Experiments with non-uniformly correlated laser beams propagating underwater

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Spatially partially coherent beams

- Objective
  - **Decrease scintillation** on target: intensity fluctuations on target resulting from constructive and destructive interference of fully coherent laser beam propagation through complex medium
  - **Maintain desired level of coherence** necessary for required directionality of laser beam.
- Method: Create spatially partially coherent beams
  - Coherent laser source beam is decomposed into spatially distributed beamlets
  - Each beamlet has prescribed phase that produces desired beam shape in far field
  - Phase screen realizations are cycled faster than propagation medium changes in order to mitigate the variations of the refraction index along the propagation path
- Benefits of using spatially partially coherent beams
  - Reduced scintillation and ability to control beam coherence in order to preserve directionality
- Drawback
  - Reduced intensity on target due to spreading of the partially coherent beams
  - Low cycling rate of phase screens due to limitations of the technology used

Non uniformly correlated (NUC) beams

- If complex degree of coherence, μ, between two spatial points is assumed to be a function of only the separation between the points than the coherence distribution is uniform over the whole field. Schell-model beams.

$$\mu_0(\boldsymbol{\rho}_1, \boldsymbol{\rho}_2) = \exp\left(-\frac{|\boldsymbol{\rho}_2 - \boldsymbol{\rho}_1|^2}{r_0^2}\right)$$

- Practically, for unfirmly correlated spatially partially coherent beams the realizations are generated (using SLM) by convolving the degree of coherence with values drawn from Gaussian random distribution.
- Lajunen and Saastamoinen introduced the first non-uniformly correlated spatially partially coherent source that has locally varying degree of coherence with given cross-spectral density and the degree of coherence that depends on the difference of the squared values of the positional coordinates and its center is shifted for x_0 [a].

$$W_0(x_1, x_2) = \exp\left(-\frac{x_1^2 + x_2^2}{2w_0^2}\right)\mu(x_1, x_2), \qquad \mu(x_1, x_2) = \exp\left\{-\frac{[(x_2 - x_0)^2 - (x_1 - x_0)^2]^2}{w_c^4}\right\},$$

- x_1 and x_2 are two spatial points. x_0 could be interpreted as focusing point, but ω_c^4 can not be interpreted as coherence width in the same way as r_0^2.
- Due to the non uniformly distributed correlations the degree of coherence can not be simply measured by Young experiment and thus verification of the NUC generation needs more work.

[a] H. Lajunen and T. Saastamoinen, "Propagation characteristics of partially coherent beams with spatially varying correlations," Opt. Lett. **36**, 4104-4106 (2011).

Properties of NUC beams

- NUC sources experience lower scintillation and achieve higher peak irradiances than coherent and uniformly correlated (Schell-Model) sources making them potentially useful for both free-space and underwater optical communications. [b].

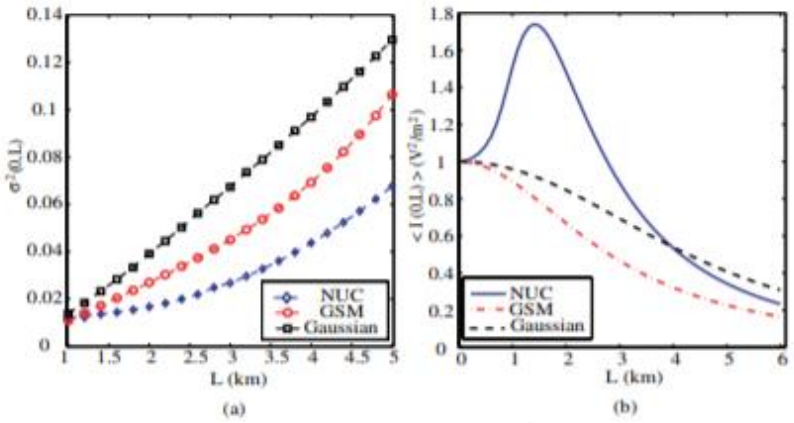


Fig. 2. (a) On-axis scintillation index $\sigma^2(0, L)$ and (b) On-axis average intensity $\langle I(0, L)\rangle$ of an NUC, a GSM, and a coherent Gaussian beam as a function of the propagation distance L. Here, $r_c = 0.91 w_0$.

The cross-spectral density of a NUC beam may be expressed more illustratively by a mode representation [5]:

$$W(\boldsymbol{\rho}_1, \boldsymbol{\rho}_2) = \int p(v) H_0(\boldsymbol{\rho}_1, v) H_0^*(\boldsymbol{\rho}_2, v) \mathrm{d}v, \tag{5}$$

where

$$p(v) = \frac{1}{\sqrt{\pi} a} \exp\left(-\frac{v^2}{a^2}\right), \tag{6}$$

and

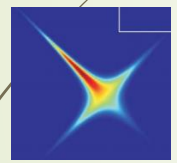
$$H_0(\boldsymbol{\rho}, v) = \exp\left(-\frac{\rho^2}{w_0^2}\right) \exp(-ikv\rho^2). \tag{7}$$

Here $k = 2\pi/\lambda$ is the wavenumber of beam and $a = 2/(r_c^2 k)$. Equations (5)–(7) show that an NUC beam can be generated by incoherent superposition of coaxial Gaussian modes represented by $H_0(\boldsymbol{\rho}, v)$. The initial radius of curvature R of these Gaussian modes is random and its reciprocal $v\,[R = 1/(2v)\,]$ follows a Gaussian distribution with a probability density $p(v)$.

