

Lightweight Deep Unfolding Network With Enhanced Robustness For Infrared Small Target Detection

Xianchao Xiu

Department of Automation

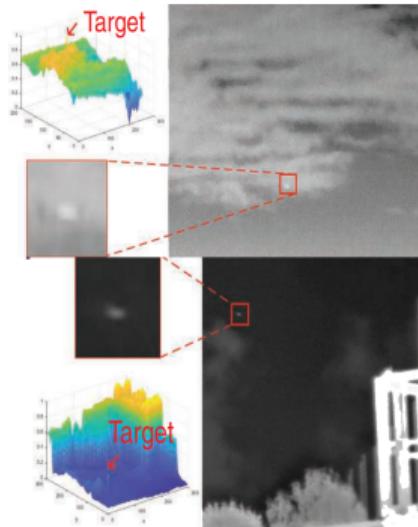
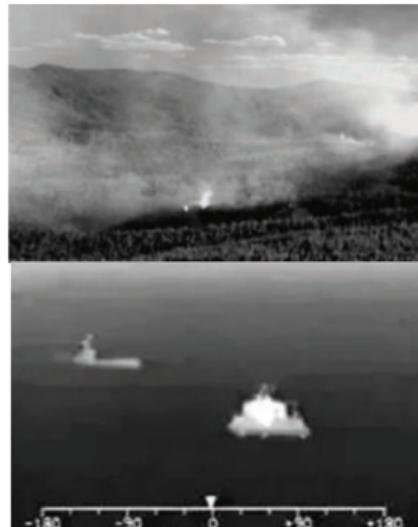


Mathematical Optimization Society, May 16-19, 2025

Joint work with [Yinчao Han](#) (SHU), [Jingjing Liu](#) (SHU) and [Wanquan Liu](#) (SYSU)

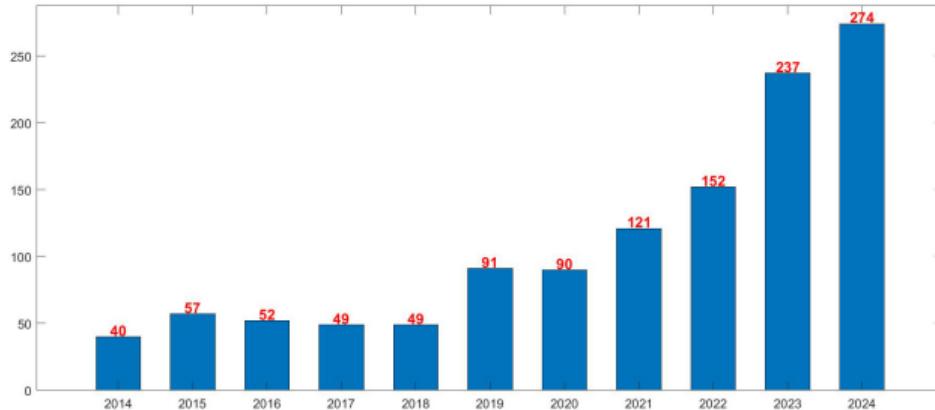
ISTD

- ▶ Infrared small target detection (ISTD)



- ▶ Difficulties: **small size, low SNR, weak contrast**
- ▶ Advantages: **strong concealment, good anti-interference**

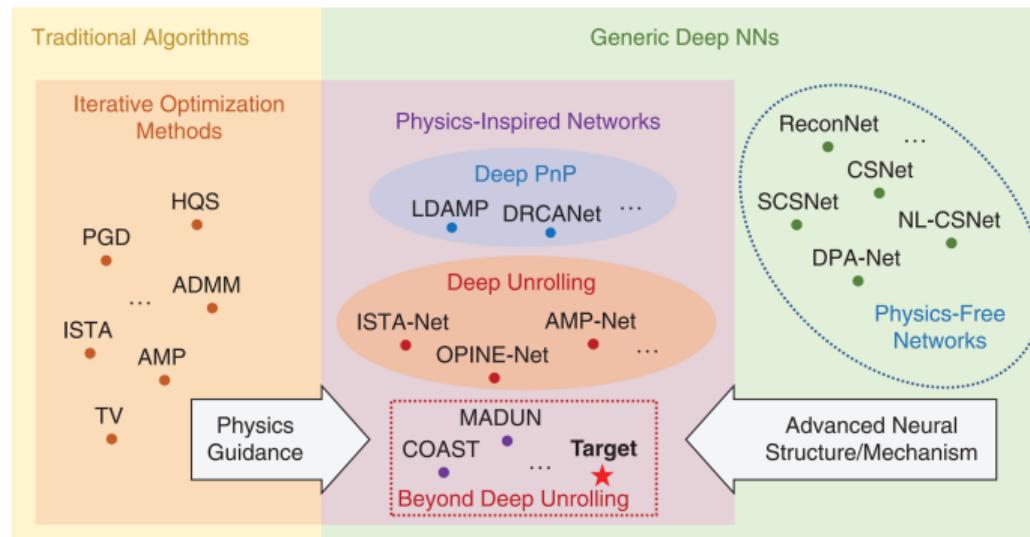
- ▶ Trends of “infrared small target detection” on Google Scholar



