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On using the BRDF for simulations with turbulence

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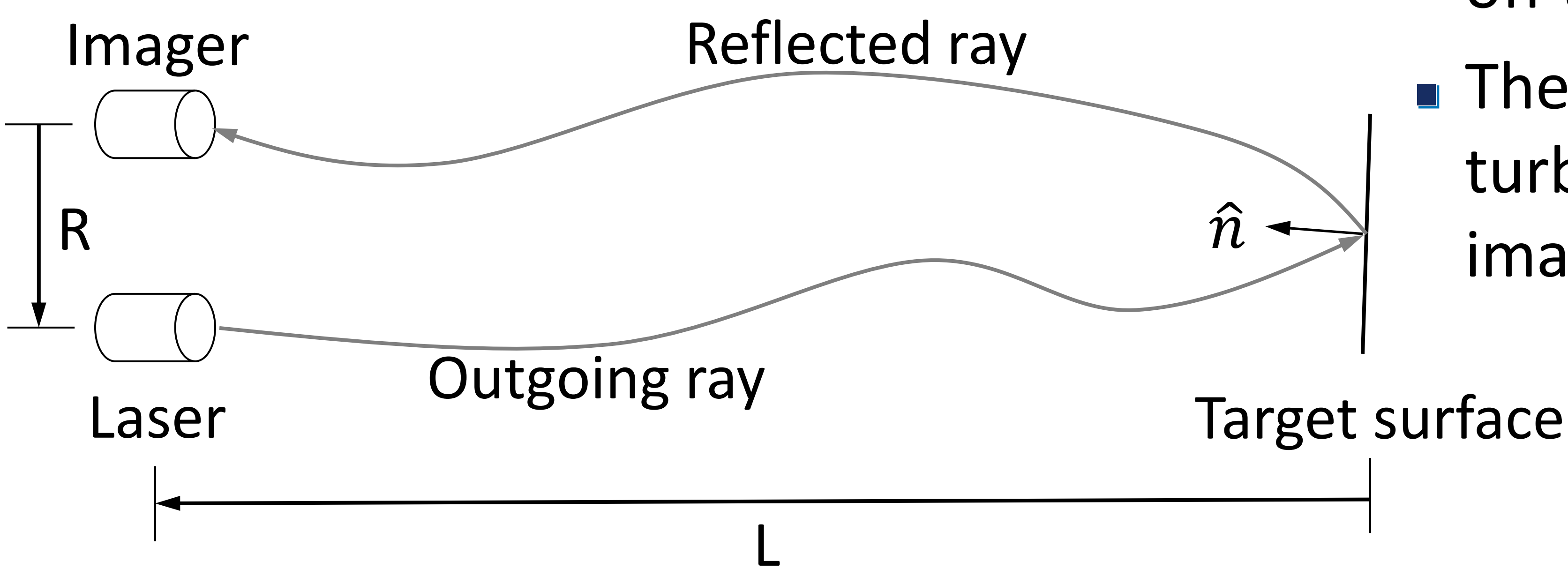
Active imaging system in turbulence

