IRD.P11

Consistency-Driven Optical Flow Technique for Nowcasting and Temporal Interpolation

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Formulation

- We have developed a novel approach to determining the motion field from consecutive radar-measured precipitation fields.
- We use a **variational** approach where the objective is to minimize

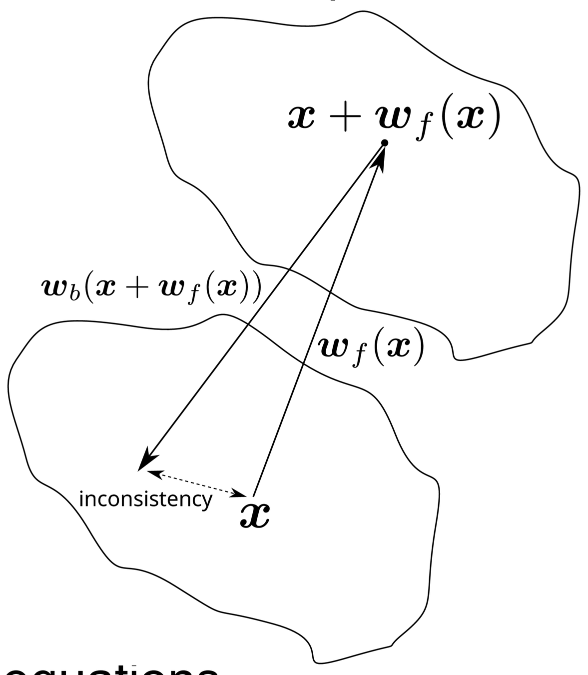
$$E_P(\boldsymbol{w}) = \int_\Omega |I_2(\boldsymbol{x}) - I_1(\boldsymbol{x} - \boldsymbol{w}_f(\boldsymbol{x}))|^2 + \lambda\gamma_f(\boldsymbol{x})[\|\nabla u(\boldsymbol{x})\|^2 + \|\nabla v(\boldsymbol{x})\|^2]d\boldsymbol{x} \quad (1)$$

- The first term comes from the **constant intensity assumption** and the second one is a **smoothness** term in order to guarantee a unique solution.
- The smoothness term is locally weighted by the function γ that measures **consistency** between the forward and backward motion fields.
- Define the (in)consistency between the forward and backward-computed motion fields $\mathbf{w}_f$ and $\mathbf{w}_b$

$$\boldsymbol{C}_f(\boldsymbol{x}) = \boldsymbol{w}_f(\boldsymbol{x}) + \boldsymbol{w}_b(\boldsymbol{x} + \boldsymbol{w}_f(\boldsymbol{x})),$$
$$\boldsymbol{C}_b(\boldsymbol{x}) = \boldsymbol{w}_b(\boldsymbol{x}) + \boldsymbol{w}_f(\boldsymbol{x} + \boldsymbol{w}_b(\boldsymbol{x}))$$

and

$$\gamma_f(\boldsymbol{x}) = \frac{\xi}{1 + \left[\frac{c_f(\boldsymbol{x})}{K}\right]^2}, \quad c_f(\boldsymbol{x}) = \|\boldsymbol{C}_f(\boldsymbol{x})\|$$

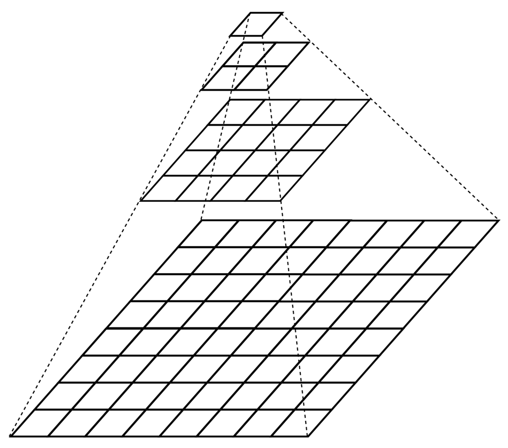


and similarly for the backward consistency γ_b.