- ▶ Existing methods
 - ▶ Filter-based: spatial domain, transformed domain
 - ▶ Local information-based: local contrast, local entropy
 - ▶ Data structure-based: subspace, dictionary, tensor representation
 - ▶ Deep learning-based

DUN

- ▶ From iterative optimization to deep unfolding networks
 - ▶ Gregor-LeCun, ICML, 2010
 - ▶ Yang-Sun-Li-Xu, IEEE TPAMI, 2020
 - ▶ Zhang-Chen-Xiong-Zhang, IEEE SPM, 2023
 - ▶ Chen-Liu-Yin, Science China Mathematics, 2024



RPCANet

► From RPCA to RPCANet

$$\min_{B, T} \|B\|_* + \lambda \|T\|_1 \quad \text{s.t.} \quad D = B + T$$

(a) Infrared Image Model



(c) Model Iterative Solving

Updating of B^k $B^k = \text{prox}_{\mu}(\mathbf{D}^{k-1} - \mathbf{T}^{k-1})$

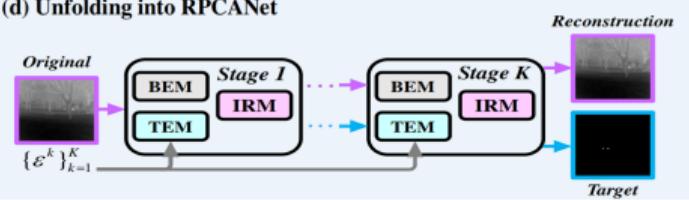
Updating of \mathbf{T}^k $\mathbf{T}^k = \mathbf{T}^{k-1} + \mathbf{D}^{k-1} - \mathbf{B}^k - \varepsilon \nabla S(\mathbf{T}^{k-1})$

Updating of \mathbf{D}^k $\mathbf{D}^k = \mathbf{B}^k + \mathbf{T}^k$

(b) RPCA Modeling

$$\begin{aligned} & \boxed{\text{Optimization Problem}} \quad \min_{\mathbf{B}, \mathbf{T}} \bar{\mathcal{R}}(\bar{\mathbf{B}}) + \bar{\lambda} \bar{S}(\bar{\mathbf{T}}), \text{ s.t. } \mathbf{D} = \bar{\mathbf{B}} + \bar{\mathbf{T}} \\ & \downarrow \\ & \boxed{\text{Unconstrained Problem}} \quad \mathcal{L}(\mathbf{B}, \mathbf{T}) = \mathcal{R}(\mathbf{B}) + \lambda S(\mathbf{T}) + \frac{\mu}{2} \|\mathbf{D} - \mathbf{B} - \mathbf{T}\|_F^2 \end{aligned}$$

(d) Unfolding into RPCANet



How to enhance robustness? How to realize lightweight?

Methodology

- ▶ From RPCANet to RPCANet+

$$\min_{B, T} \|B\|_* + \lambda \|T\|_1$$

$$\text{s.t. } D = B + T$$

↓

$$\min_{B, T, N} \|B\|_* + \lambda \|T\|_1 + \mu \|N\|_F^2$$

$$\text{s.t. } D = B + T + N$$

↓

$$\min_{B, T, N} \mathcal{R}(B) + \lambda \mathcal{S}(T) + \mu \mathcal{G}(N)$$

$$\text{s.t. } D = B + T + N$$

- ▶ Unconstrained version

$$\mathcal{L}(B, T, N) = \mathcal{R}(B) + \lambda \mathcal{S}(T) + \mu \mathcal{G}(N) + \frac{\alpha}{2} \|D - B - T - N\|_F^2$$

Update B

- Background estimation module + squeeze-and-excitation network (SEBEM)

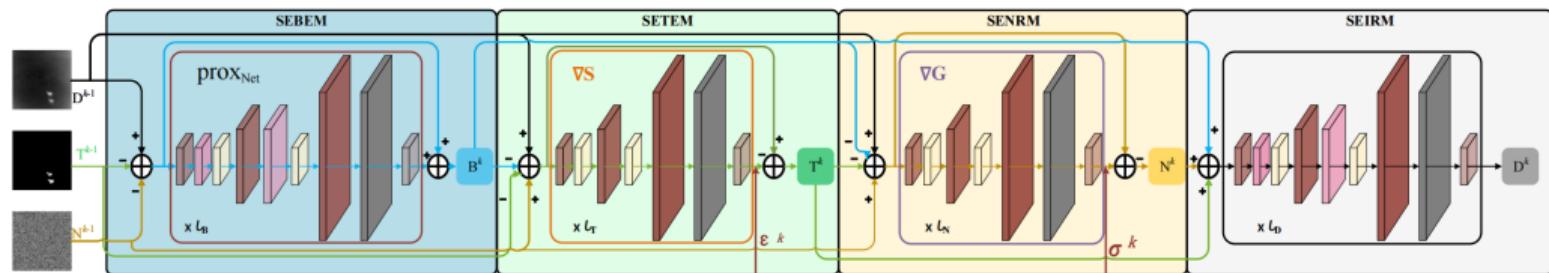
$$B^k = \arg \min_B \mathcal{R}(B) + \frac{\alpha}{2} \|D^{k-1} - B - T^{k-1} - N^{k-1}\|_F^2$$

