Karlsruher Institut für Technologie

Final presentation for “Data acquisition of atmospherically-induced optical signal fluctuations”

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Motivation

Deutsches Zentrum
für Luft- und Raumfahrt
German Aerospace Center

Karlsruher Institut für Technologie

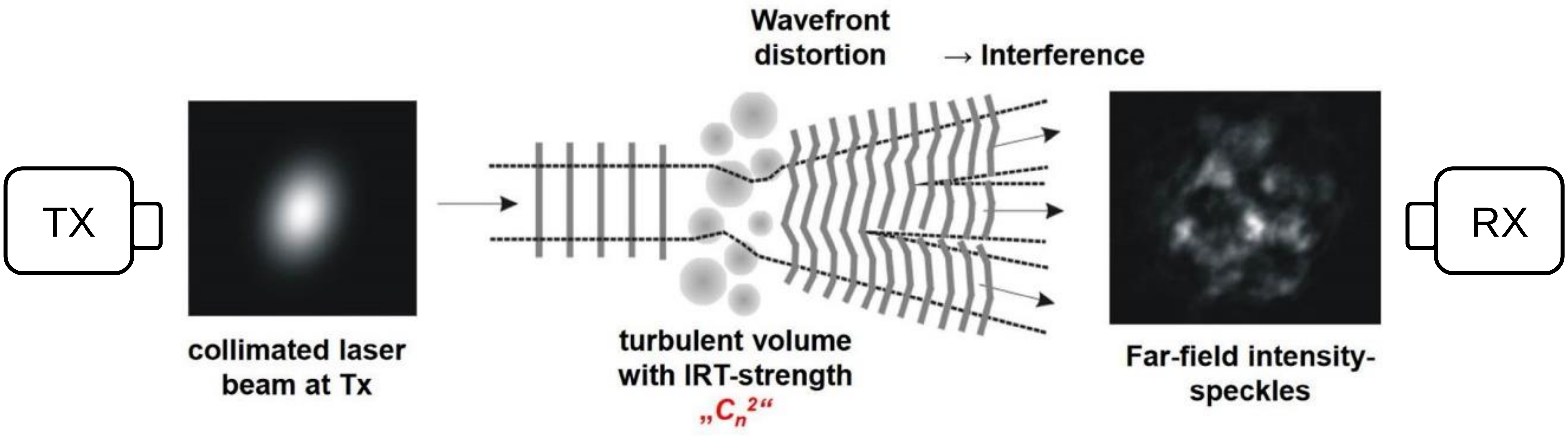
Advantages

- Larger bandwidths
- High-data-rate
- Low-cost ease deployment
- High security

Disadvantage :
Atmospheric Effects

- Absorption
- Scattering
- Cloud Blockage
- Sky Background light
- Atmospheric turbulence

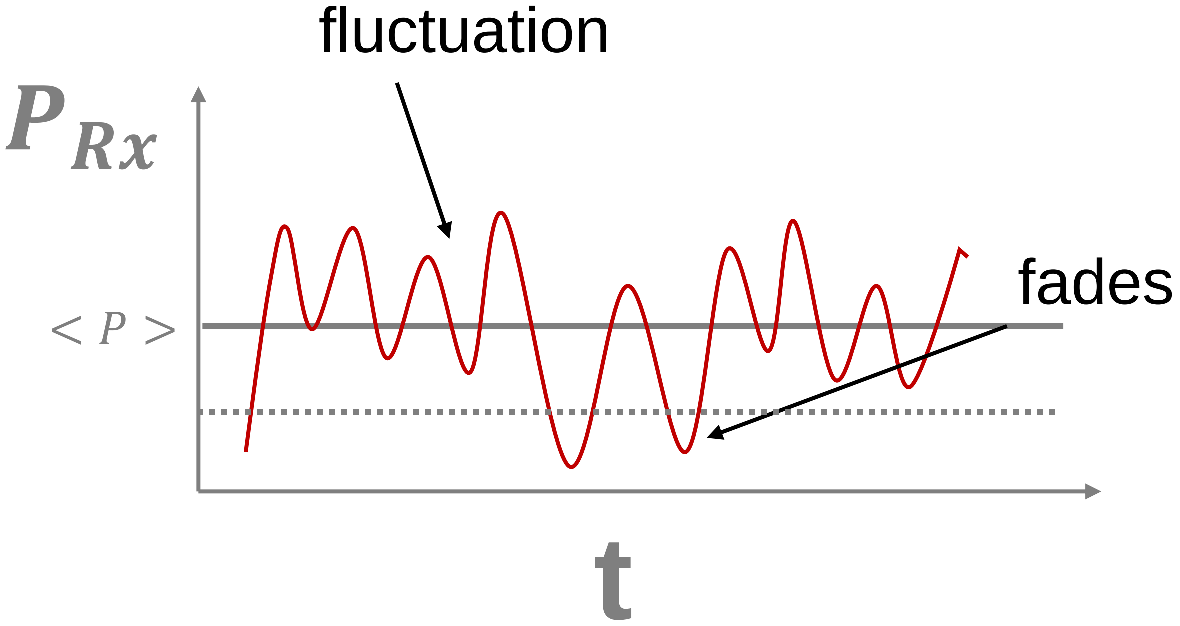
Introduction



[Figure 1 Atmospheric Turbulence]

[Ref : Giggenbach_FSO_for_Sat-GND-Links_Tutorial_ASMS2014_20140908_HANDOUT20160818

Introduction



[Figure 2 Received power with fluctuations]

- (Power) Scintillation Index

: normalized intensity variation

$$\sigma_P^2 = \frac{< P^2 >}{< P >^2} - 1$$

< > denotes average

- Fades

: decrease in signal strength,
caused by variation

  - (general case) -3dB from mean power
  - (our case) -1.5dB from mean power

Thesis goals

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- Application of transmitter diversity with different divergence angles

