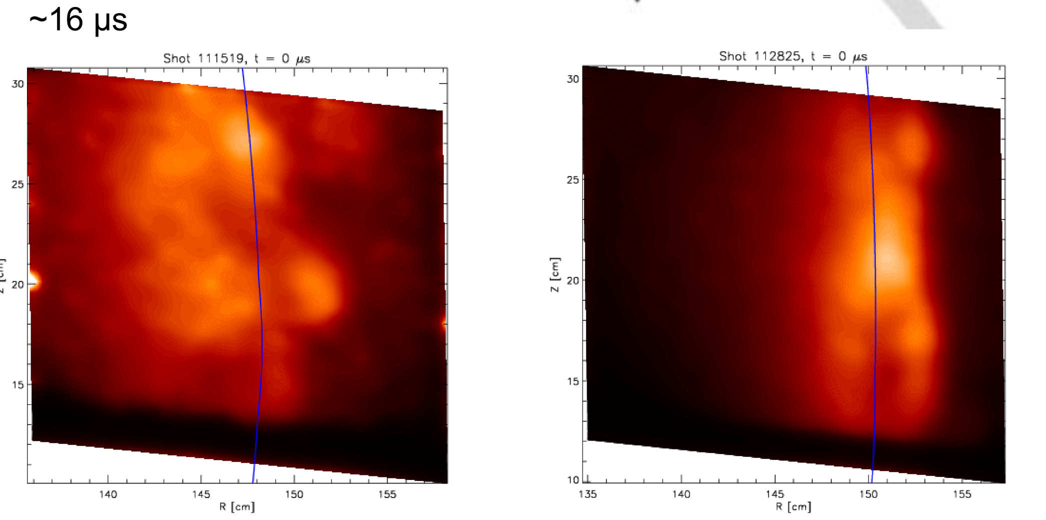
$$I(\vec{r},t) \propto n_e^{0.5}(\vec{r},t)\, T_e^{0.7}(\vec{r},t)$$



Fast-framing camera views along field lines from reentrant viewport:

- View area:
  - 22×22 cm (64×64 pixels)
- Spatial resolution:
  - ~1.5 cm
- Frame rate:
  - 250 kHz
- Length of single dataset (shot):
  - 300 frames
- Turbulent plasma autocorrelation time:
  - ~16 μs





Hybrid Optical Flow Velocimetry (HOP-V)

HOP-V employs a hybridized technique to derive velocity fields:

- Optical Flow
  - Basic Equation

$$\frac{dI}{dt} = \frac{\partial I}{\partial t} + \vec{\nabla}\cdot(I\vec{v}) = \frac{\partial I}{\partial t} + \vec{\nabla} I\cdot\vec{v} + (\vec{\nabla}\cdot\vec{v}) I = 0$$

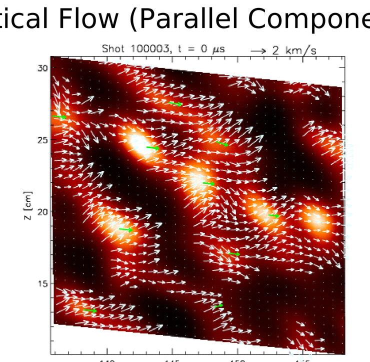
  - V-field Decomposition and Partial Solution

$$\vec{\nabla}\cdot\vec{v}=0,\ \vec{v}=\vec{v}_{para}+\vec{v}_{perp},\ \vec{\nabla} I\cdot\vec{v}=|\vec{\nabla} I||\vec{v}_{para}|,\ \vec{v}_{para}=\frac{\frac{-\partial I}{\partial t}\vec{\nabla} I}{|\vec{\nabla} I|^2}$$

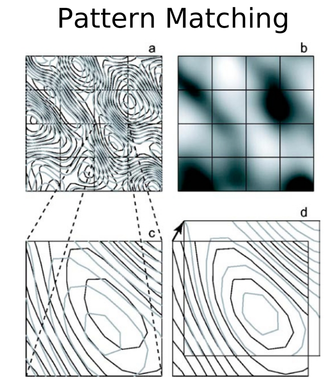
note: This technique is valid only for solenoidal (divergence-free) fields, and can only determine the component of the field parallel to the image gradient.