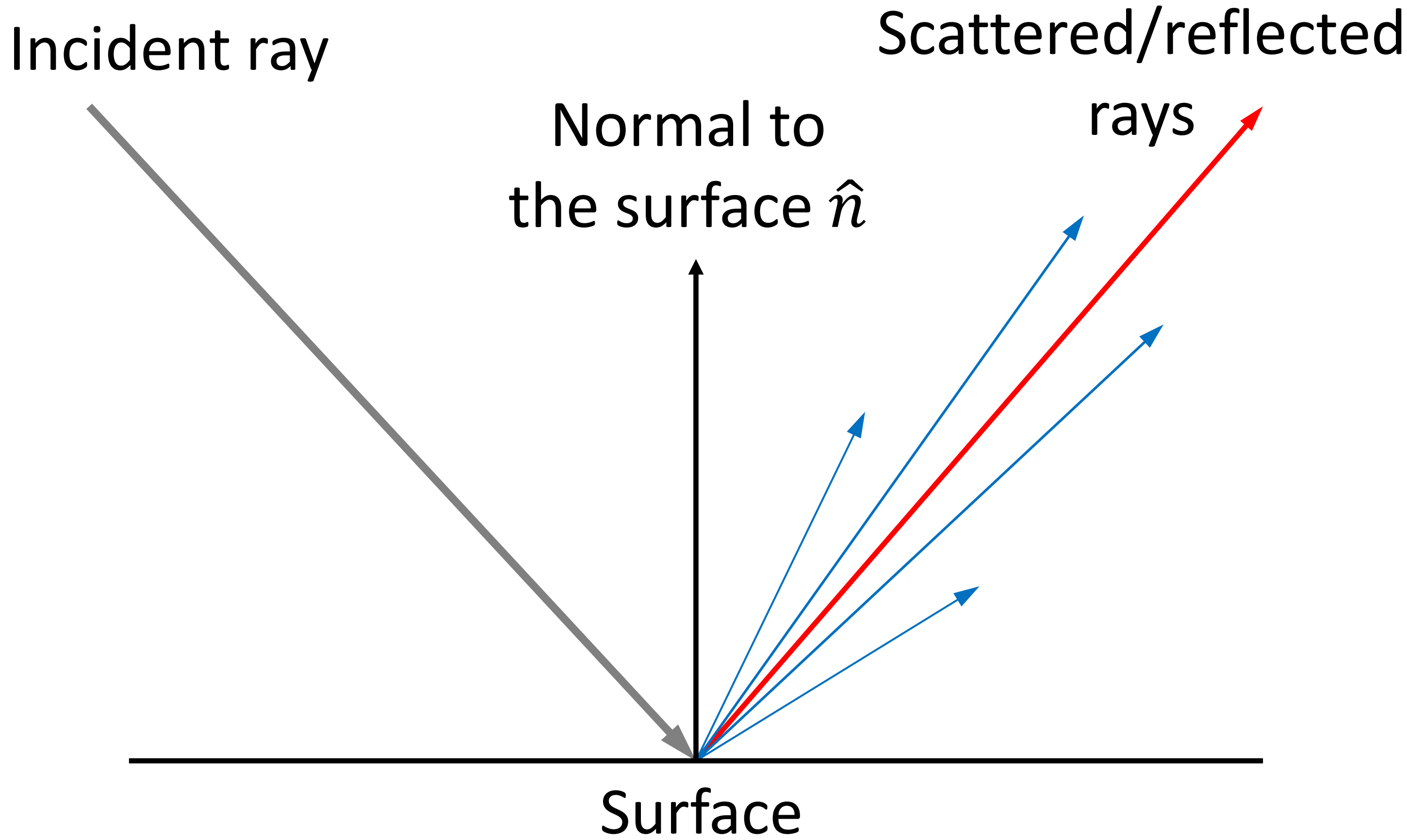
- R = Bi-static separation
- L = Range
- $\hat{n}$ = Normal vector of the target surface



- The laser emits rays towards the target
- These rays are deviated by turbulence.
- They are reflected or scattered off the target surface.
- They then propagate through turbulence towards the imager.

Bi-directional Reflectance Distribution Function

- The BRDF is the distribution of reflected/scattered rays (on the right) for a given incident ray (on the left).
- The red ray corresponds to reflection.
- Whereas the blue rays represent scattering.



The paraxial propagation approximation

- We assume that propagation occurs principally along the z-axis

- The propagator for the electric field is $U = e^{ikz}u$, where k is the wavenumber and u obeys the paraxial equation: $2ik\partial_z u + \nabla^2 u + 2k^2 n_1 u = 0$, where $n_1 \ll 1$ is the refractive index fluctuation.

- We assume that the Rytov approximation holds so that $u_0 = u\exp[\chi + iS]$.

- We will use the MCF of the field: $\Gamma\left(\vec{R}, \vec{\Delta}, z\right) = u\left(\vec{R} + \frac{1}{2}\vec{\Delta}, z\right)u^*\left(\vec{R} - \frac{1}{2}\vec{\Delta}, z\right)$.

- The Wigner function is: $W\left(\vec{R}, \vec{P}, z\right) = \int \mathrm{d}^2\Delta\, \Gamma\left(\vec{R}, \vec{\Delta}, z\right)\exp\left[-ik\vec{P}\cdot\vec{\Delta}\right]$, where $\vec{P}$ is the slope of the ray.