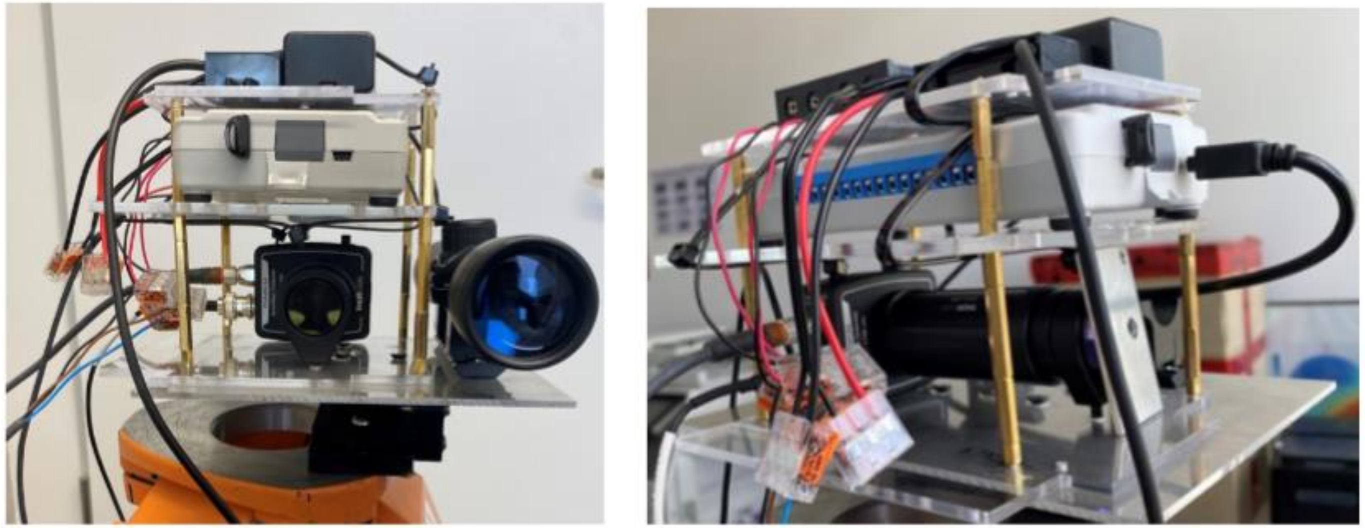
$$< P_T > = N \times < P_{RX} >, \qquad \sigma_T^2 = \frac{\sigma_I^2}{N}$$

  - two identical transmitters
  - CW collimated gaussian beam @1550nm
  - FWHM 330urad/545urad/924urad

$$< P_T > = 2 \times < P_{RX} >, \qquad \sigma_T^2 = \frac{\sigma_I^2}{2}$$

Thesis goals

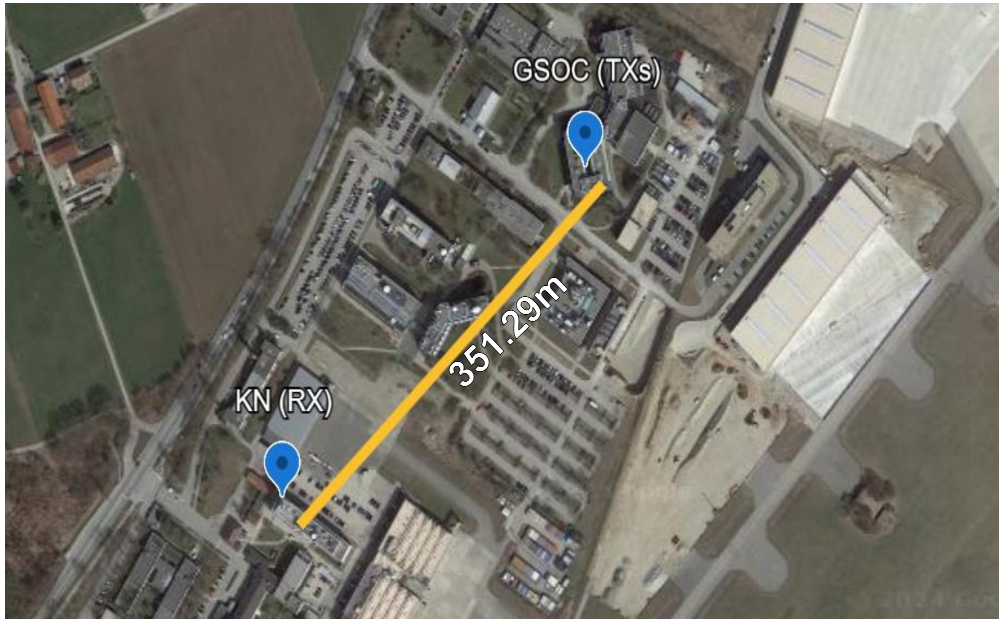
- Development of portable/ low weight receiver with data logger
  - can be applied to many area in the future (e.g.) installation on a drone



(a) front (b) side

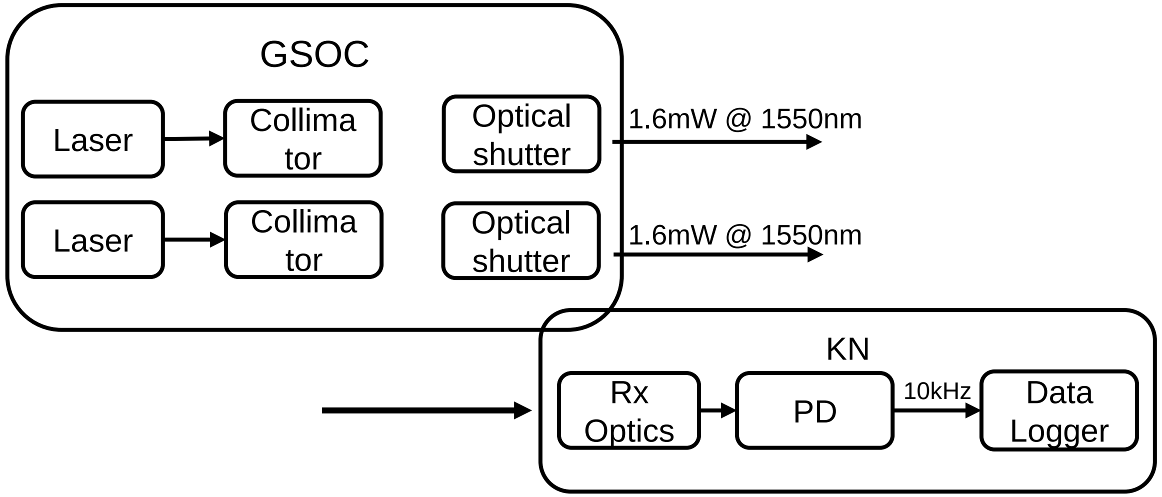
[Figure 3 developed optical receiver system]