- Pattern Matching
  - Start with Optical Flow solution
  - Decompose frame into several sub-images
  - Displace each sub-image, finding optimum match on subsequent frame
  - Best matching field minimizes a designed objective function:
    - Penalize the absolute integrated difference in intensity of each sub-image to its position on the subsequent frame
    - Penalize shearing in the derived field

Optical Flow (Parallel Component)

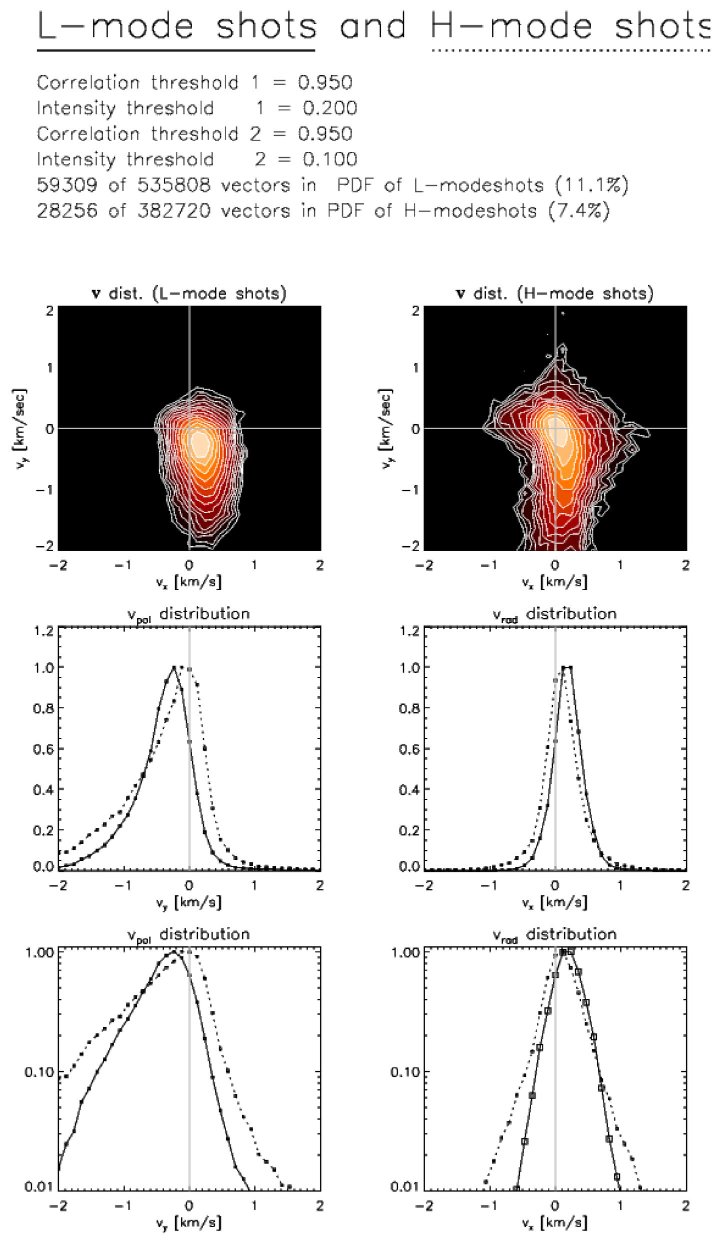


Pattern Matching



Recent statistical analysis of NSTX GPI datasets (shots):

- ~5 similar shots each of L-mode and H-mode operation
- L-mode Statistics:
  - Peak radial velocity of 0.15 km/s, Peak poloidal velocity of -0.25 km/s
  - Distribution reflects bulk unidirectional (mostly) poloidal flow
- H-mode Statistics:
  - Peak radial and poloidal velocities are very close to zero
  - Distribution reflects stronger unidirectional poloidal flow (extended wings)
  - PDF made of fewer ballistic "blobs" due to intensity thresholding



Solenoidal (Divergence-Free) Optical Flow Estimation

Following the work of J. Yuan and C. Schnörr (2007), we employ the finite mimetic difference method and Helmholtz decomposition:

- Represent the image set and velocity field on primal/dual scalar/vector grids
- Discretize primal/dual differential operators that mimic their continuous counterparts

$$\vec{\nabla} f,\ \vec{\nabla}\cdot\vec{u},\ \vec{\nabla}\times\vec{u},\ D_t f$$

note: These operators must preserve similar identities, e.g., discretized versions of the Gaussian integral identity and the Helmholtz decomposition.