The BRDF equation

- We assume that the outgoing Wigner function is related to the incident Wigner function by an integral transform.
- $W_o(\vec{R},\vec{P},0) = \int \mathrm{d}^2\, P' W_i(\vec{R},\vec{P}',0) T(\vec{P},\vec{P}')$

- For the BRDF, we assume a Gaussian scattering function:
- $T(\vec{P},\vec{P}') = \frac{1}{2\pi\sqrt{|\Sigma|}} \exp\left[-\frac{1}{2}(P_i + P_i' - 2Q_i){\Sigma_{ij}}^{-1}(P_j + P_j' - 2Q_j)\right]$
- Where the symmetric matrix Σ_{ij} represents the spreads of the scattering function and $\vec{Q}$ is the slope of the normal of the target surface.

- Note that the spreads can be a function of the position.

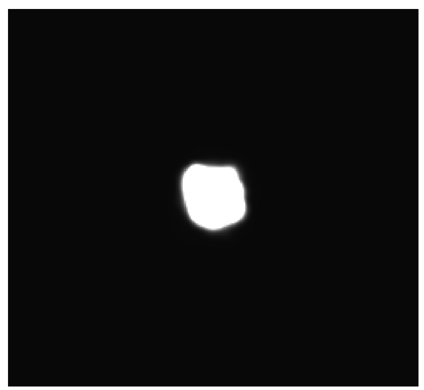
The MCF transfer function

- While the previous equations may look daunting, in terms of the MCFs we get the straightforward relation:
- $\Gamma_o\left(\vec{R},\vec{\Delta},0\right) = \Gamma_i\left(\vec{R},-\vec{\Delta},0\right)\exp\left[-\frac{k^2}{2}\Delta_i\Sigma_{ij}\Delta_j + 2ik\vec{Q}\cdot\vec{\Delta}\right]$
- Note that for a Lambertian (incoherent) surface, we have $\Sigma_{ij} = \sigma^2\delta_{ij}$ where $\sigma^2 \gg 1$ because the surface scatters over a wide range of angles.
- In that case, the exponential approximates a Dirac delta function $\delta\left(\vec{\Delta}\right)$ and the surface slope no longer matters.

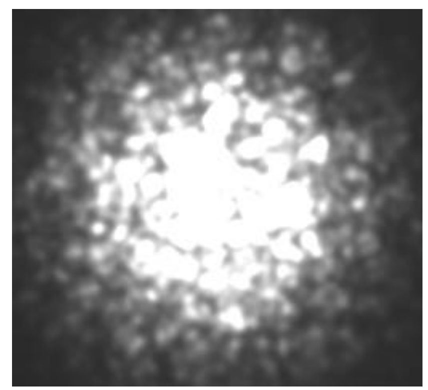
The active imaging model

- We have adapted the DRDC passive imaging model to an active model and we use the BRDF formalism previously developed.
- We tested it on a uniform grey surface with an isotropic BRDF $\Sigma_{ij} = \sigma^2 \delta_{ij}$ characterized by a length scale $l = 1/k\sigma$ that describes its specularity.
- Range = 2.3 km, Outer scale = 10 m, Inner scale = 6 mm, Cn2 = 5e-14, Wavelength = 4.2 µm, IFOV = 3.83 µrad, Aperture = 18.36 cm, Source = 1 cm.