Introduction : Optical Link and overall system



[Figure 3 optical link set-up]

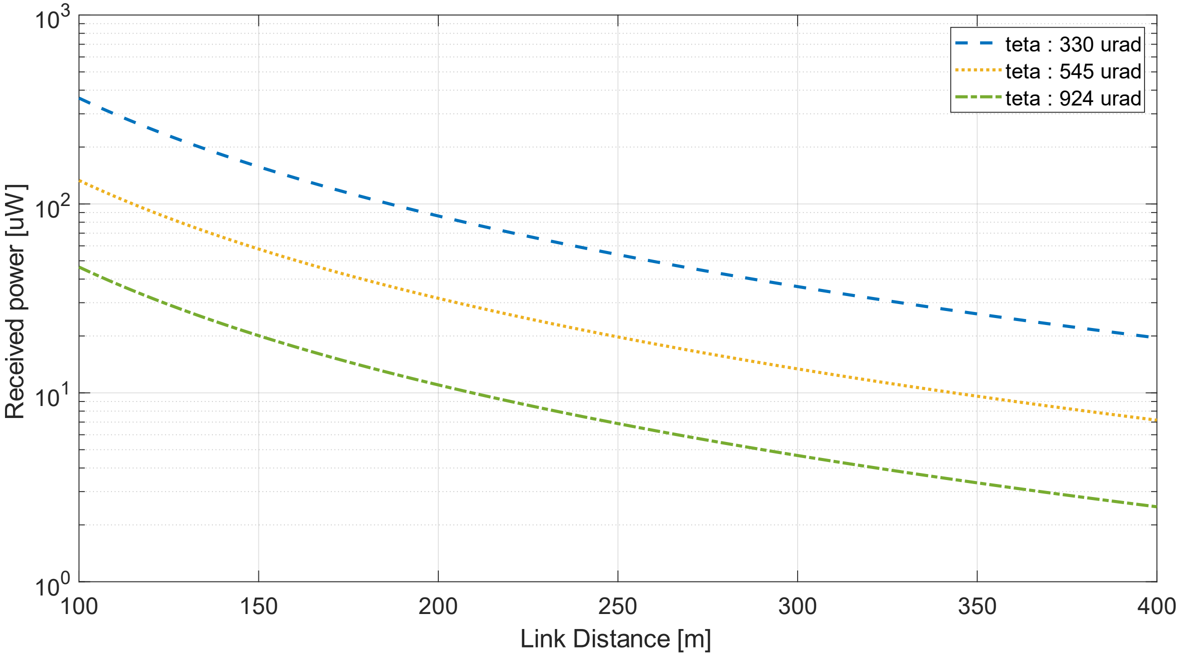
[Google Earth]



[Figure 4 optical link set-up]

Location	Description	Scenario properties
GSOC	Altitude	580m s.l.
	Location	47.09, 11.28
	Number of transmitter	1 or 2
	Transmitter aperture diameter	
	Wavelength	1550nm
	Divergence angle (FWHM)	330urad, 545urad, 924urad
	Transmitter power	1.6mW
KN	Altitude	580m s.l.
	Location	47.09, 11.28
	Number of receiver	1
	Receiver aperture diameter	
	Noise Equivalent Power	0.213nW

Introduction : Link Budget



* PD NEP : 0.213 nW

[Figure 5] Link Budget in log-scale in [uW]]

Divergence Angle	@350m
330urad	29.41 uW
545urad	10.78 uW
924urad	3.75 uW

[Table 1] Estimated received power (uW)]

Hardware - transmitters

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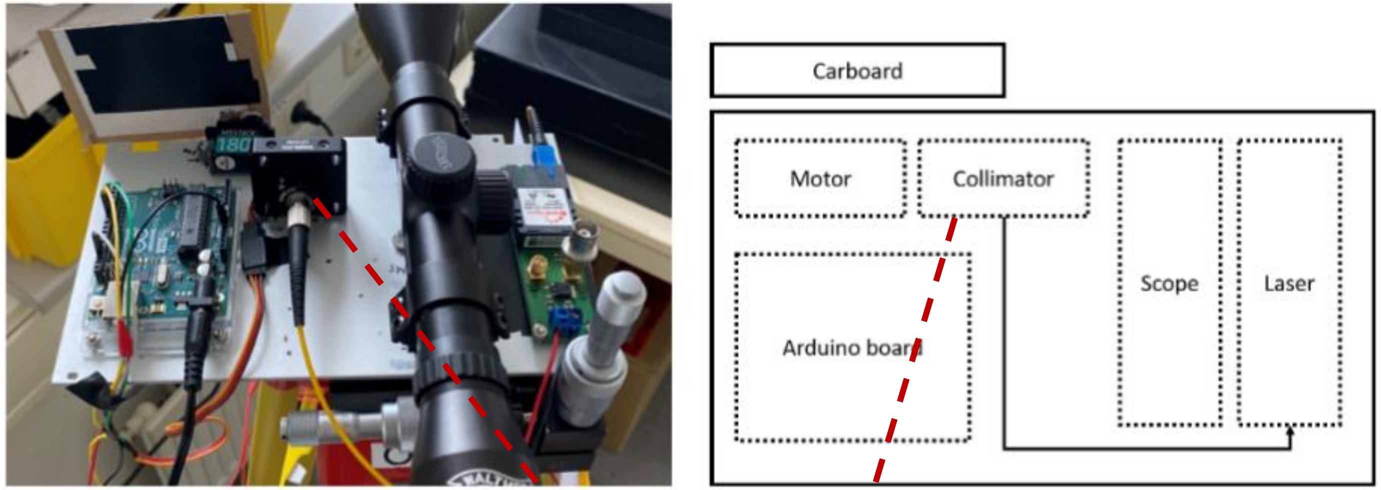
[Figure 6] Transmitter Distance