- This yields a set of Euler-Lagrange -type differential equations

$$\lambda\nabla\cdot(\gamma_f\nabla u_f) = I_{1,x}(\nabla I_1 \cdot \boldsymbol{w}_f + \tilde{I}_{1,t}(\tilde{\boldsymbol{w}}_f)),$$
$$\lambda\nabla\cdot(\gamma_f\nabla v_f) = I_{1,y}(\nabla I_1 \cdot \boldsymbol{w}_f + \tilde{I}_{1,t}(\tilde{\boldsymbol{w}}_f)),$$
$$\lambda\nabla\cdot(\gamma_b\nabla u_b) = I_{2,x}(\nabla I_2 \cdot \boldsymbol{w}_b + \tilde{I}_{2,t}(\tilde{\boldsymbol{w}}_b)),$$
$$\lambda\nabla\cdot(\gamma_b\nabla v_b) = I_{2,y}(\nabla I_2 \cdot \boldsymbol{w}_b + \tilde{I}_{2,t}(\tilde{\boldsymbol{w}}_b)).$$

- We have implemented a numerical finite-difference scheme for solving these equations.
- The solution is done in a **multigrid** fashion by using **image pyramids**.



Confidence estimates

- We have developed a novel methodology for estimating the confidence of optical flow fields.
- The value of the cost function (1) gives a robust confidence estimate, as it incorporates both intensity preservation and consistency. We denote it by $\mathcal{C}$.
- For temporal interpolation between two precipitation fields with parameter 0<t<1, we use the weighted confidence

$$\mathcal{C}(\boldsymbol{x};t) = (1-t)\cdot\mathcal{C}_f(\boldsymbol{x}) + t\cdot\mathcal{C}_b(\boldsymbol{x}),$$

where γ_f is used for $\mathcal{C}_f$ and γ_b is used for $\mathcal{C}_b$.

- For extrapolation, we integrate the confidence along the flow

$$\bar{\mathcal{C}}(\boldsymbol{x}) = \frac{1}{L}\int_0^t \mathcal{C}(\gamma(\tau))d\tau, \quad \text{where } L = \int_0^t \|\gamma'(\tau)\|d\tau$$

denotes the length of the trajectory γ. This is analogous to the semi-Lagrangian extrapolation scheme.