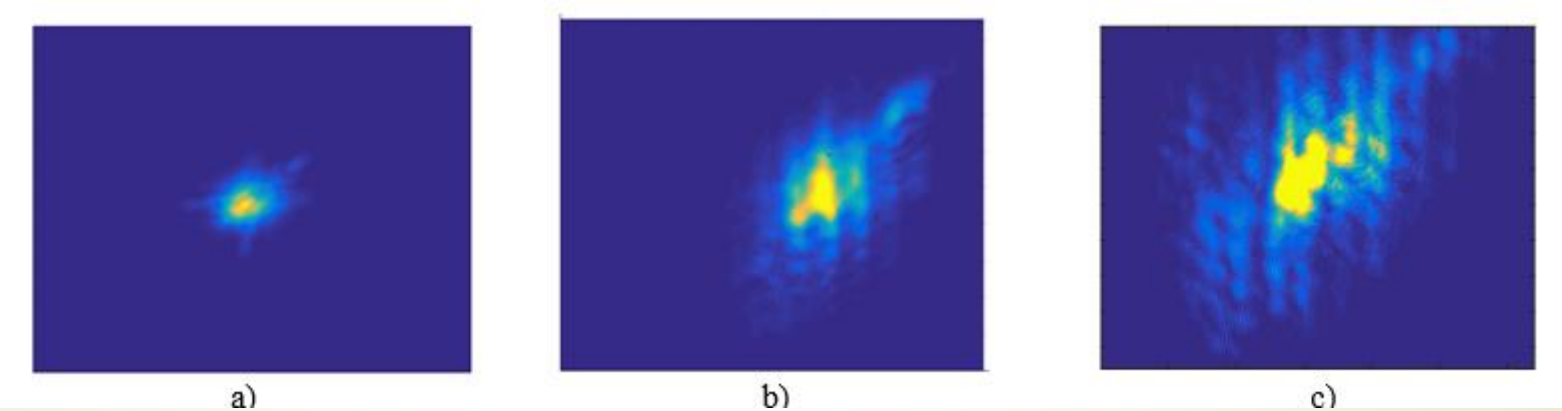
[b] Y. Gu and G. Gbur, "Scintillation of nonuniformly correlated beams in atmospheric turbulence," Opt. Lett. **38**, 1395-1397 (2013).

NUC Generation using random focus generated by SLM (c)

Step 1 : Generate distance grid (matrix of all possible pixel locations on SLM, Xslm Yslm)
Step 2 : Introduce location shift x_0 : $A=(Xslm - x_0)^2 + (Yslm - x_0)^2$
Step 3 : Calculate S= Gaussian random number / σ_0^2
Step 4 : Find SLM screen from $e^{j\,S*A}$



Comparison from (a)



Initial results

Light intensity distribution for non-uniformly correlated laser beam (random focus generated by SLM)
a) simulation of the generated beam,
b) recorded image before
c) recorded image after underwater propagation

(c) Synthesis of non-uniformly correlated partially coherent sources using a deformable mirror M. W. Hyde IV,S. R. Bose-Pillai, R. A. Wood APPLIED PHYSICS LETTERS111, 101106 (2017)

Source spectral degree of coherence μ

$$\mu SFB^{(0)}(\rho_1, \rho_2) = exp\left[-\frac{(|\rho_2 - \rho_1|^2)^2}{\delta^4}\right]$$

Self focusing beams

$$\mu MGSM^{(0)}(\rho_1, \rho_2) = \frac{1}{C_0}\sum_{m=1}^{M}\binom{M}{m}\frac{(-1)^{m-1}}{m} exp\left[-\frac{|\rho_2 - \rho_1|^2}{2m\delta^2}\right]$$

$$C_0 = \sum_{m=1}^{M}\binom{M}{m}\frac{(-1)^{m-1}}{m}$$

Uniformly correlated
Flat top profile: Multi Gaussian Schell Model beams

$\boldsymbol{\delta}$ is the r.m.s. width of the degree of coherence which describes the degree of coherence of the beam

$\boldsymbol{\rho_1}$ and $\boldsymbol{\rho_2}$ are position distances and superscript (0) refers to the source plane

$\boldsymbol{M}$ relates to the flatness of the intensity profile formed in the far field, $M \rightarrow \infty$ corresponds to sources producing far fields with flat centres and abrupt decays at the edges

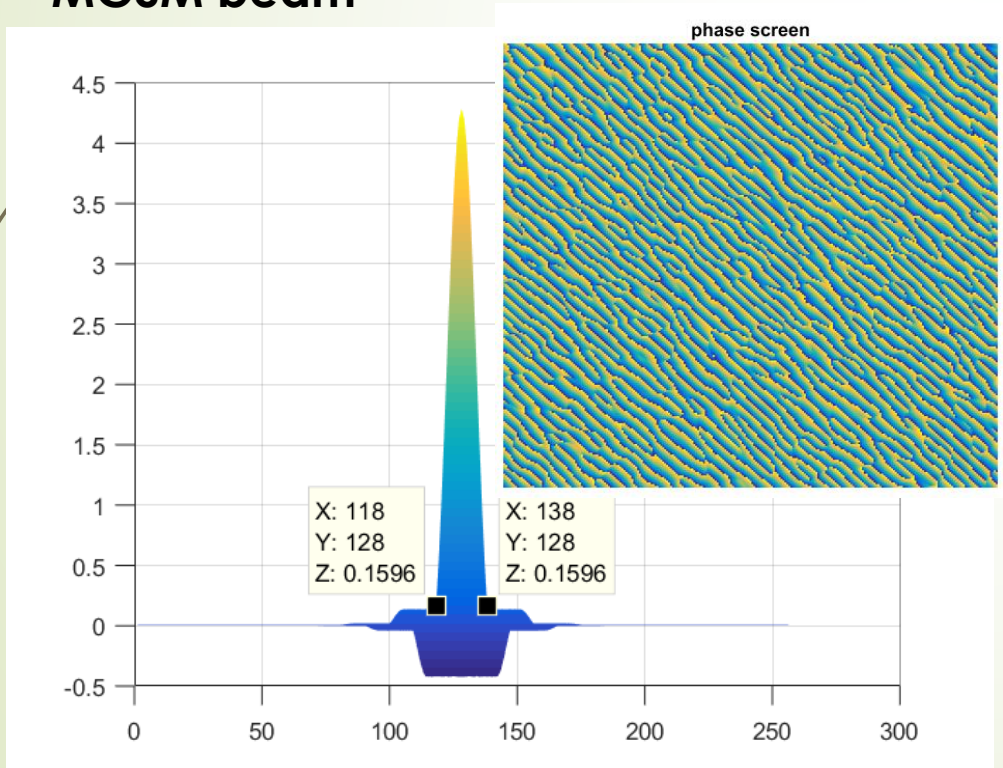
Generating spatially coherent beams using SLM
Self focusing and MGSM beams with the same coherence width