(a) picture (b) diagram

[Figure 7] Transmitter Assembly

Full range angle $2\omega_0$	$559\mu rad$	$925\mu rad$	$1570\mu rad$
FWHM divergence angle ω_{FWHM}	$330\mu rad$	$545\mu rad$	$924\mu rad$
Diameter at $\frac{1}{e^2}$	3.6mm	2.1mm	1.21mm

[Table 2] Collimators characteristics

Hardware – Receiver (Approx. 730g)

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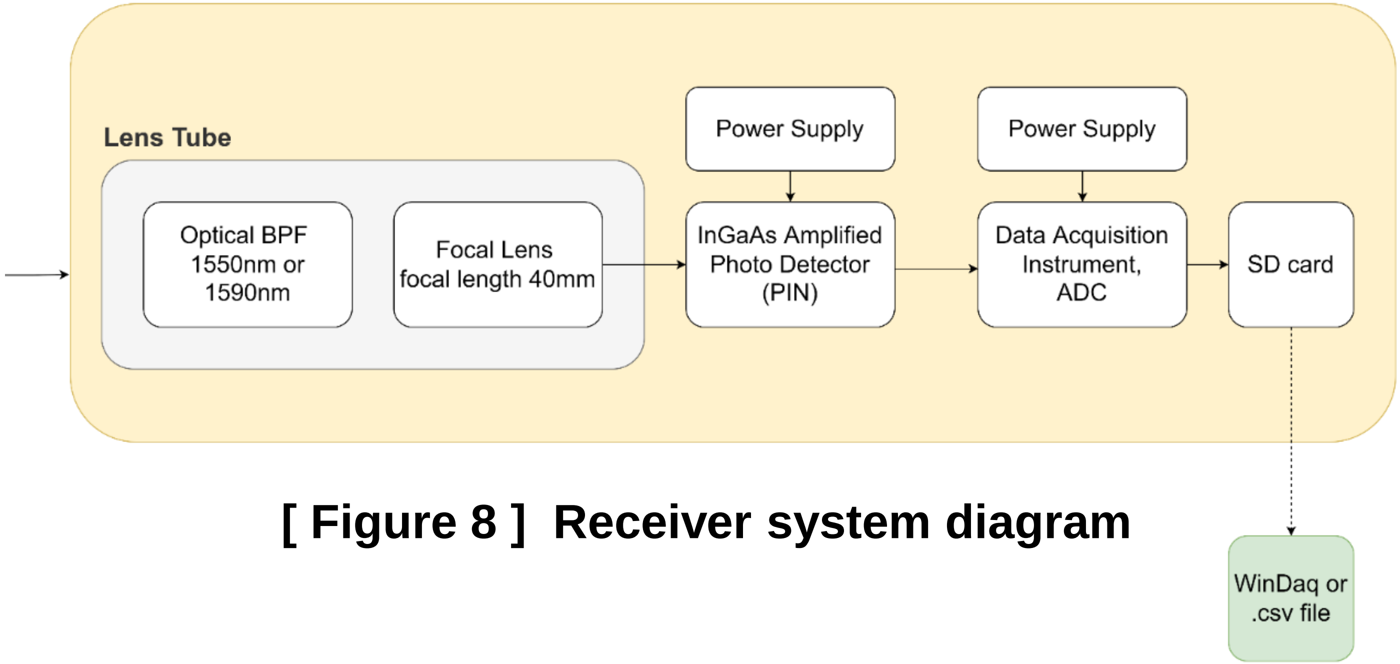
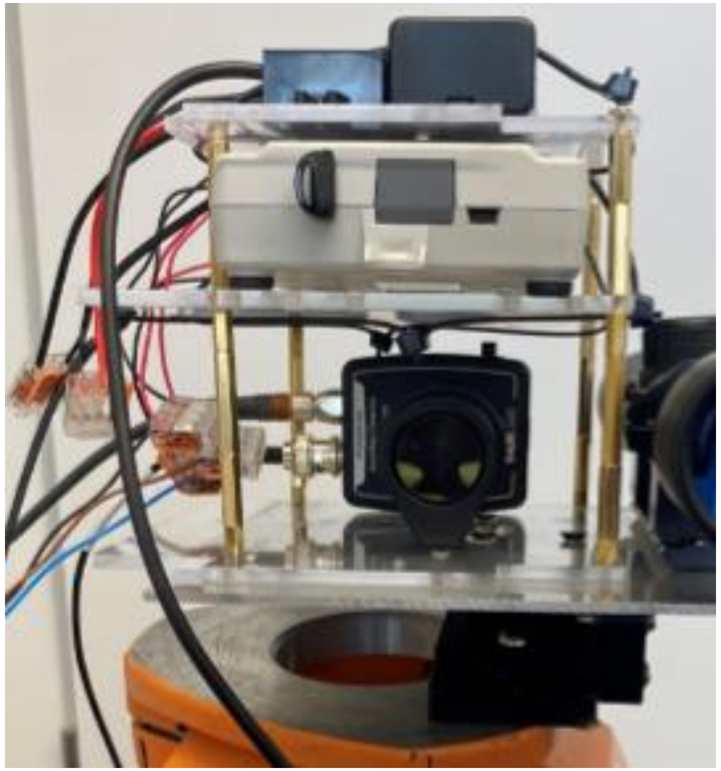
Field of View = $\frac{active\ region\ diameter}{focal\ length} = \frac{2mm}{40mm} = 50\ mrad = 3\ degree$