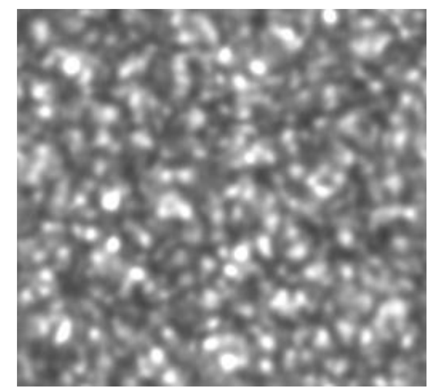
Original



8 mm



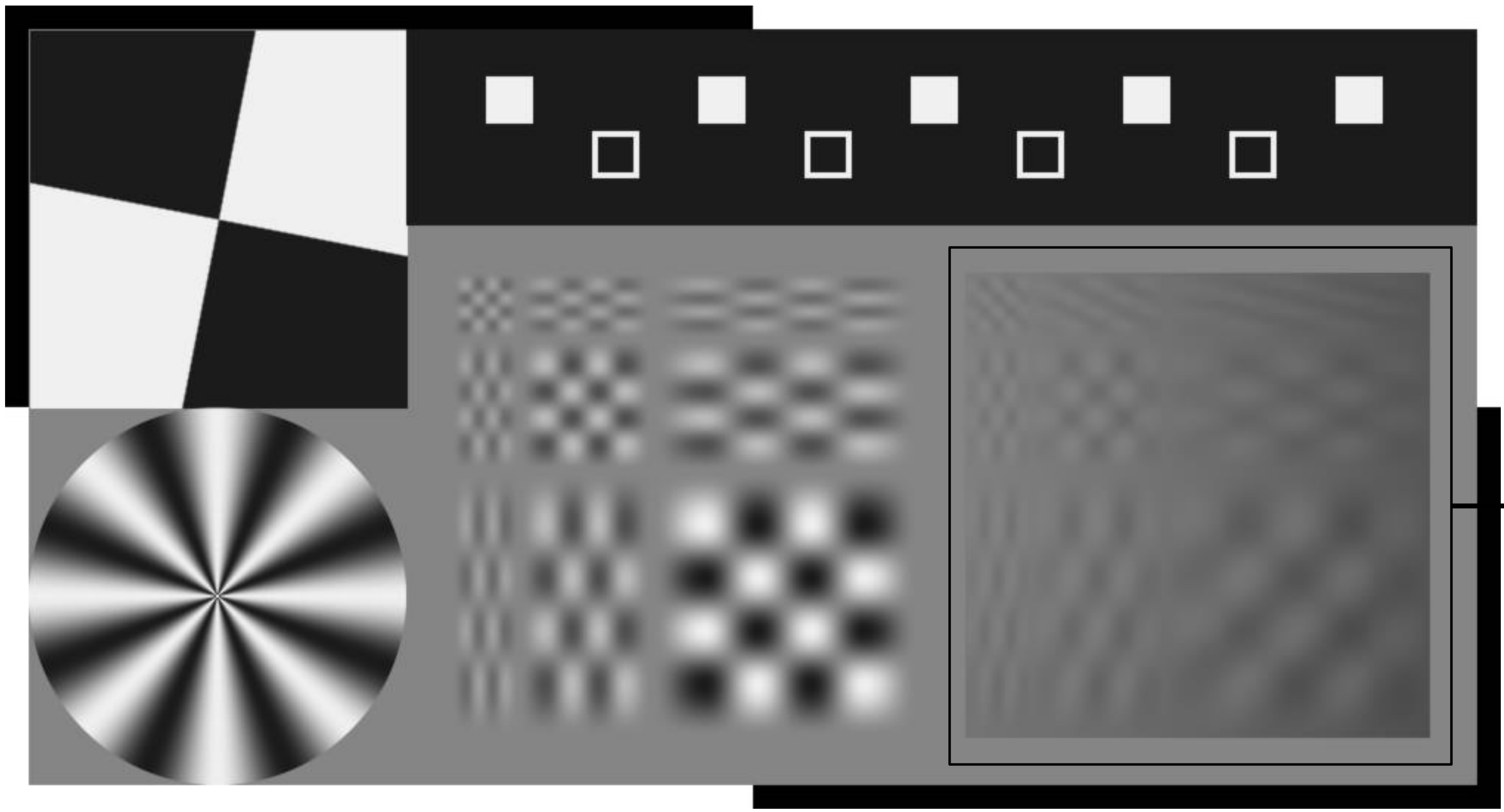
800 µm



Lambertian

No turbulence case