↓

$$B^k = \text{prox}_{\alpha}(D^{k-1} - T^{k-1} - N^{k-1})$$

↓

$$B^k = D^{k-1} - T^{k-1} - N^{k-1} + \mathcal{W}^k(D^{k-1} - T^{k-1} - N^{k-1})$$



Update T

- Target estimation module + squeeze-and-excitation network (SETEM)

$$T^k = \arg \min_T \lambda \mathcal{S}(T) + \frac{\alpha}{2} \|D^{k-1} - B^k - T - N^{k-1}\|_F^2$$

\Downarrow

$$T^k = \arg \min_T \frac{\lambda L_S}{2} \|T - T^{k-1} + \frac{1}{L_S} \nabla \mathcal{S}(T^{k-1})\|_F^2 + \frac{\alpha}{2} \|D^{k-1} - B^k - T - N^{k-1}\|_F^2$$

\Downarrow

$$T^k = \frac{\lambda L_S}{\lambda L_S + \alpha} T^{k-1} + \frac{\alpha}{\lambda L_S + \alpha} (D^{k-1} - B^k - N^{k-1}) - \frac{\lambda}{\lambda L_S + \alpha} \nabla \mathcal{S}(T^{k-1})$$

\Downarrow

$$T^k = \gamma T^{k-1} + (1 - \gamma)(D^{k-1} - B^k - N^{k-1}) - \varepsilon \nabla \mathcal{S}(T^{k-1})$$

Update T

- Set $\gamma = 0.5$

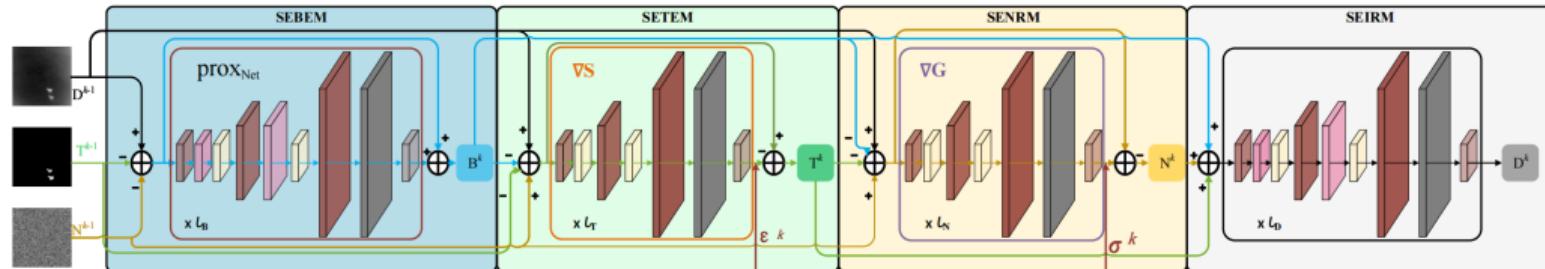
$$T^k = \gamma T^{k-1} + (1 - \gamma)(D^{k-1} - B^k - N^{k-1}) - \varepsilon \nabla \mathcal{S}(T^{k-1})$$

↓

$$T^k = T^{k-1} + D^{k-1} - B^k - N^{k-1} - \varepsilon \nabla \mathcal{S}(T^{k-1})$$

↓

$$T^k = T^{k-1} + D^{k-1} - B^k - N^{k-1} - \varepsilon^k \mathcal{H}^k(T^{k-1} + D^{k-1} - B^k - N^{k-1})$$



Update N

- Noise reduction module + squeeze-and-excitation network (SENRM)