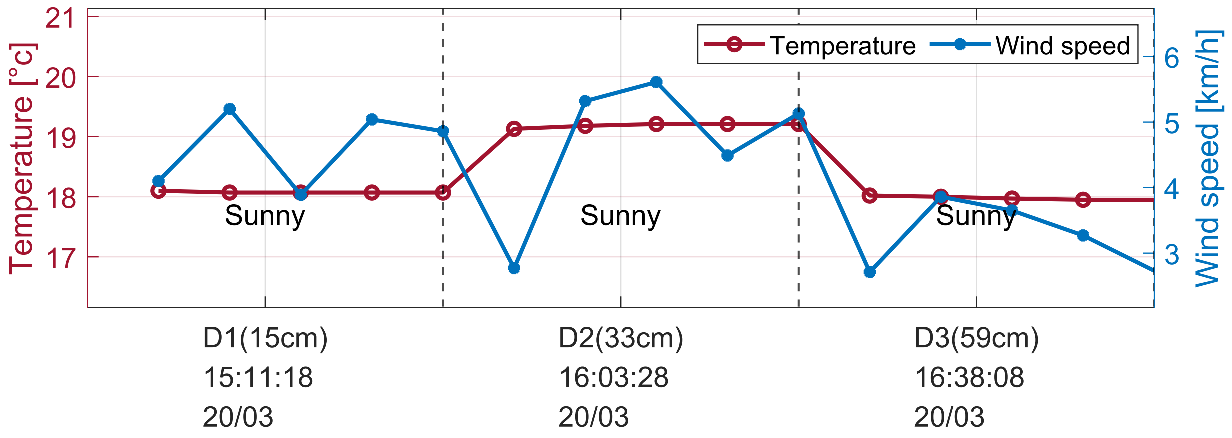


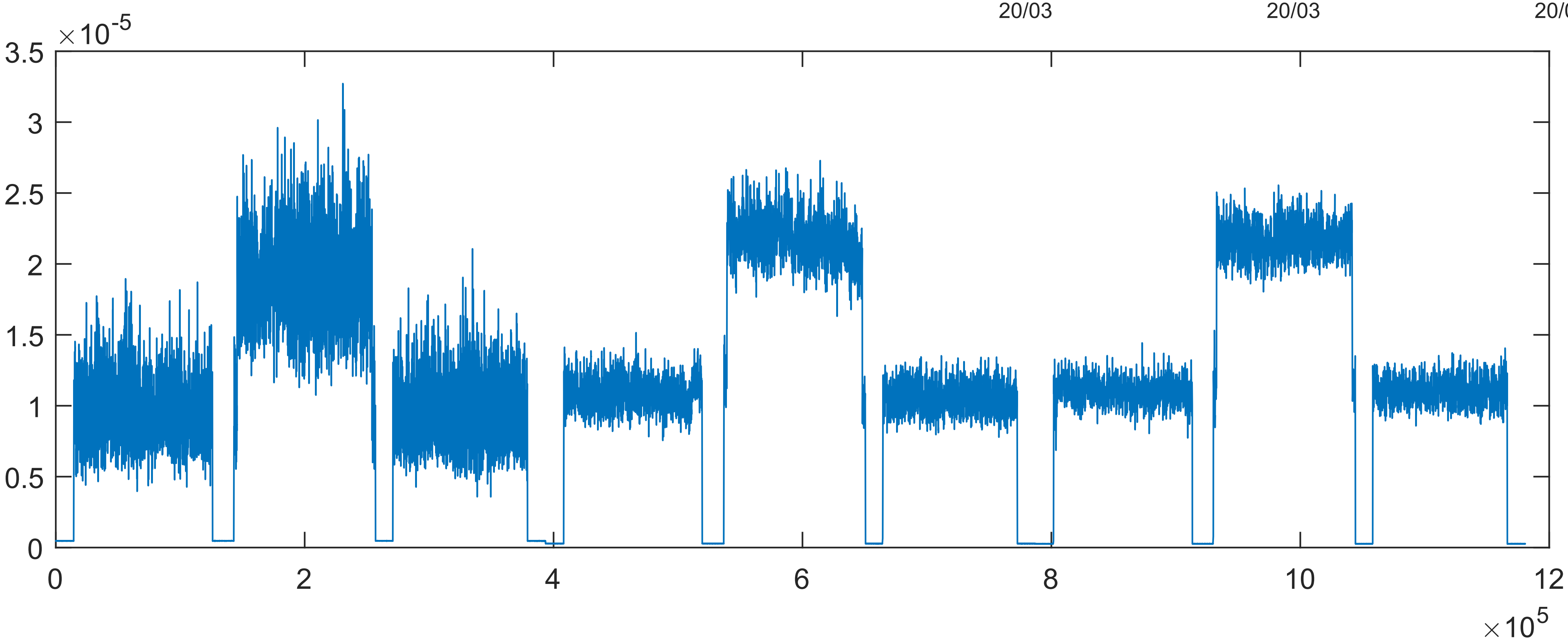
[Figure 8] Receiver system diagram



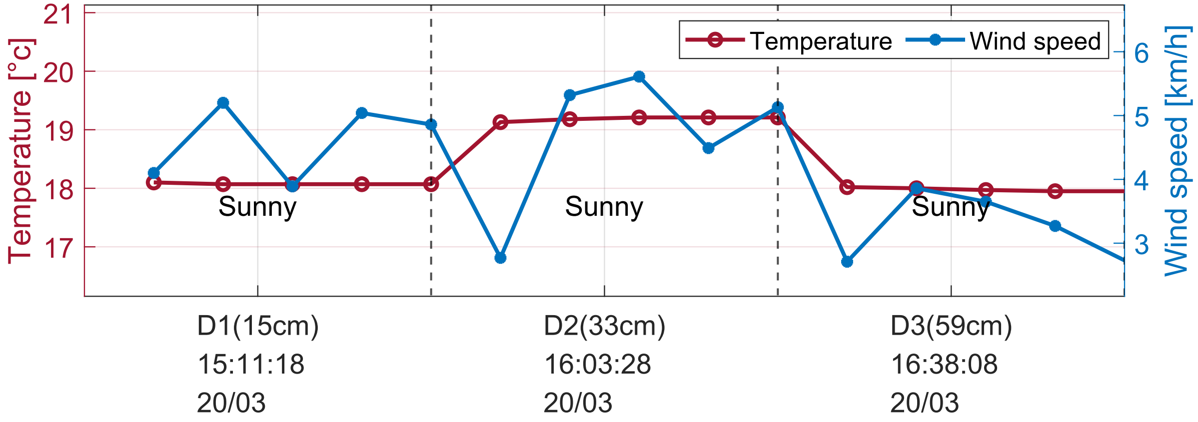