- **MGSM**
- Step 1 : Generate distance grid (matrix of all possible pixel locations on SLM, Xslm Yslm)
- Step 2 : Select center of the SLM (c_x and c_y) and calculate the distance from each point $|\rho_1 - \rho_2|^2 = (Xslm - c_x)^2 + (Yslm - c_y)^2$
- Step 3 : Calculate $\mu MGSM^{(0)}(\rho_1, \rho_2) = \frac{1}{C_0}\sum_{m=1}^{M}\binom{M}{m}\frac{(-1)^{m-1}}{m} exp\left[-\frac{|\rho_2-\rho_1|^2}{2m\delta^2}\right]$
- Step 4 : Convolve $\mu MGSM^{(0)}$ with SLM size matric of random values drawn from Gaussian distribution
- Step 5 : Find SLM screen
- **Self Focusing beam**
- Repeat steps 1 and 2
- Step 3 : Calculate $\mu SFB^{(0)}(\rho_1, \rho_2) = exp\left[-\frac{\left(|\rho_2-\rho_1|^2\right)^2}{\delta^4}\right]$
- Repeat steps 4 and 5.

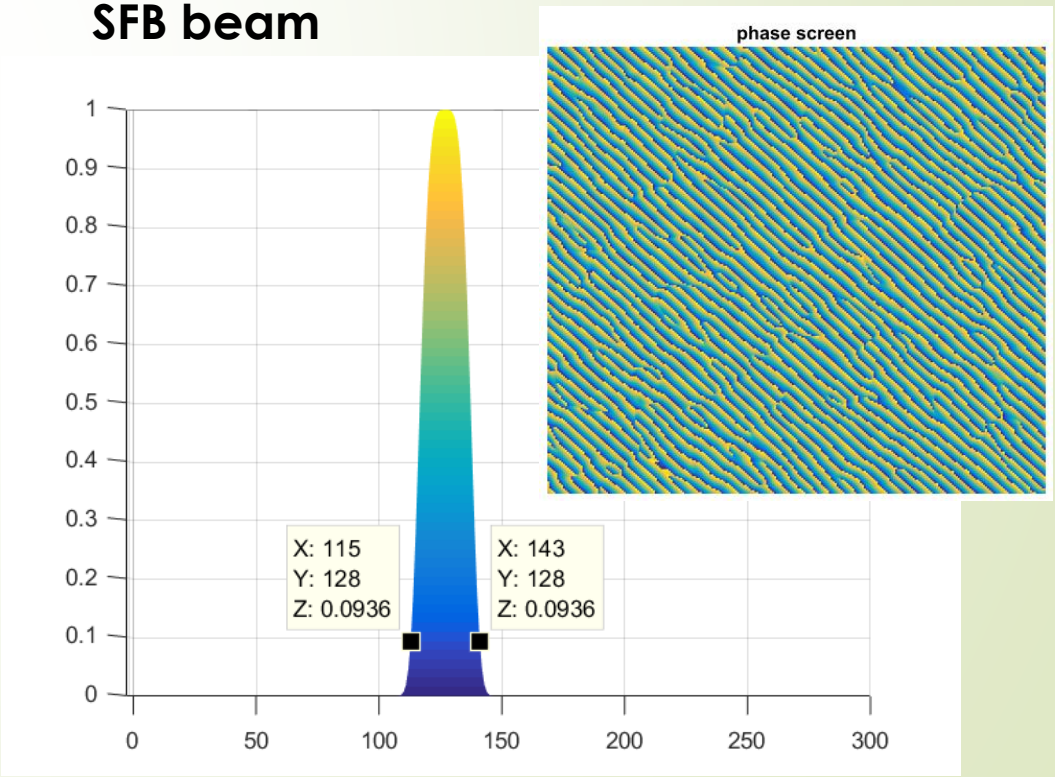
Source spectral degree of coherence and phase screens generated for SLM