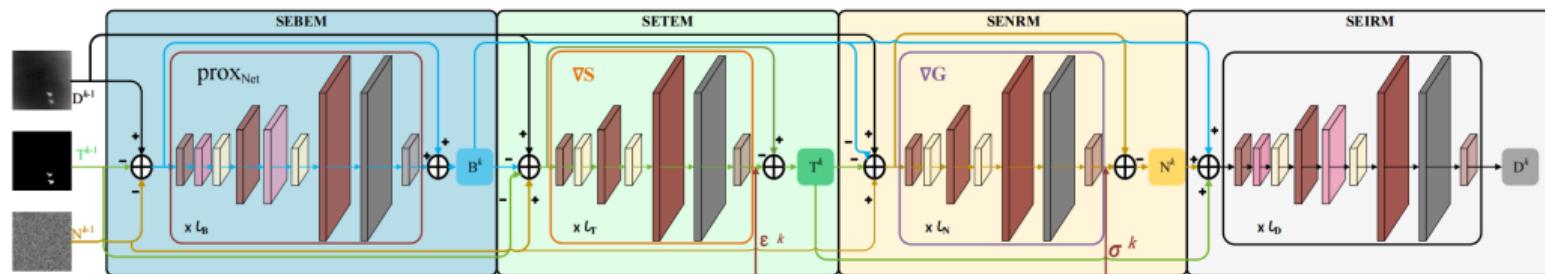
$$N^k = \arg \min_N \mu \mathcal{G}(N) + \frac{\alpha}{2} \|D^{k-1} - B^k - T^k - N\|_F^2$$



$$N^k = \arg \min_N \frac{\mu L_N}{2} \|N - N^{k-1} + \frac{1}{L_N} \nabla \mathcal{G}(N^{k-1})\|_F^2 + \frac{\alpha}{2} \|D^{k-1} - B^k - T^k - N\|_F^2$$



$$N^k = N^{k-1} + D^{k-1} - B^k - T^k - \sigma^k \mathcal{F}^k(N^{k-1} + D^{k-1} - B^k - T^k)$$



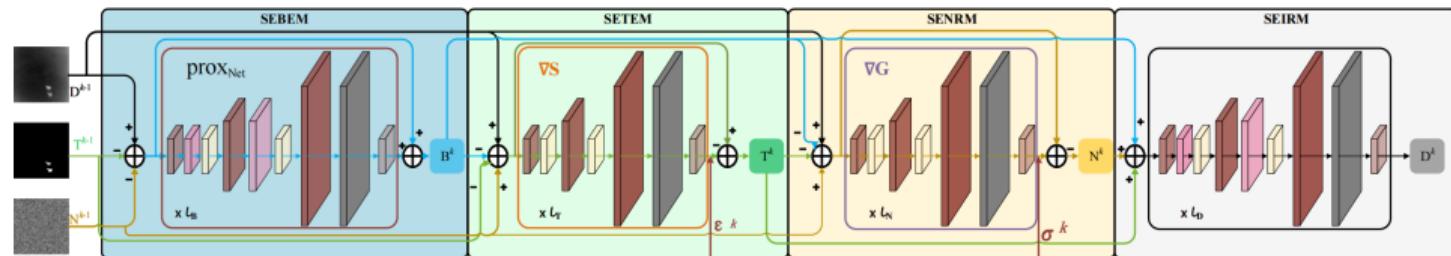
Update D

- ▶ Image reconstruction module + squeeze-and-excitation network (SEIRM)