[Figure 9] Receiver system picture

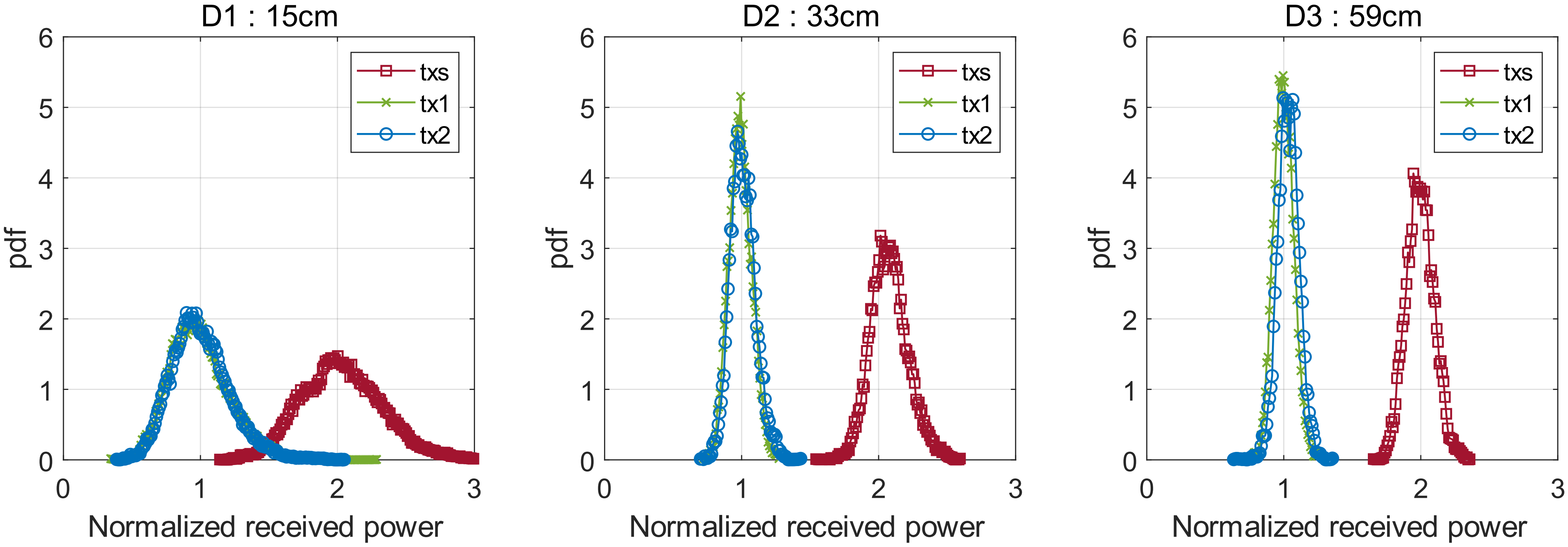
Transmitter Distance



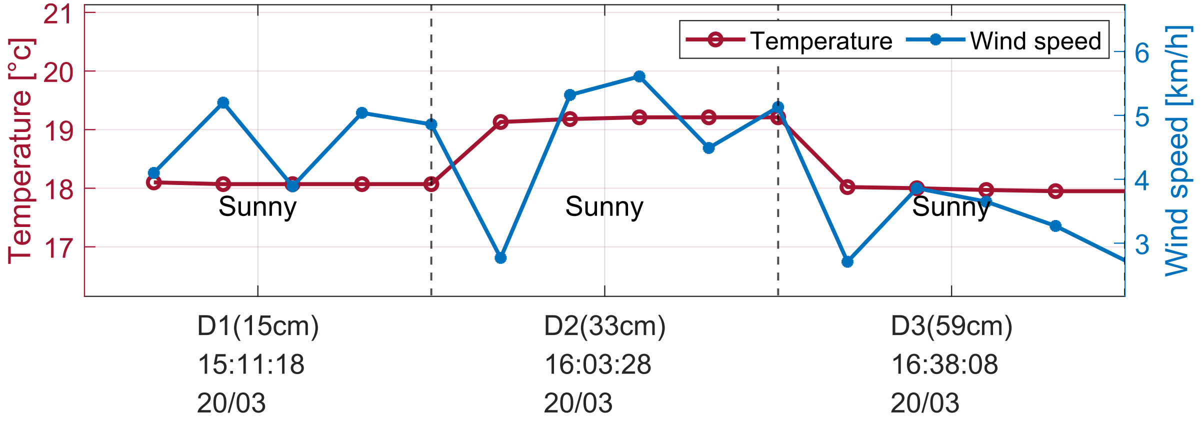


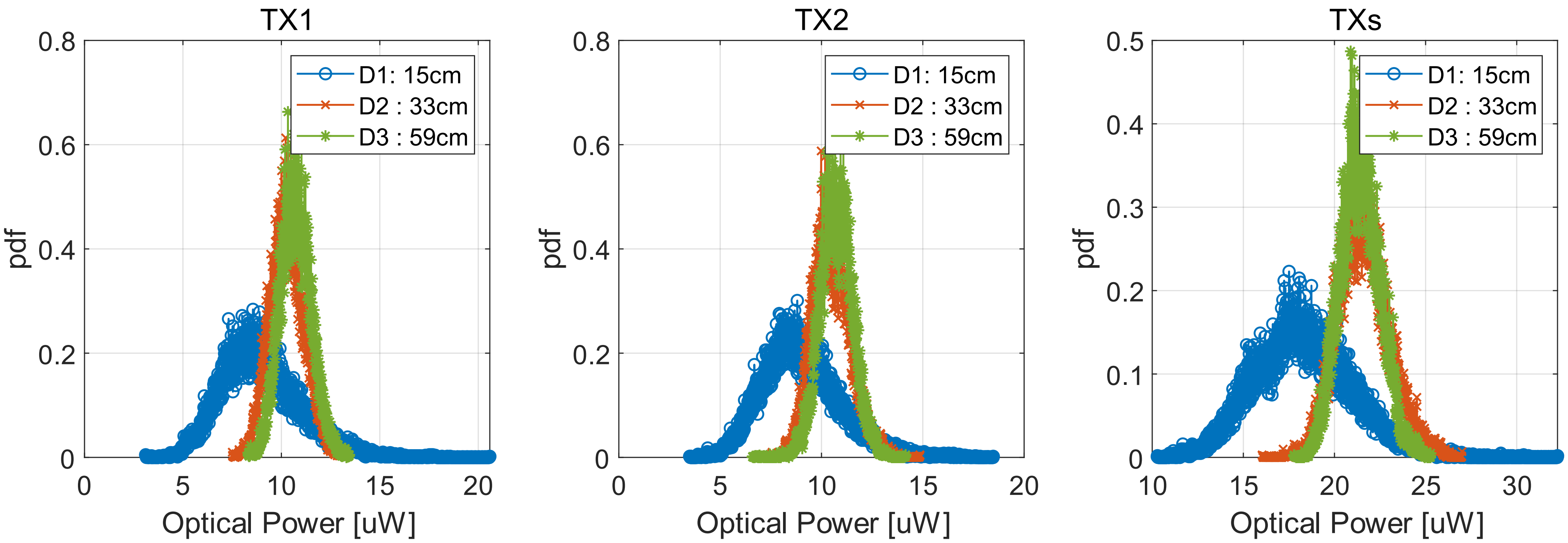