δ (width of the degree of coherence) = 0.19 mm

MGSM beam

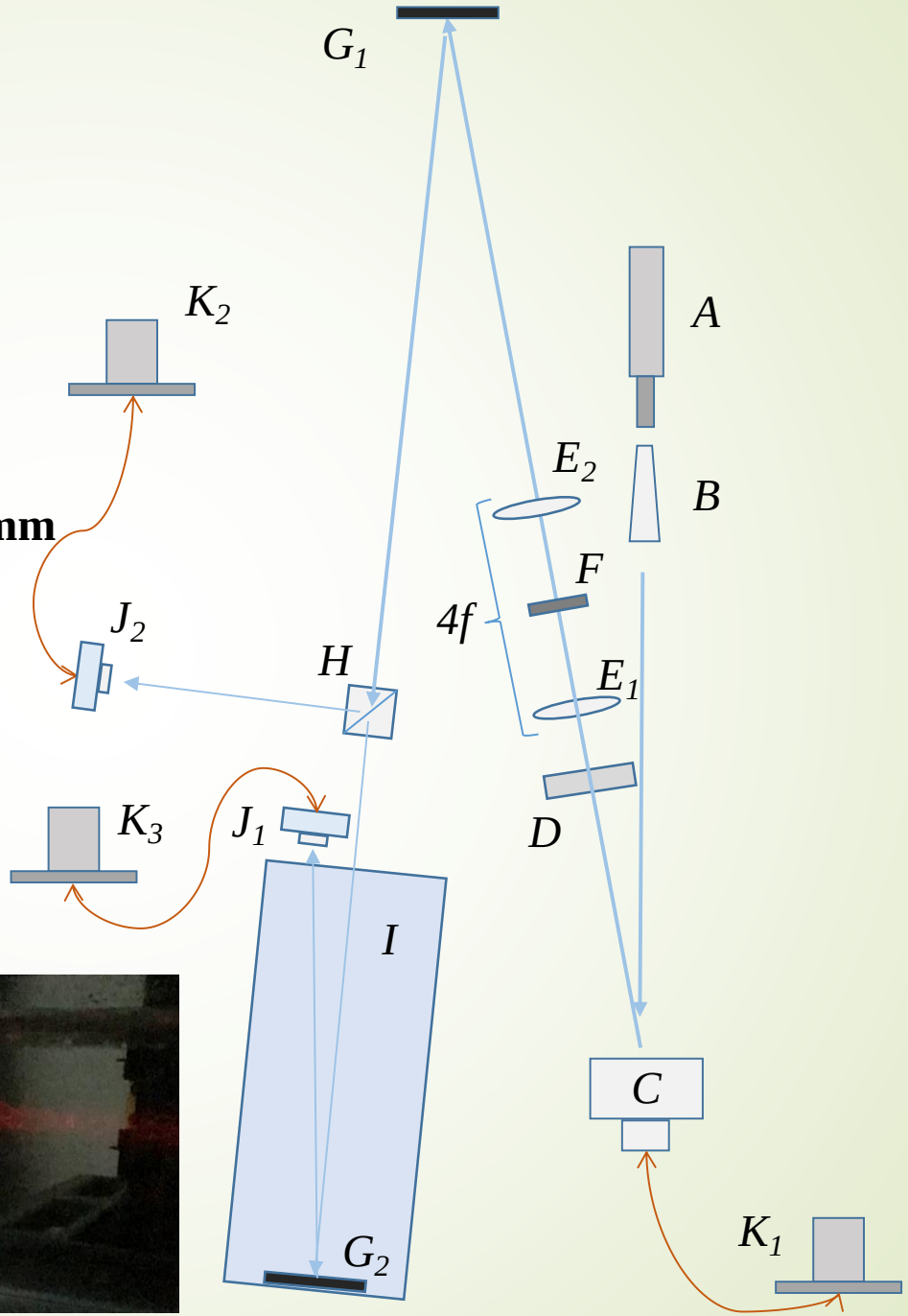


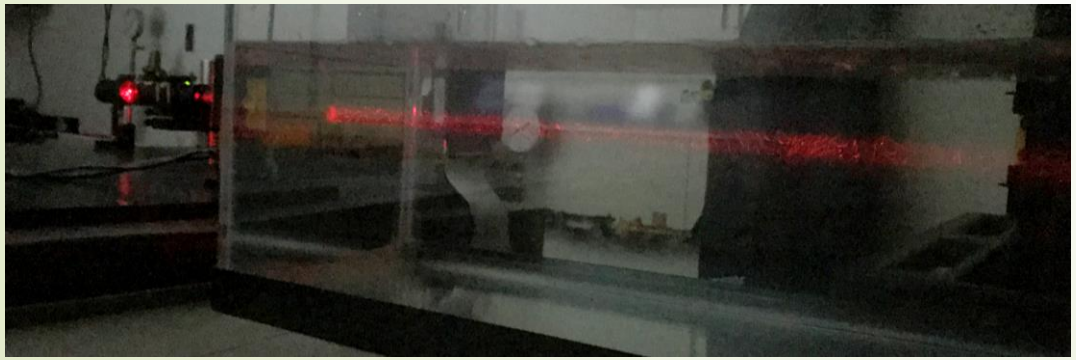
SFB beam



Experimental Set up

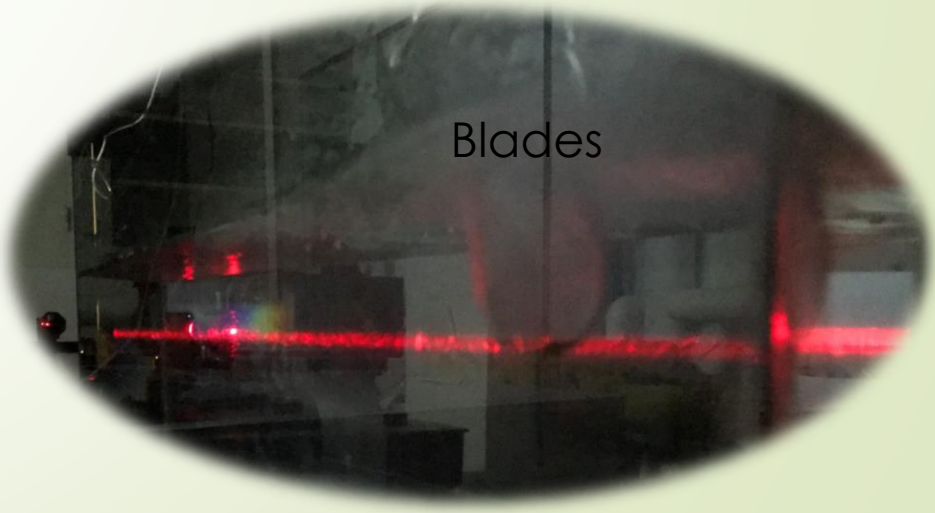
A **– HeNe laser**
B **– beam expander**
C **– spatial light modulator**
D **– linear polarizer**
$E_{1,2}$ **– lens with focal lengths of 400 mm**
F **– mechanical iris**
placed at the focal point of $E_{1,2}$
$G_{1,2}$ **– mirror**
H **– beam splitter**
I **– 1 m propagation tank**
$J_{1,2}$ **– camera**
$K_{1,2,3}$ **– computer**





Underwater scenarios

- MGSM and SFB beams were propagated trough air for 7 m and than for 2 m under water using a double pass through a 1 m long water tank.
- Tank was filled with distilled water and air born scatterers were introduced.
- Tested the laser propagation in three scenarios:
  - CALM water environment was kept stationary.
  - MEDIUM Level water was mechanically agitated using blades rotating at medium speed.
  - HIGH Level water was mechanically agitated using blades rotating at high speed.