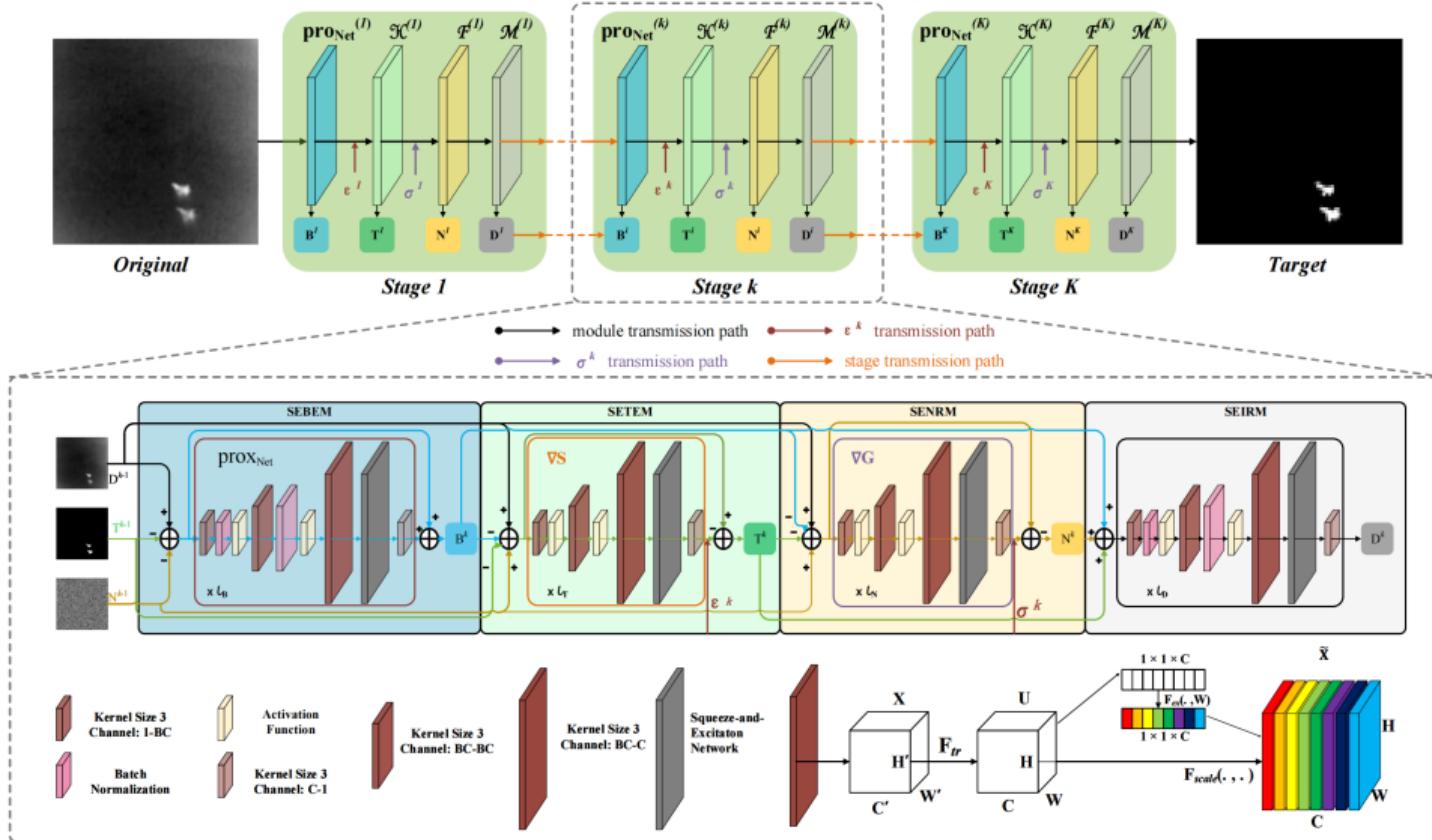
$$D^k = B^k + T^k + N^k$$

↓

$$D^k = \mathcal{M}^k(B^k + T^k + N^k)$$



Architecture



Experiment

- ▶ Compared methods
 - ▶ IPI: Gao-Meng-Yang-Wang-Zhou-Hauptmann, IEEE TIP, 2013
 - ▶ MPCM: Wei-You-Li, PR, 2016
 - ▶ PSTNN: Zhang-Peng, RS, 2019
 - ▶ AGPCNet: Zhang-Li-Cao-Pu-Peng, IEEE TAES, 2023
 - ▶ UIUNet: Wu-Hong-Chanussot, IEEE TIP, 2023
 - ▶ MSHNet: Liu-Liu-Zheng-Wang-Fu, CVPR, 2024
 - ▶ RPCANet: Wu-Zhang-Li-Huang-Peng, WACV, 2024
- ▶ Evaluation metrics
 - ▶ Mean intersection over union ($mIoU \uparrow$), F_1 -score ($F_1 \uparrow$), Probability of detection ($P_d \uparrow$)
 - ▶ False alarm rate ($F_a \downarrow$)
- ▶ Loss function

$$\mathcal{L}_{\text{total}} = \mathcal{L}_{\text{segmentation}} + \eta \mathcal{L}_{\text{fidelity}} = \left(1 - \frac{1}{M_t} \sum_{i=1}^{M_t} \frac{\text{TP}}{\text{FP} + \text{TP} + \text{FN}} \right) + \frac{\eta}{M_t M} \sum_{i=1}^{M_t} \|D^K - D\|_F^2$$