- For yes/no rainfall ($R>R_{min}$ or $R<R_{min}$ with R_{min}=0.1 mm/h), we use

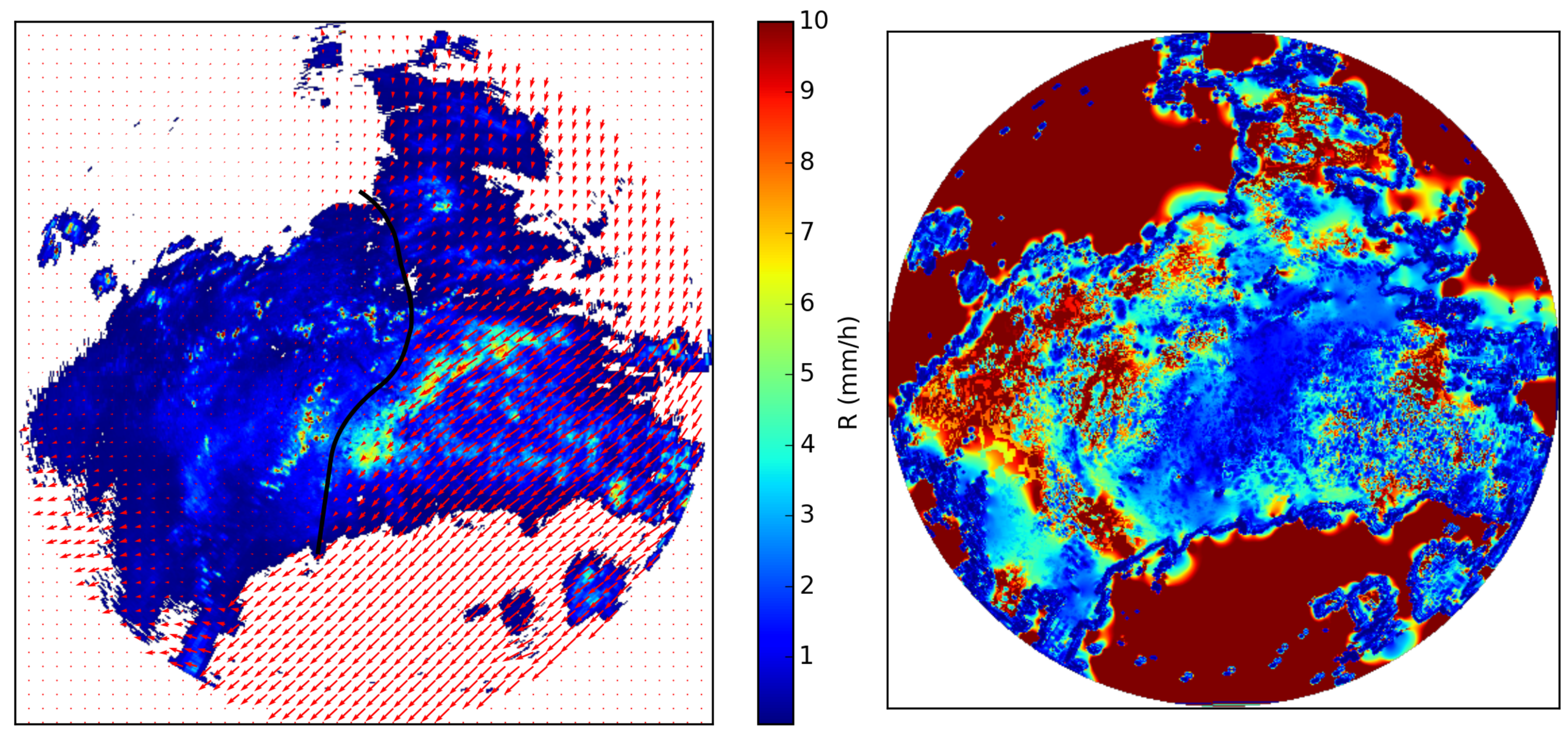
$$\mathrm{CSI} = \frac{\text{hits}}{\text{hits} + \text{misses} + \text{false alarms}}$$

and root mean squared error or fraction (RMSE,RMSF) for the case $R>R_{min}$.

- When removing a percentage of pixels where the motion field has the lowest confidence:
  - **CSI should approach one.**
  - **RMSE and RMSF should approach zero.**