Transmitter Distance



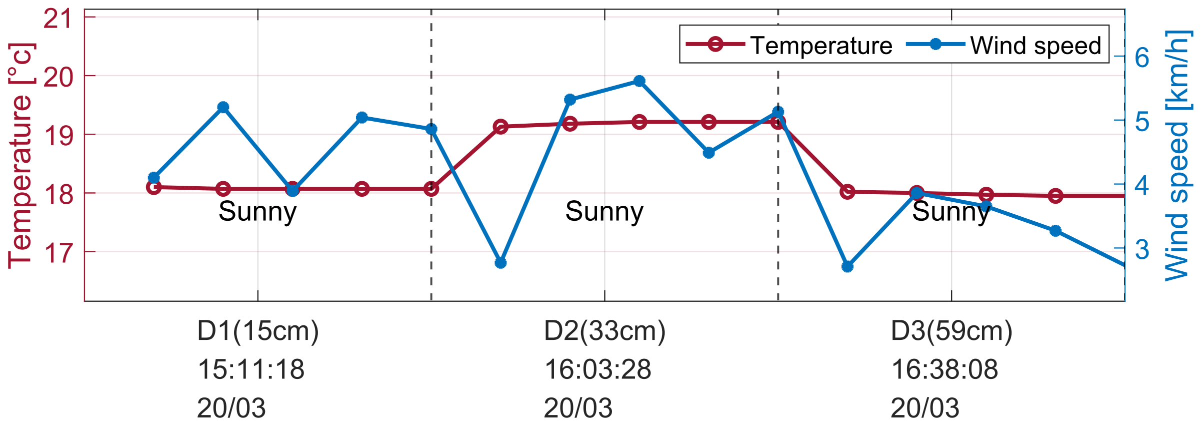


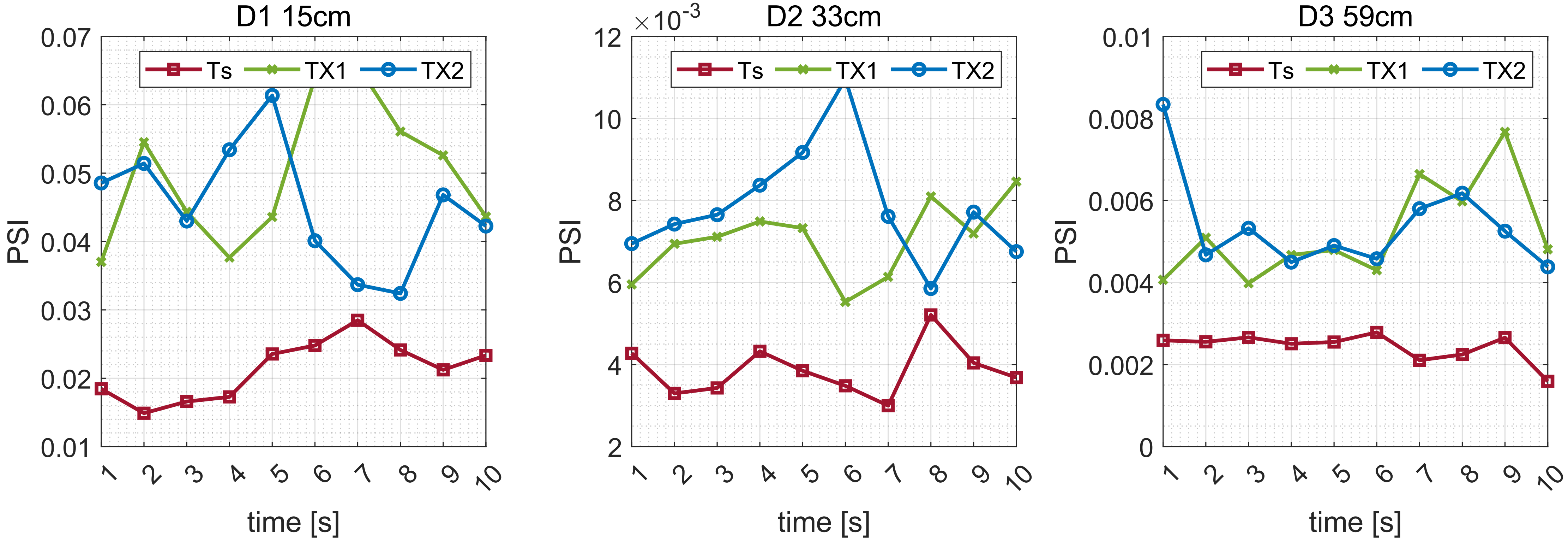
Transmitter Distance



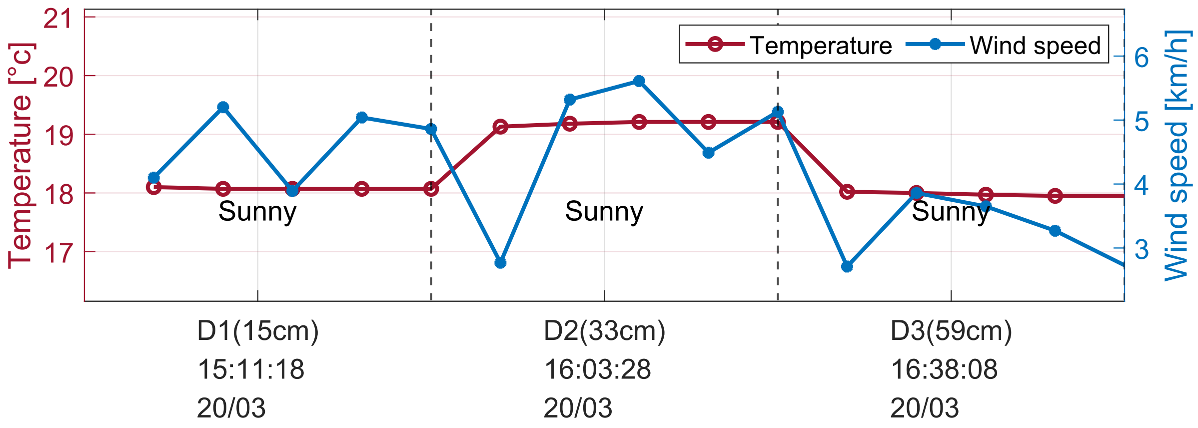