Performance

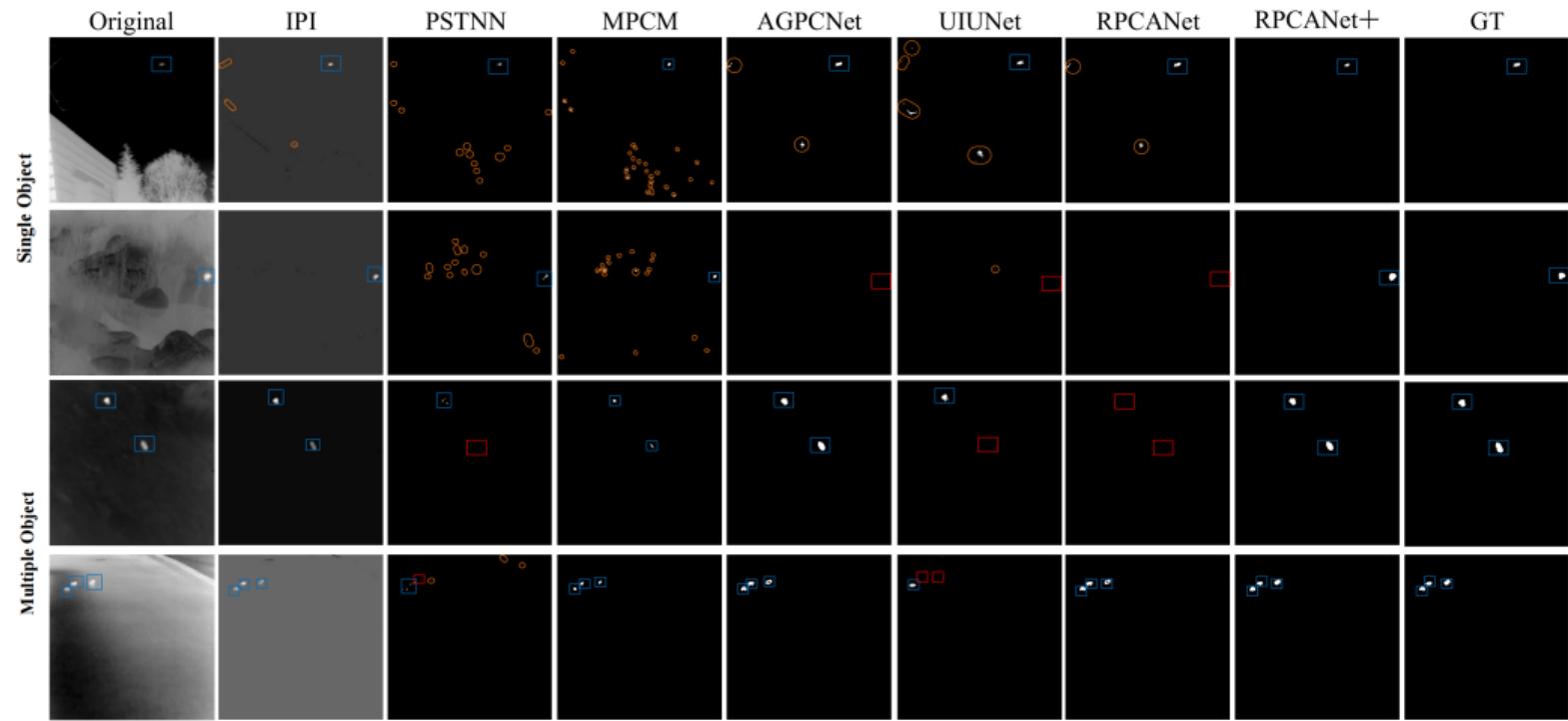
► Quantitative results

Methods	#Params	NUDT-SIRST				IRSTD-1k				SIRST-Aug				Time(s) CPU/GPU
		mIoU ↑	F ₁ ↑	P _d ↑	F _a ↓	mIoU ↑	F ₁ ↑	P _d ↑	F _a ↓	mIoU ↑	F ₁ ↑	P _d ↑	F _a ↓	
IPI	-	34.83	51.49	92.58	7.14	18.67	31.48	78.54	11.11	21.90	35.97	80.36	2.20	3.0972/-
PSTNN	-	25.46	40.58	78.52	7.95	14.87	25.89	68.73	6.51	19.76	33.00	93.40	3.14	0.2249/-
MPCM	-	25.96	40.78	78.59	7.91	14.81	25.93	69.03	6.51	19.49	33.00	93.58	3.04	0.0624/-
AGPCNet	12.360M	85.41	92.15	98.10	4.72	61.00	75.75	89.35	5.34	72.36	83.83	99.03	35.56	-/0.0205
UIUNet	50.540M	88.71	94.01	91.43	1.89	63.06	77.35	93.60	6.57	71.80	83.59	98.35	28.29	-/0.0317
MSHNet	4.065M	75.99	86.57	96.07	2.63	64.50	77.55	91.68	4.46	71.64	84.16	90.78	23.09	-/0.0245
RPCANet	0.680M	89.31	94.35	97.14	2.87	63.21	77.45	88.31	4.39	72.54	84.08	98.21	34.14	-/0.0096
RPCANet+	0.216M	92.37	96.04	98.41	1.79	64.68	78.55	89.39	4.66	74.56	85.43	99.17	29.78	-/0.0072

	NUDT-SIRST	IRSTD-1k	SIRST-Aug
#Size	256 × 256	512 × 512	256 × 256
#Training	663	800	8525
#Testing	662	201	545