Illustrative examples

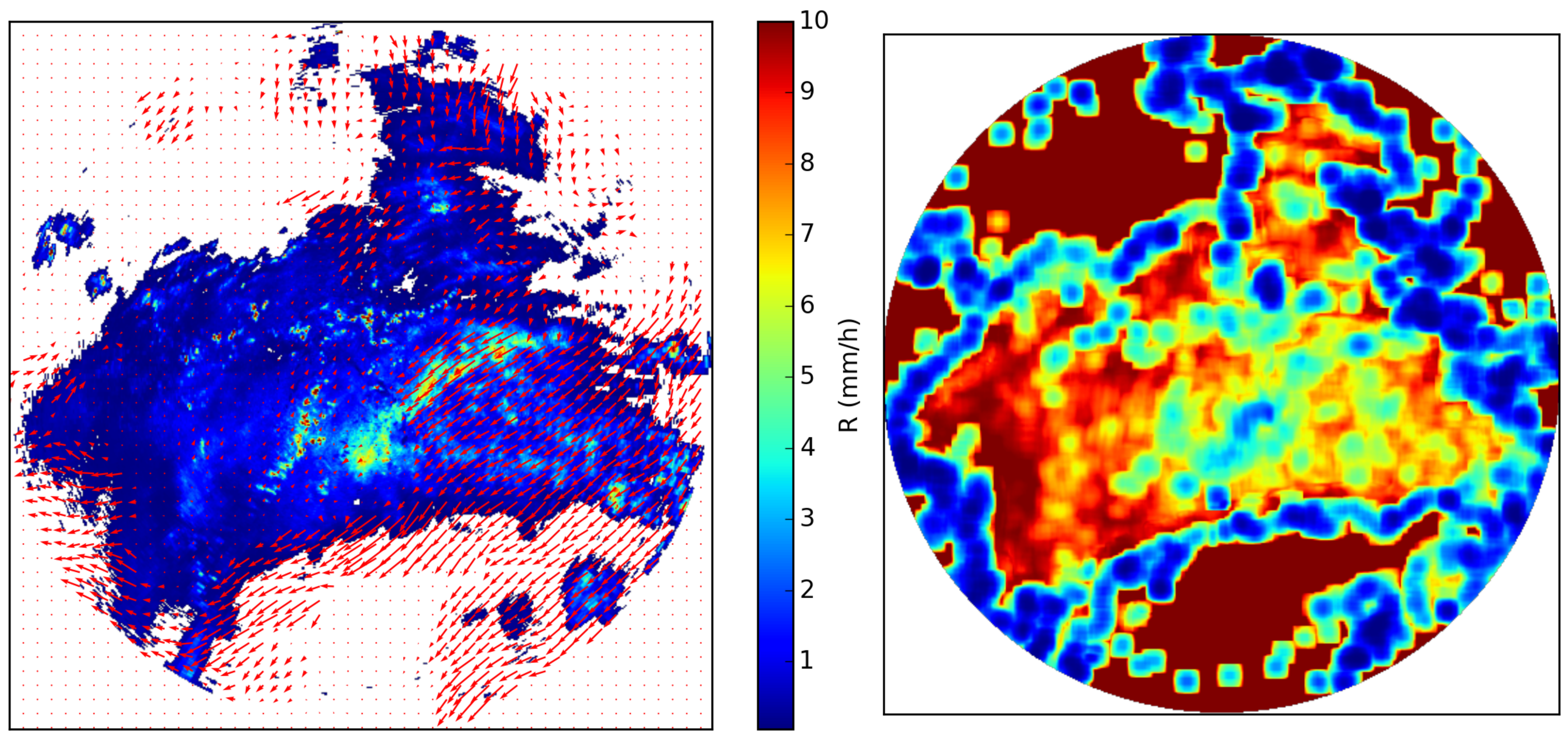
(Ikaalinen radar, 500m pseudo-CAPPI)



(a) Motion field

(b) Confidence field
(blue=bad, red=good)