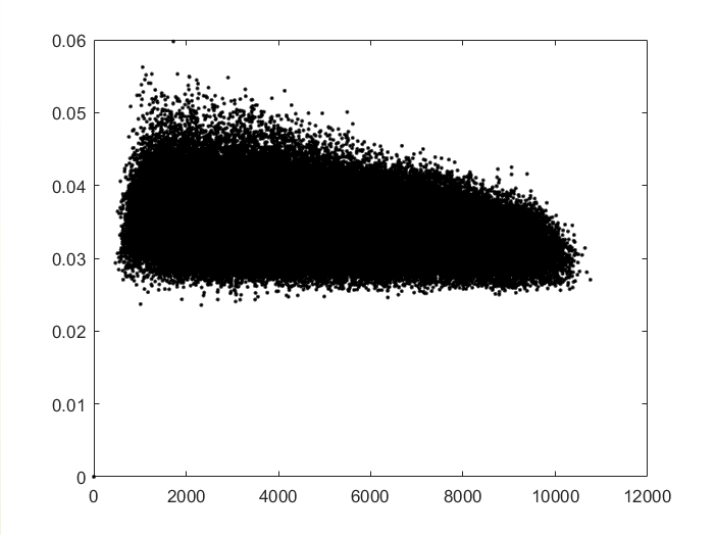


Analysis Method for beam Intensity and Scintillation at the reception

- To generate SFB and MGSM we cycled 8000 respective phase screen realizations on SLM at the rate of 333 Hz
- Camera captured 120 seconds of laser propagation through water under various conditions with exposure time of 100 ms
- Intensity, im_i, measured at each pixel location was adjusted for the background level B_{avg}
- Measured Mean Intensity level I_{avg} for each pixel over the 120 seconds was used to find the scintillation index

$$SI_B = \frac{\frac{\sum_{i=1}^{N}\left((im_i - B_{avg}) - (I_{avg} - B_{avg})\right)^2}{N}}{(I_{avg} - B_{avg})^2}$$

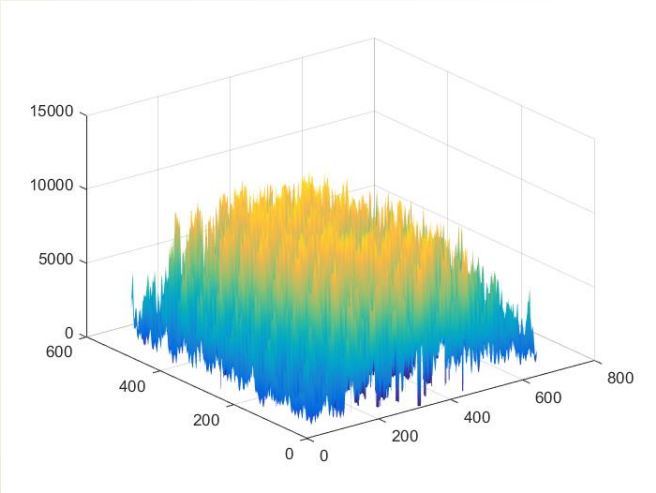
Measured Intensity and scintillation index across the whole camera sensor area
SFB $\boldsymbol{\delta}$ (width of the degree of coherence) = 0.54 mm



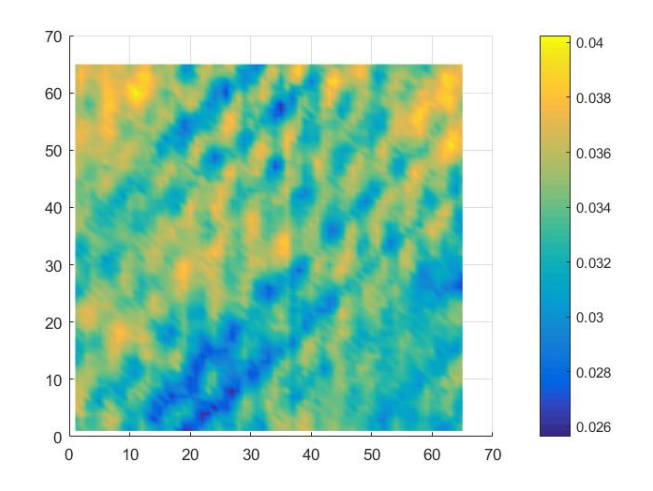
Note: Not correlated measurements between the scintillation index and Intensity across sensor area

Analysis Method for beam Intensity and Scintillation at the reception

- The center of the SFB beam $\boldsymbol{\delta}$ = 0.54 mm was identified and 65x65 pixel area aligned at the peak of the SFB beam was used as the averaging area for the reported results
- The average values of SI_B and I_{avg} across the selected receiver area (0.481x0.481mm^2) was reported as a comparison measure

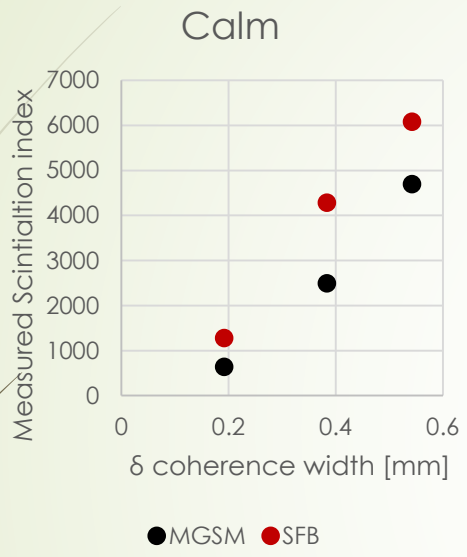


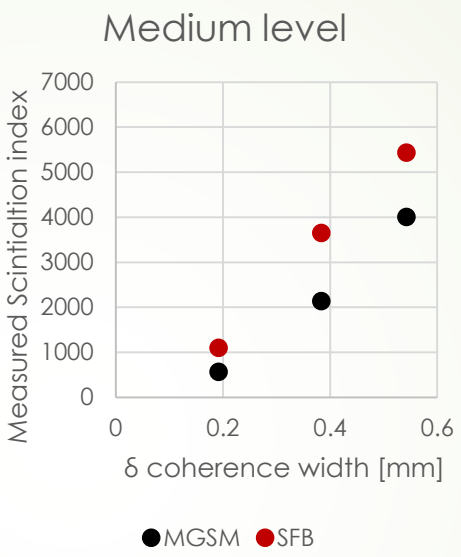
Measured **Intensity** across the whole camera sensor area
SFB $\boldsymbol{\delta}$ (width of the degree of coherence) = 0.54 mm