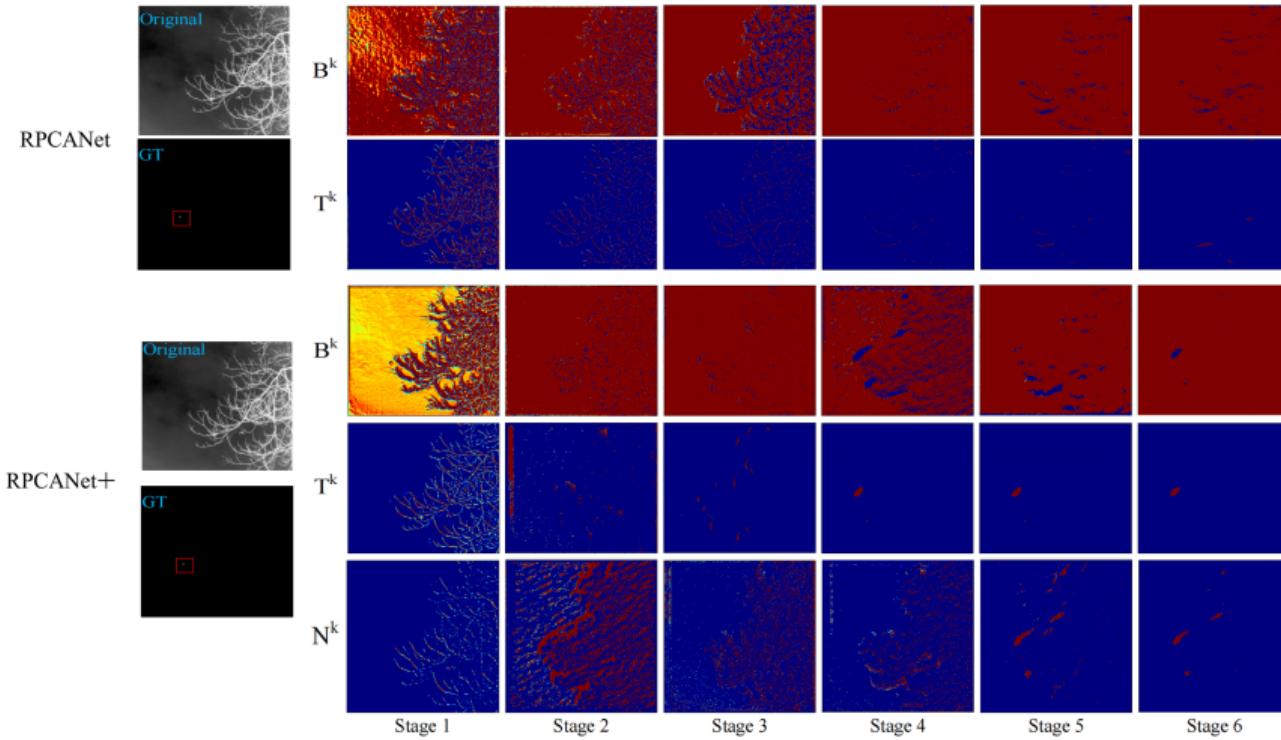
Visualization

► Comparisons on IRSTD-1k



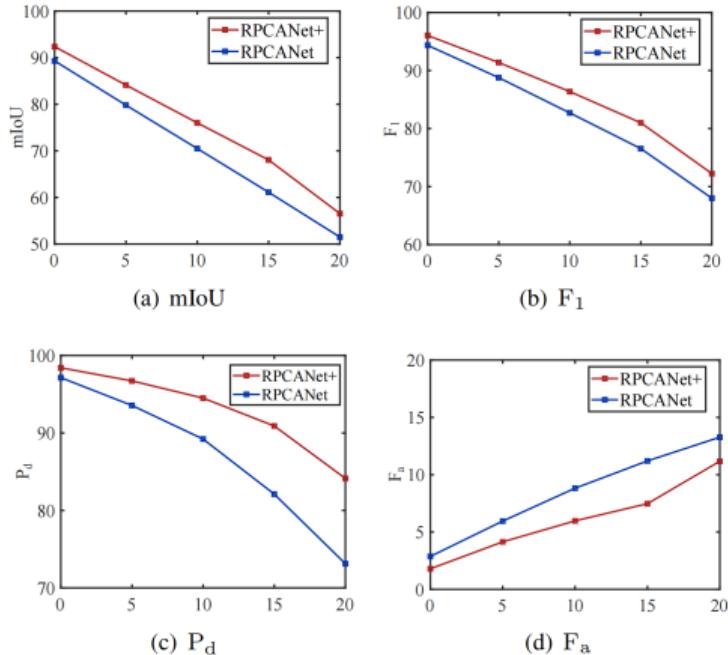
Visualization

► A close look at stages

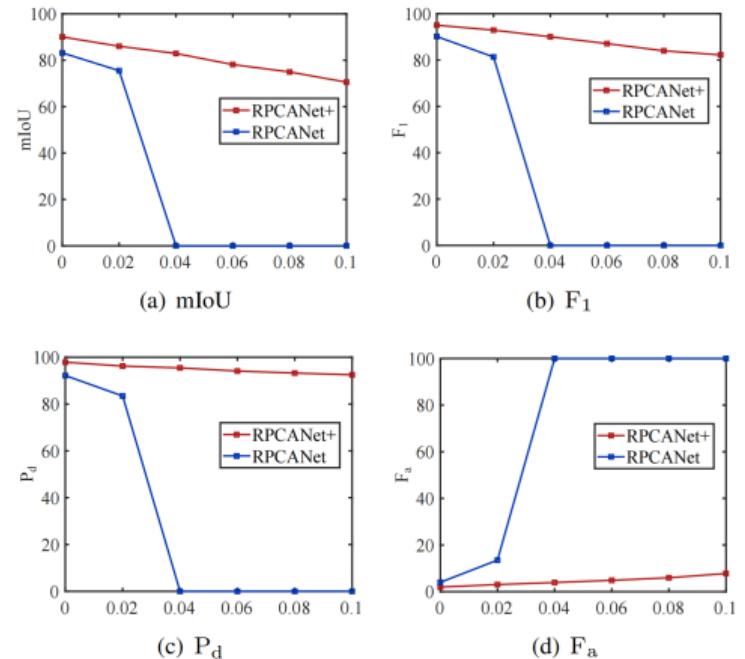


Robustness

► Gaussian noise



► Salt-and-pepper noise



Discussion

► Effects of stage K

K	#Params	NUDT-SIRST		IRSTD-1k		SIRST-Aug	
		mIoU ↑	F ₁ ↑	mIoU ↑	F ₁ ↑	mIoU ↑	F ₁ ↑
1	0.0360M	72.83	84.28	91.39	95.51	61.26	75.98
2	0.0720M	72.96	84.37	91.61	95.62	61.59	76.24
3	0.1080M	73.58	84.78	91.53	95.58	62.60	77.00
4	0.1439M	73.81	84.93	90.06	95.06	61.98	76.53
5	0.1799M	74.28	85.24	91.64	95.64	63.45	77.63
6	0.2159M	74.56	85.43	92.37	96.04	64.68	78.55
7	0.2519M	72.29	83.92	88.53	93.58	62.29	76.76

► Effects of bottleneck channel (BC) and total channel (TC)

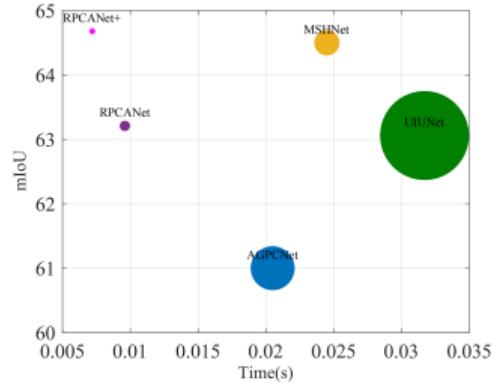
#BC	#TC	mIoU ↑	F ₁ ↑
4	32	74.56	85.43
4	40	72.54	83.08
4	48	72.10	82.59
4	56	70.34	80.08
4	64	68.54	78.35
8	32	73.96	85.03
16	32	71.19	83.17

Conclusion

► Conclusion

- How to enhance robustness? \Rightarrow RPCA + noise reduction + attention mechanism
- How to realize lightweight? \Rightarrow intermediate bottleneck + multi-layer mapping