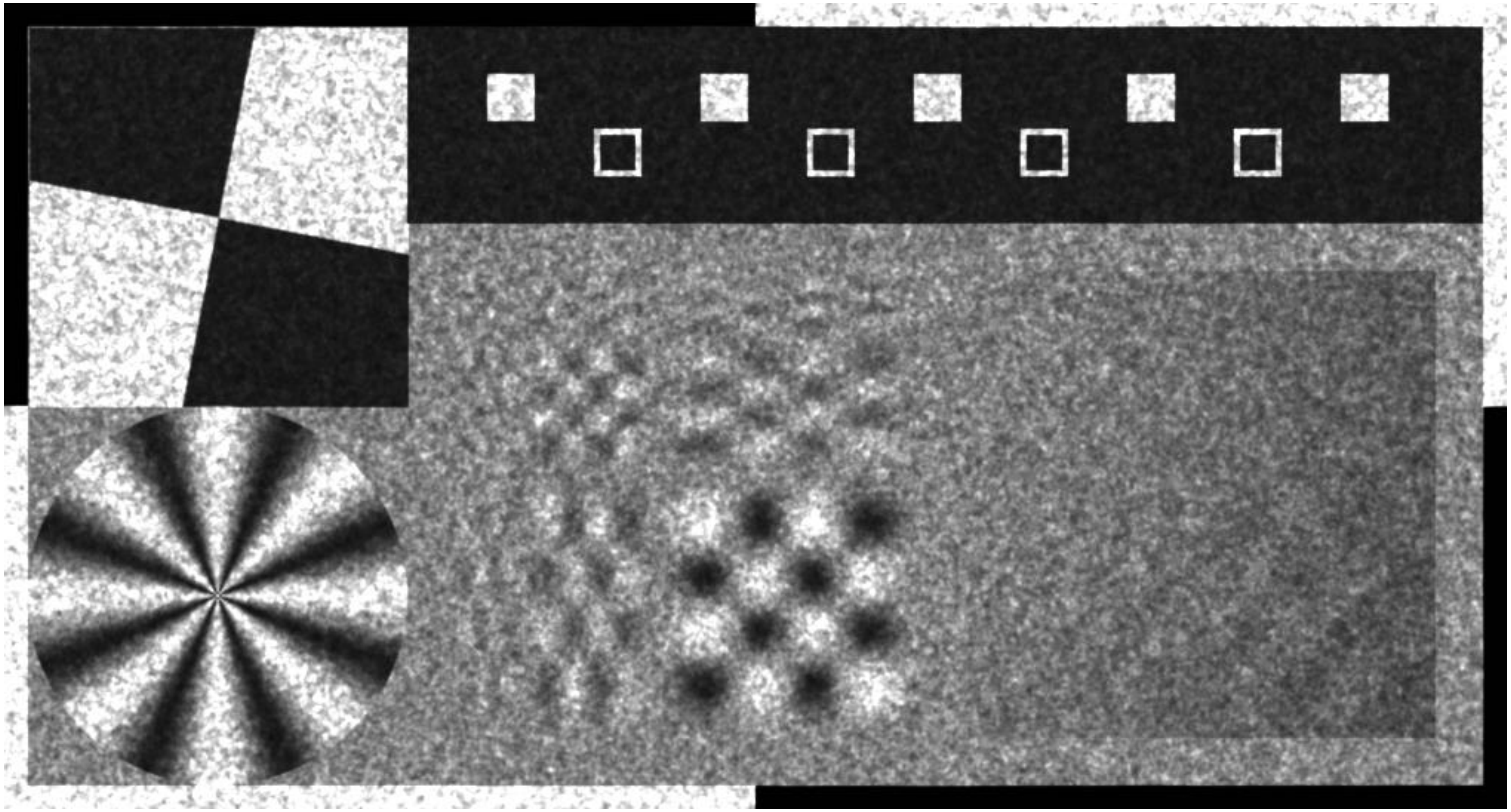
- Range = 2 km, Outer scale = 2 m, Inner scale = 1 cm, Wavelength = 1.55 µm, IFOV = 6.25 µrad, Aperture = 24 cm, Source = 1 cm.