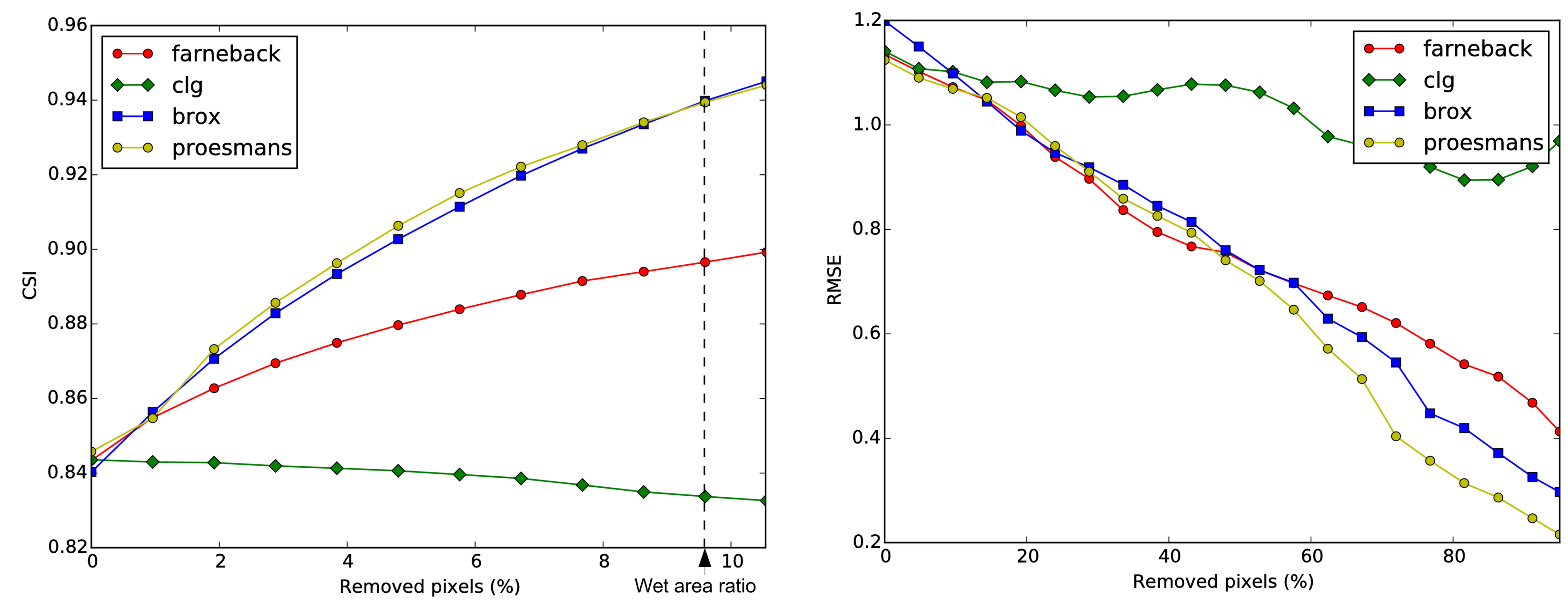
Figure 1. A sharp boundary in the motion field is correctly identified by the diffusion method. The multiscale variational approach is also able to fill the motion field to areas with no radar echoes.



(a) Motion field

(b) Confidence field
(blue=bad, red=good)

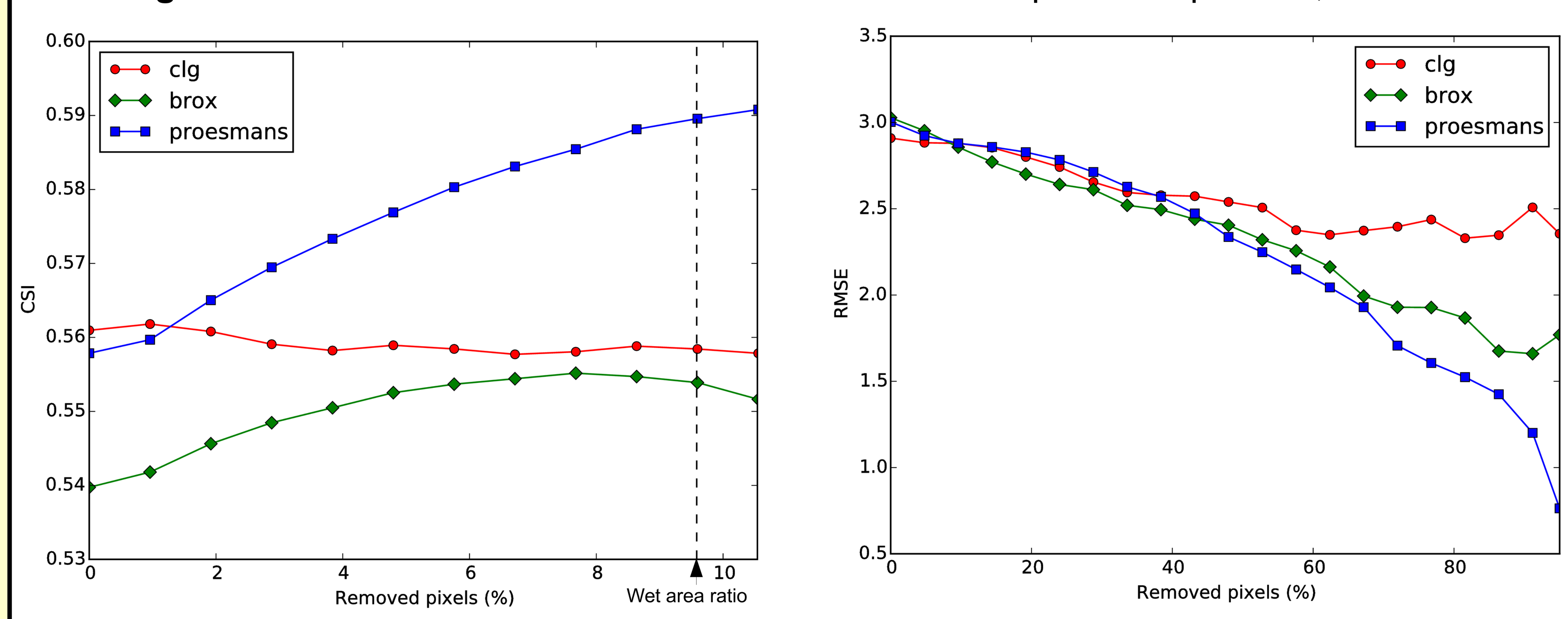
Figure 2. Motion field and the confidence estimates computed with the pattern matching method of Farneback (2003). Note the blocky appearance and inability to identify edges in the motion field.