Methods	mIoU \uparrow	F ₁ \uparrow	P _d \uparrow	F _a \downarrow
IPI	25.13	39.65	83.83	6.81
PSTNN	20.03	33.16	80.22	5.87
MPCM	20.09	33.24	80.40	5.82
RPCANet+	77.20	86.67	95.66	12.08



► What about the convergence?

- Ryu-Liu-Wang-Chen-Wang-Yin, ICML, 2019
- Mukherjee-Hauptmann-Öktem-Pereyra-Schönlieb, IEEE SPM, 2023

References

- ▶ Gao-Meng-Yang-Wang-Zhou-Hauptmann, Infrared Patch-Image Model for Small Target Detection in A Single Image, [IEEE TIP](#), 2013
- ▶ Zhang-Ghanem, ISTA-Net: Interpretable Optimization-Inspired Deep Network for Image Compressive Sensing, [CVPR](#), 2018
- ▶ Zhao-Li-Li-Hu-Ma-Tao, Single-Frame Infrared Small-Target Detection: A Survey, [IEEE GRSM](#), 2022
- ▶ Liu-Liu-Zheng-Wang-Fu, Infrared Small Target Detection with Scale and Location Sensitivity, [CVPR](#), 2024
- ▶ Wu-Zhang-Li-Huang-Peng, RPCANet: Deep Unfolding RPCA Based Infrared Small Target Detection, [WACV](#), 2024
- ▶ Liu-Han-Xiu-Zhang-Liu, Lightweight Deep Unfolding Networks with Enhanced Robustness for Infrared Small Target Detection, [arXiv:2509.08205](#)

Thank you for your attention!

xcxiu@shu.edu.cn