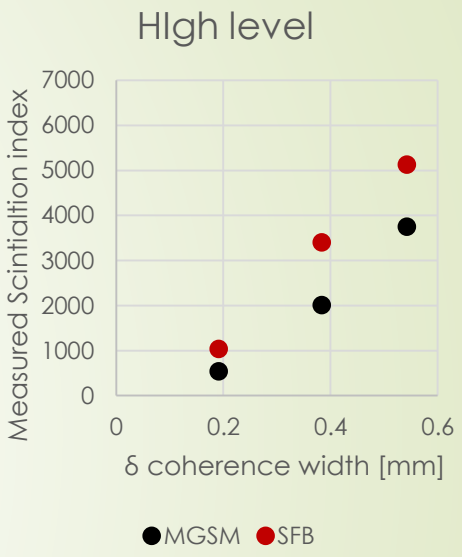


Measured **Scintillation**
across the selected receiver area

Intensity MGSM vs SFB





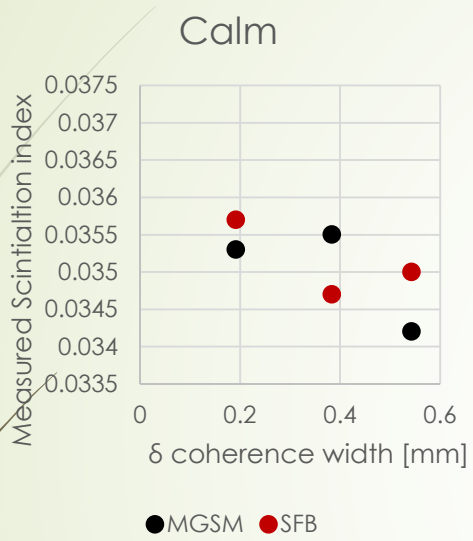


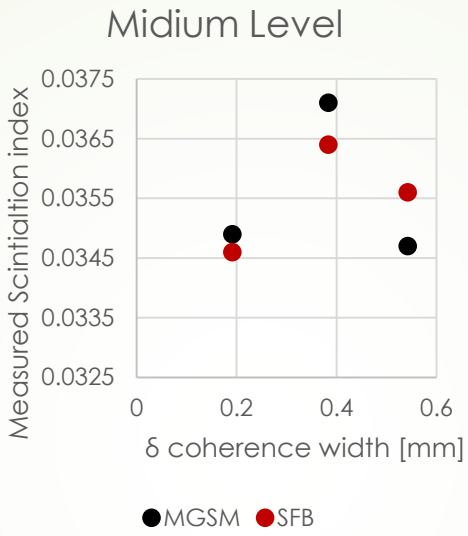
Self focusing spatially partially coherent beams deliver
higher level of energy at the reception when compared to MGSM beams.

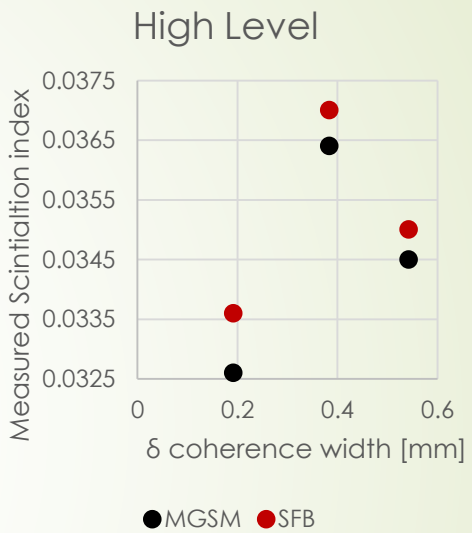
For less coherent beams the intensity advantage is 32%
and for more coherent beams the advantage is 15%.

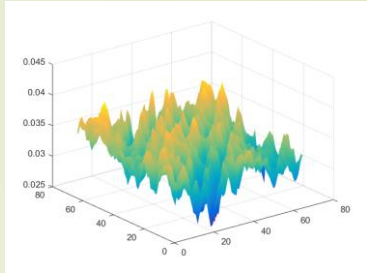
Note: the reception aperture averaging plays the role
when there is more coherent beam, with more pronounced peak.

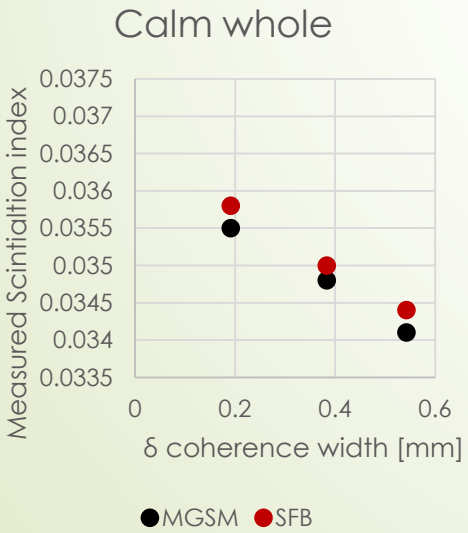
Scintillation index: *range of change 5.6% for all scenarios*
No significant difference between MGSM and SFB beams