- Decompose the velocity field into the gradient of two scalar potentials

$$\vec{v}=\vec{\nabla}\psi+\vec{\nabla}\phi$$

  - Laminar and curl-free flows are captured by the gradient of ψ

$$\vec{\nabla}\psi=\vec{v}_{laminar}+\vec{v}_{curl-free},\ \vec{\nabla}\times(\vec{\nabla}\psi)=0$$

  - Solenoidal flows are captured by the gradient of φ

$$\vec{\nabla}\phi=\vec{v}_{solenoidal},\ \vec{\nabla}\cdot(\vec{\nabla}\phi)=0$$

Design regularizing objective functionals for each velocity potential that are minimized by the "best" optical flow field estimate with vanishing divergence:

- Optical flow objective functional

$$J_0(\psi,\phi)=\left|D_t I+\vec{\nabla} I\cdot(\vec{\nabla}\psi+\vec{\nabla}\phi)\right|^2$$

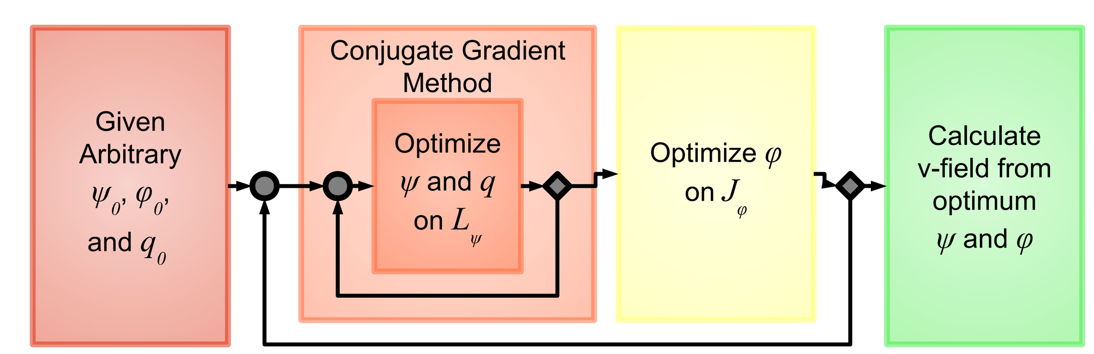
- ψ Augmented Lagrangian (with φ held constant and Lagrange multipliers q)