(a) CSI

(b) RMSE

Figure 3. CSI and RMSE curves for advection-based temporal interpolation, Case 5.



(a) CSI

(b) RMSE

Figure 4. CSI and RMSE curves for extrapolation +30 minutes, Case 5.

Optical flow methods:

- The proposed method based on the consistency-driven diffusion method (Proesmans et al., 1994)
- Pattern matching method with polynomial expansions (Farneback, 2003)
- Extended Horn-Schunck variational method (Brox et al., 2004)
- Combined local-global (CLG) method (Bruhn et al., 2005)

Rainfall events

Case	Radar	Date	Description
1	Utajärvi	31 May 2015 12:00-23:00	Complex case (convergence zone, different scales have different movement) + growth and decay.
2	Vantaa	8 Jun 2015 08:00-15:00	Growth and movement of intensive convective cells, small scale structures in urban Helsinki applications.
3	Vantaa	23 Jun 2015 12:00-16:00	Large scale frontal band, relatively “easy” case but rainfall patterns moving in different directions.
4	Vantaa	24 Jun 2105 9:00-16:00	Complex convective movement & development, urban Helsinki case.
5	Vantaa	26 Jun 2015 9:00-16:00	Complex convective development and movement, the “threat” never arrives Helsinki.
6	Korppoo	6 Jul 2015 10:00-18:00	Small scale embedded in large scale, with different motions (~120 degree difference).
7	Kuopio	29 Jul 2015 10:00-13:00	Two motion directions in different scales opposite to each other, the other one very slow.

Table 1. Rainfall events used for comparison of different optical flow methods.

Validation results

- We **integrate** the above CSI and RMSE curves in order to obtain a single performance measure.
- For temporal interpolation, the differences between optical flow methods are small, but significant differences arise with extrapolation.
- The proposed method outperforms the others in a number of cases and is never significantly worse.

Case	1			2			3			4			5			6			7		
Method	Brox	CLG	Proposed	Brox	CLG	Proposed	Brox	CLG	Proposed	Brox	CLG	Proposed	Brox	CLG	Proposed	Brox	CLG	Proposed	Brox	CLG	Proposed
CSI	0.262	0.267	**0.270**	0.056	0.059	**0.060**	0.236	**0.248**	0.247	0.131	0.126	**0.135**	0.058	0.059	**0.061**	0.451	**0.484**	0.473	0.404	**0.422**	0.412
RMSE	0.572	0.619	**0.532**	6.726	**5.672**	6.732	**0.535**	0.646	0.566	3.600	2.210	**2.040**	2.218	2.440	**2.136**	0.619	0.618	**0.578**	**0.816**	1.053	0.884

Table 2. Integrated CSI and RMSE scores for extrapolation +30 minutes.