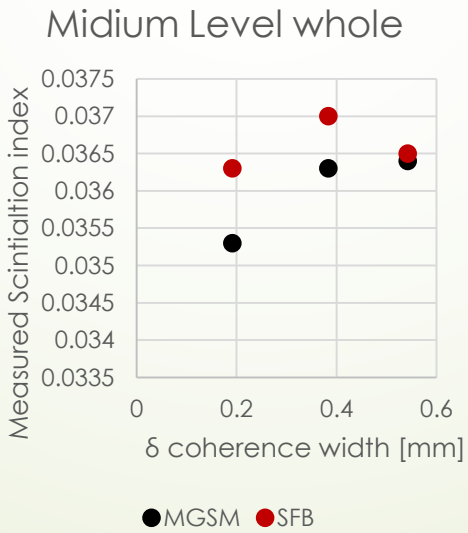


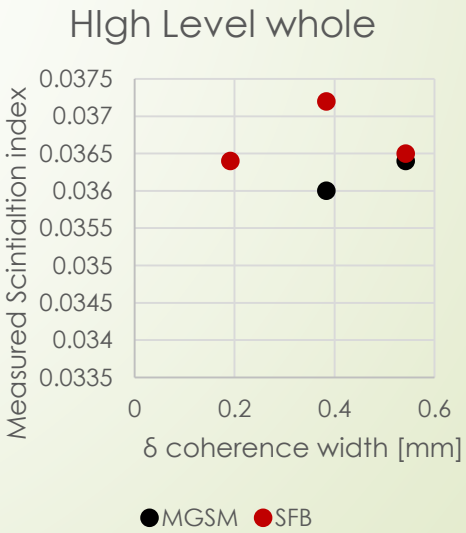


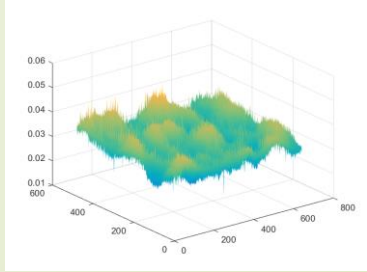








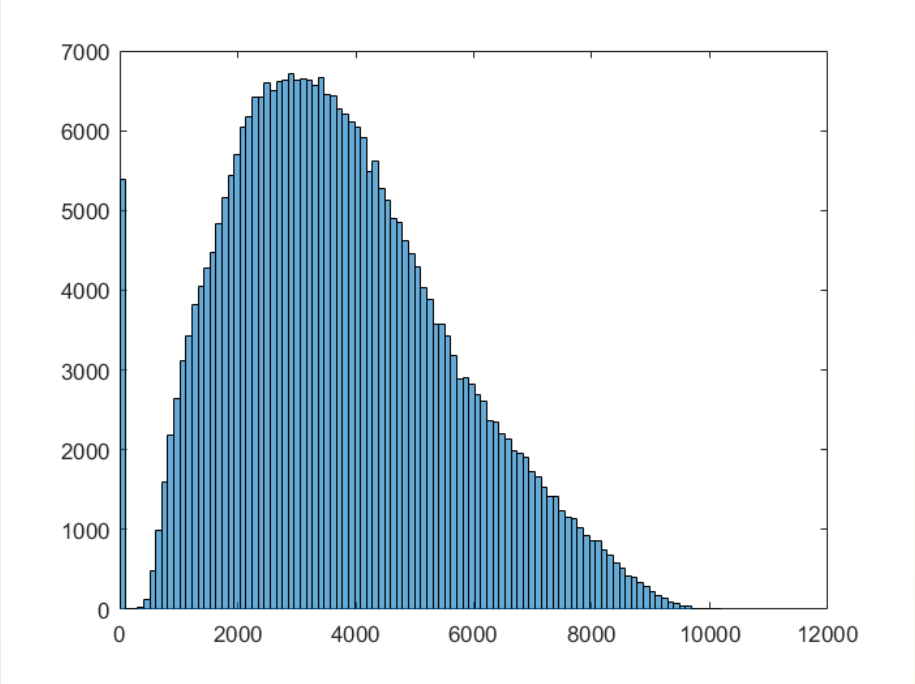




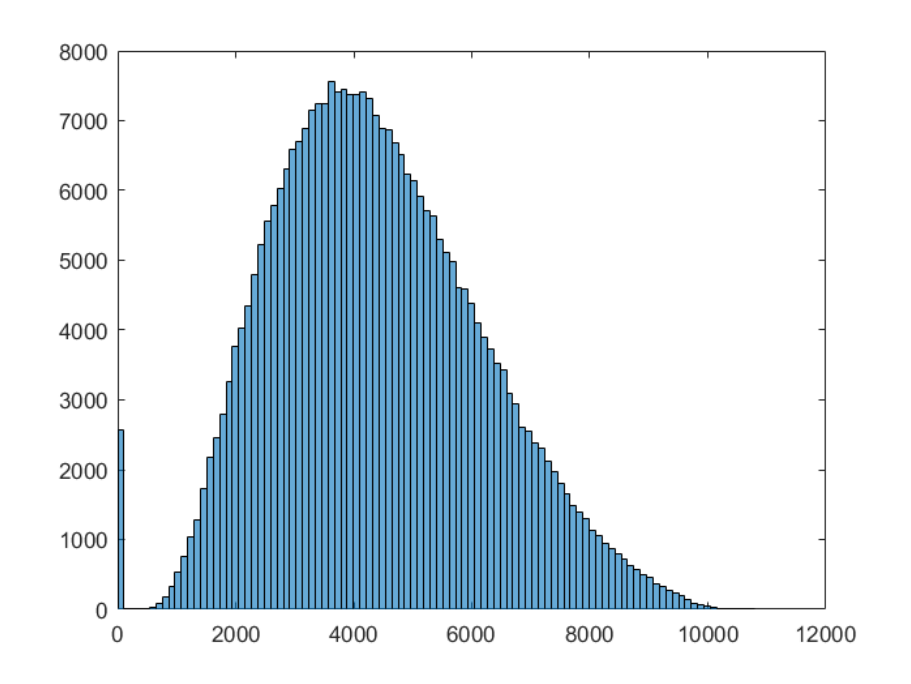
Note
No significant change in results due to the observation area selection