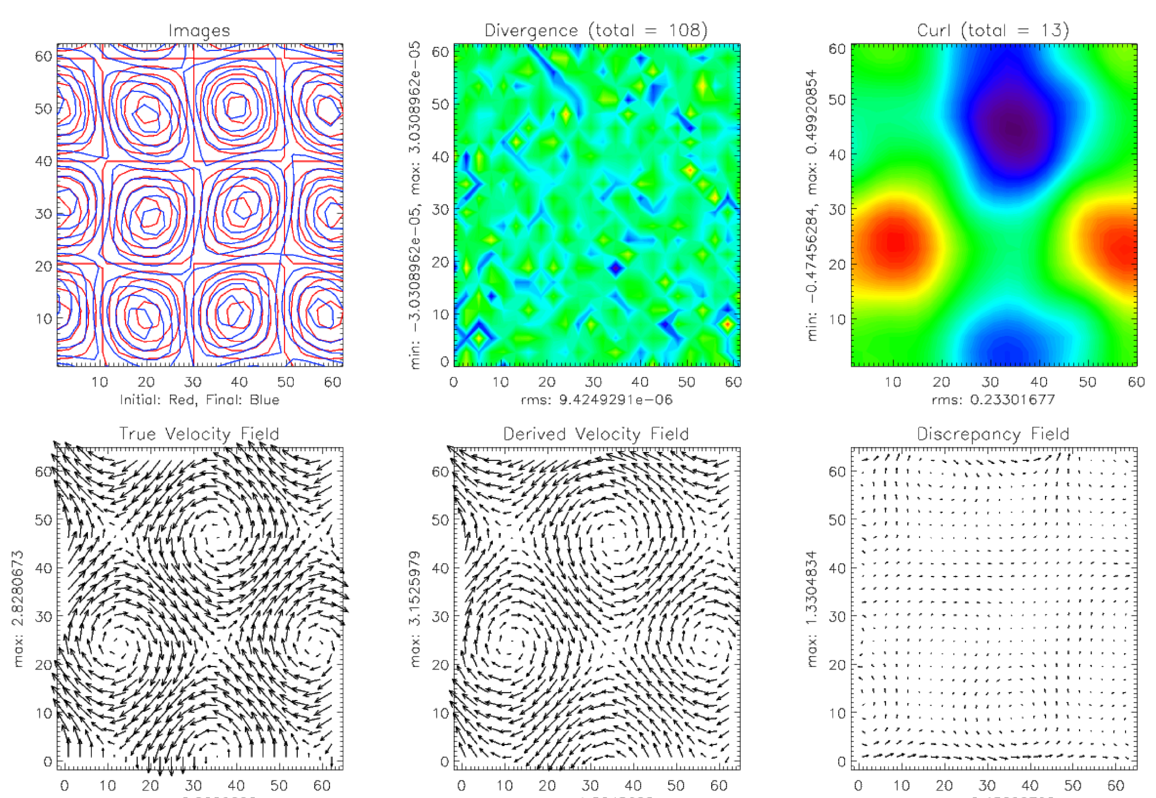
$$L_\psi(\psi,\bar{\phi},q)=J_0(\psi,\bar{\phi})+\langle q,\vec{\nabla}\cdot(\vec{\nabla}\psi)\rangle+\frac{r}{2}\left|\vec{\nabla}\cdot(\vec{\nabla}\psi)\right|^2+\frac{\gamma}{2}\left|B_n\cdot\vec{\nabla}\psi\right|^2$$

- φ objective functional (with ψ held constant)

$$J_\phi(\bar{\psi},\phi)=J_0(\bar{\psi},\phi)+\frac{\lambda_c}{2}\left|\vec{\nabla}(\vec{\nabla}\times(\vec{\nabla}\phi))\right|^2$$