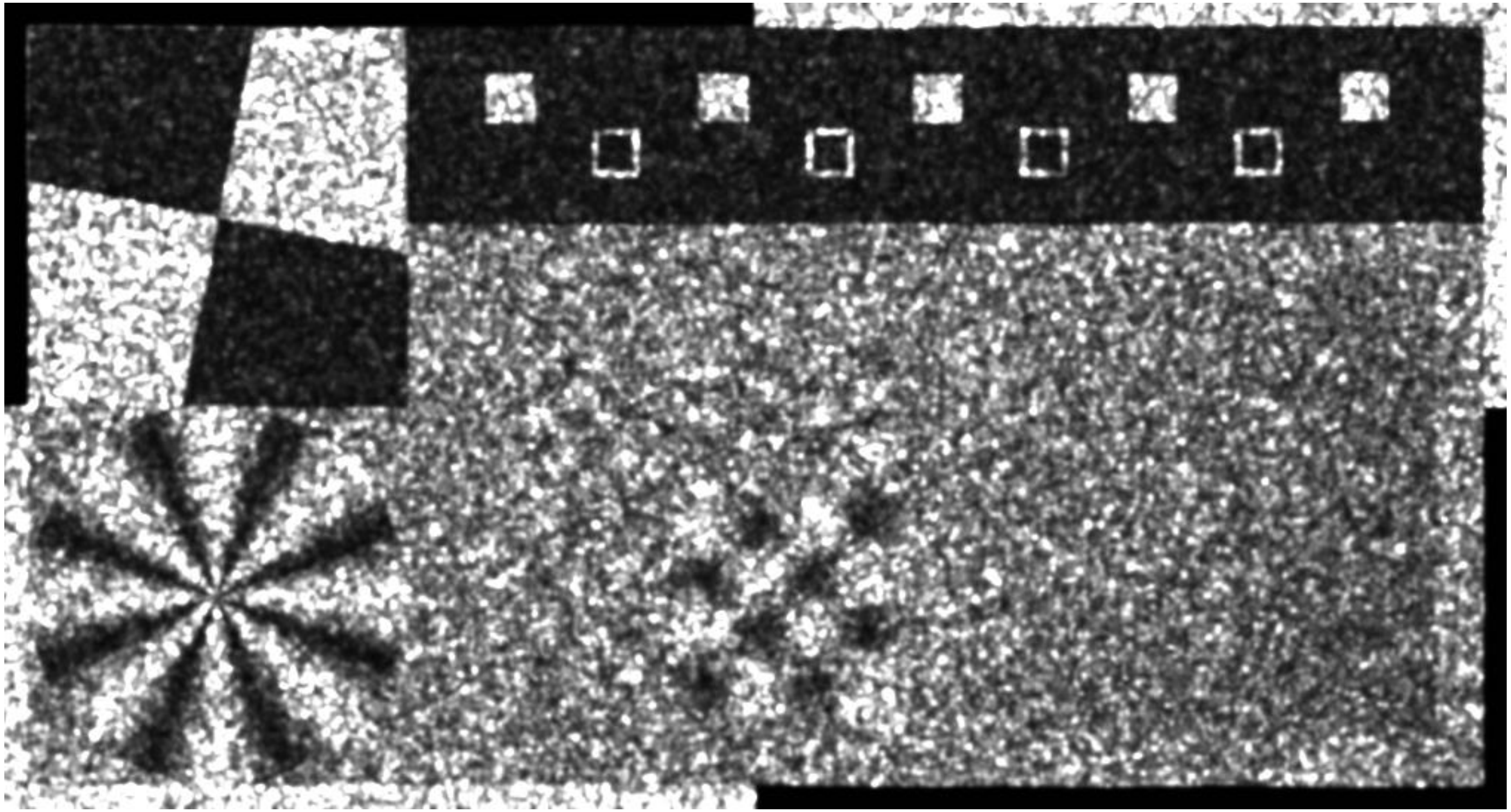
Specular Zone with bumps

Coherence length = 39.5 µm

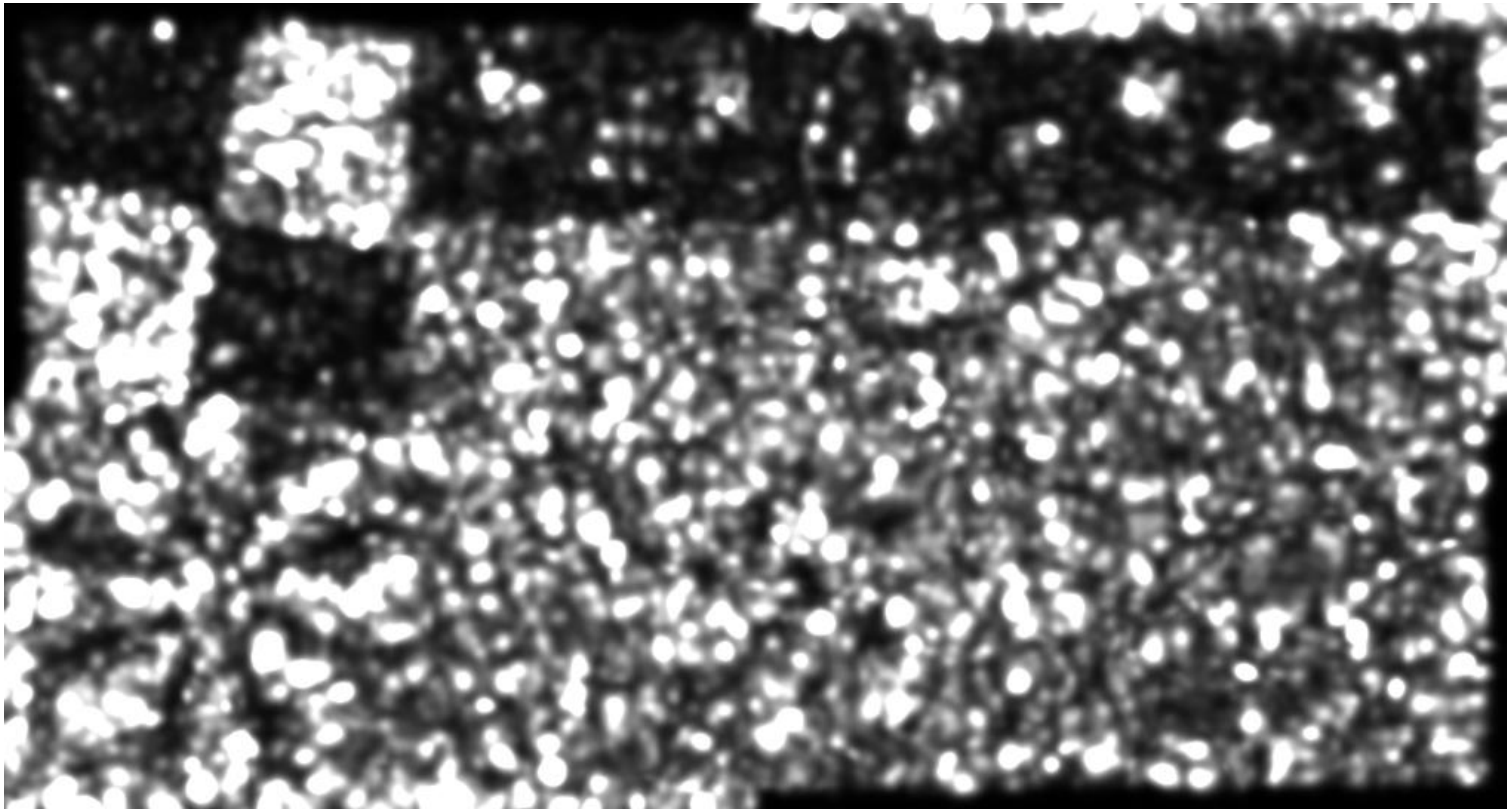
Cn2 = 1e-15 case



Cn2 = 1e-14 case



Cn2 = 1e-13 case



Evaluation of results

- We have developed a rough model for weakly specular surfaces for active imaging through weak turbulence.
- It requires the coherence lengths of the reflecting surface and its orientation with respect to the line-of-sight.
- It assumes that the slopes of the incoming and outgoing rays are small, along with the slope of the surface normal.
- More work is needed to handles cases where
    - Turbulence is strong,
    - The target is highly specular,
    - The surface normal has a large slope,
    - The illuminating beam creates speckle.