Statistical properties based on the intensity fluctuations measurements

- Statistical properties characterization via Histogram
- Cumulative Density Function obtained integrating the histogram

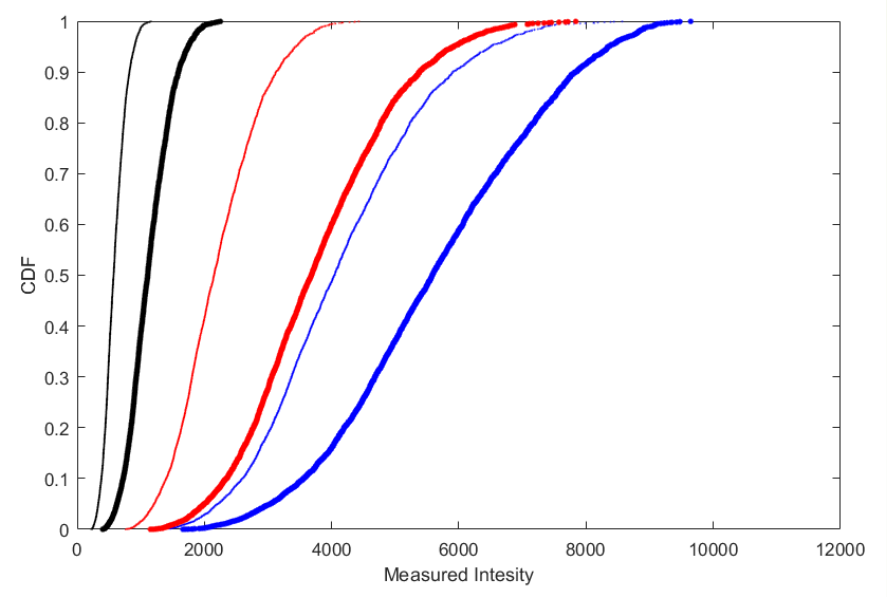


SFB ***δ*** (width of the degree of coherence) = 0.54 mm, scenario high level

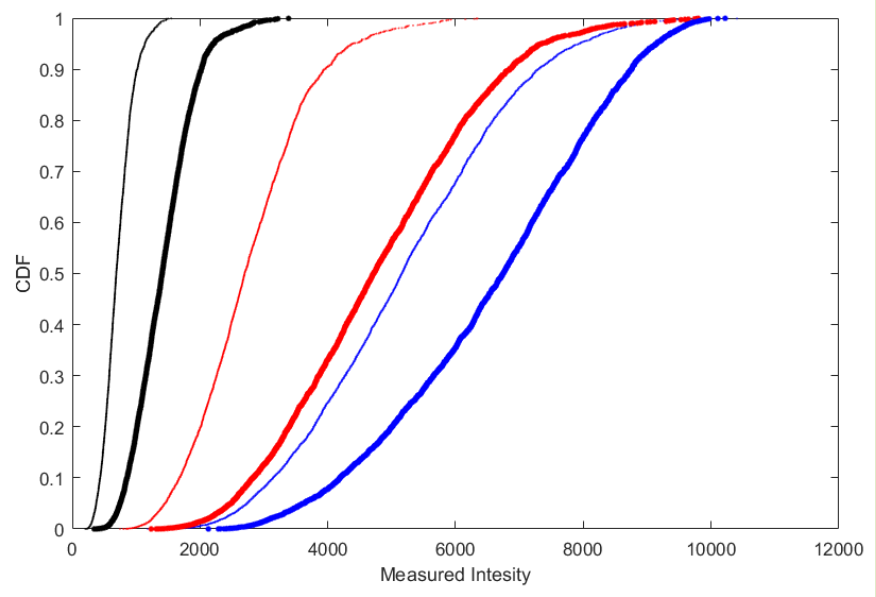


MGSM ***δ*** = 0.54 mm, scenario calm

Measured CDFs for MGSM vs SFB

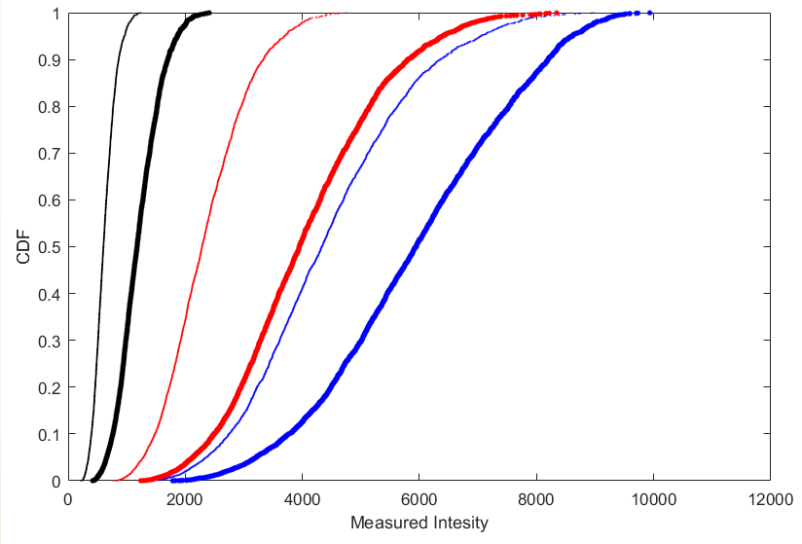


MGSM and SF beams
δ (width of the degree of coherence)
0.19 0.38 and 0.54 mm



Scenario: Medium level

Scenario: High level



Scenario: Calm

Conclusions

- We demonstrated that **Self Focusing** spatially partially coherent beams **deliver higher energy** on the target when compared to the Multi Gaussian Schell model beams.
- We did not observe significant difference in scintillation index performance between the SF and MGSM beams in the underwater scenarios we tested
- Note: reported experimental results are directly related to the underwater scenarios we measured and further research needs to be performed to establish full range of performance properties.