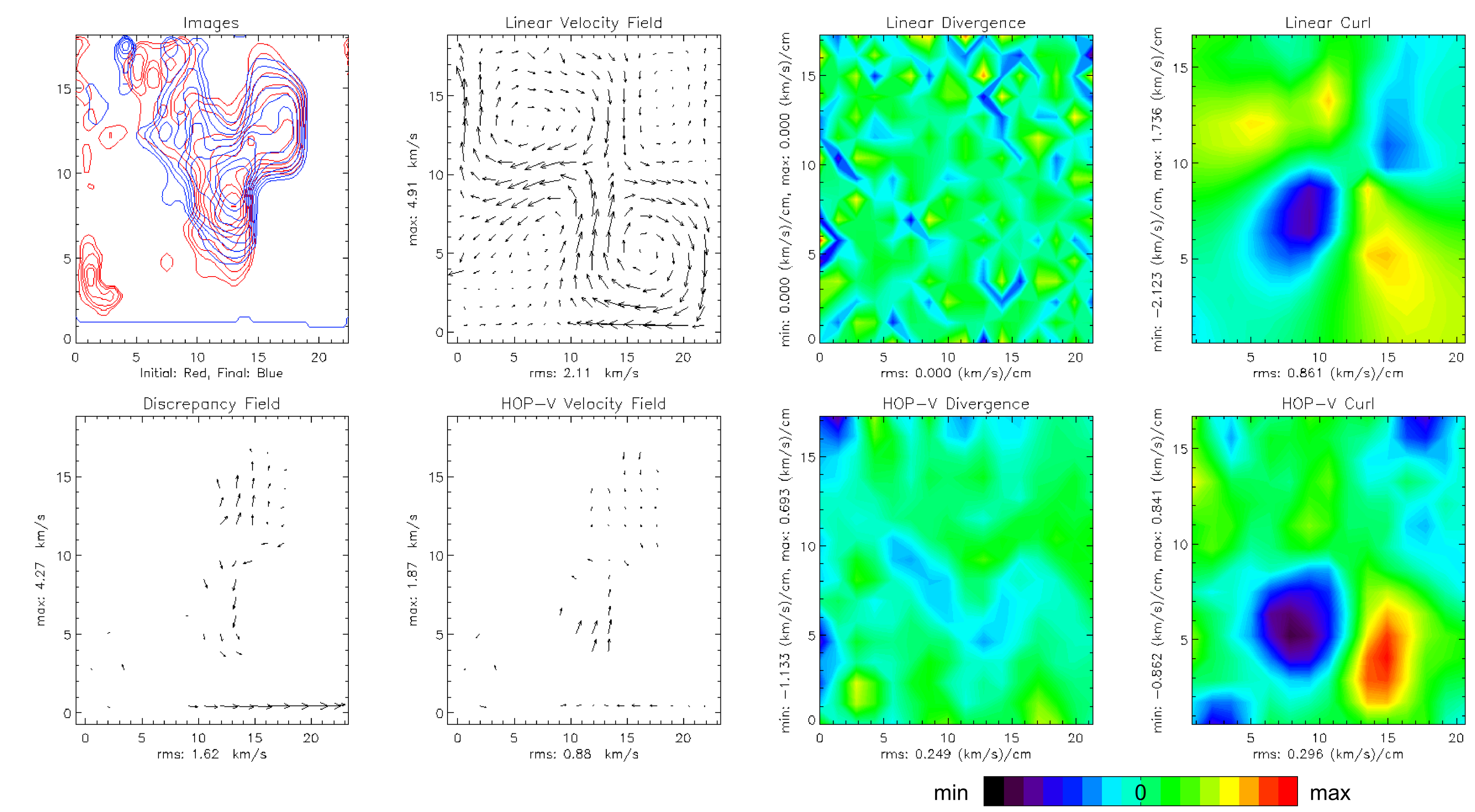
Iterated Successive Subspace Corrections





Preliminary Results

We have begun to validate the solenoidal field linear algorithm (simply "Linear" in the plots below) for a variety of artificial test patterns of convective flow. Typical results for one such test pattern are shown in the previous section. Our current goal is to compare the new linear algorithm to the HOP-V code for typical NSTX GPI datasets. Below are the results from both the HOP-V code and the linear algorithm for a typical GPI frame:



The HOP-V velocity field is shown only where the cross correlation is relatively high (cutoff at 0.75). Derived velocity vectors with higher cross correlations are more reliable than those without

- The direction of the solenoidal field closely corresponds to that of the high correlation HOP-V field
- The linear algorithm tends to derive fields with greater magnitude than HOP-V
- The divergence of the solenoidal field is incredibly small compared to that of the HOP-V field.
- The curl of the solenoidal field captures similar patterns as the divergence of the HOP-V field. The magnitude of the curl of the solenoidal field is typically higher than that of the HOP-V field.

Future Plans

We plan to continue analyzing the differences between the HOP-V velocity field results and those estimated by the solenoidal field linear algorithm. The linear algorithm will need to be tested on many more of the NSTX datasets in order to make a complete comparison of the two techniques.

In addition, we plan on creating artificial GPI datasets from 3-D BOUT turbulence simulation results and compare the derived optical flow fields to various plasma drift velocities. We expect to see a strong correlation between the derived velocity fields and the E × B plasma drift velocity.

Acknowledgments

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References

Munsat, T., Zweben, S. J. "Derivation of time-dependent two-dimensional velocity field maps for plasma turbulence studies," Review of Scientific Instruments **77**, 103501 (2006).

Yuan, J., Schnörr, C., Steidl, G. "Simultaneous Higher-Order Optical Flow Estimation and Decomposition," SIAM Journal on Scientific Computing **29** (2007), pp. 2283-2304.