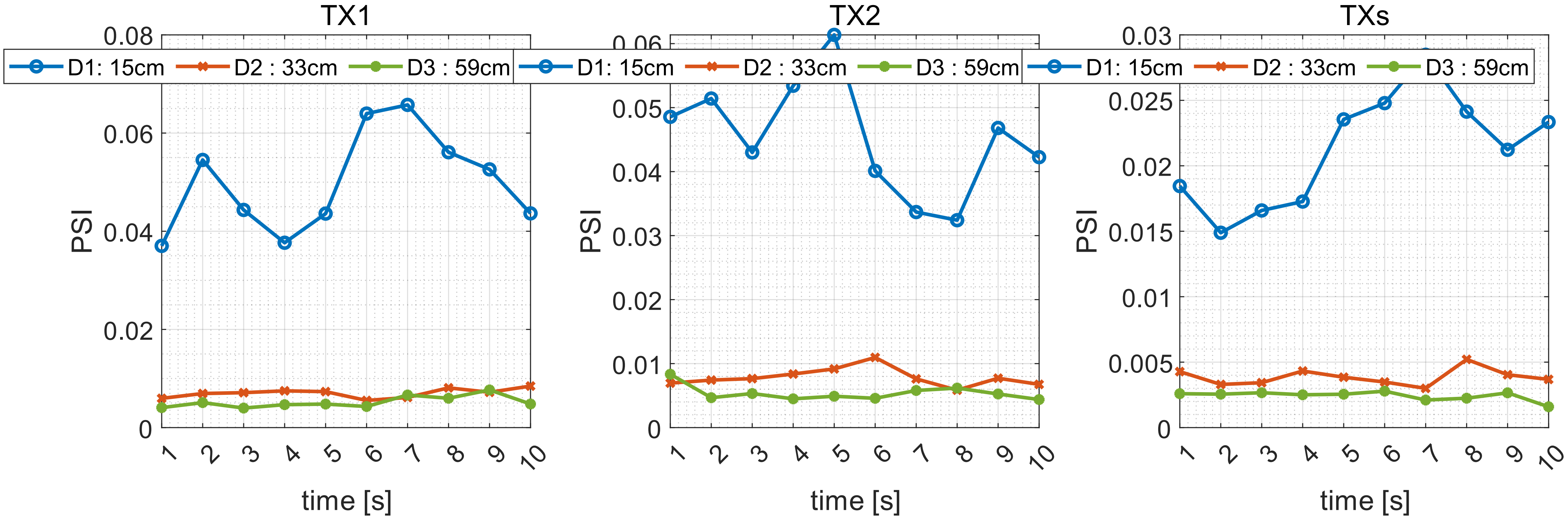
Transmitter Distance





Transmitter Distance





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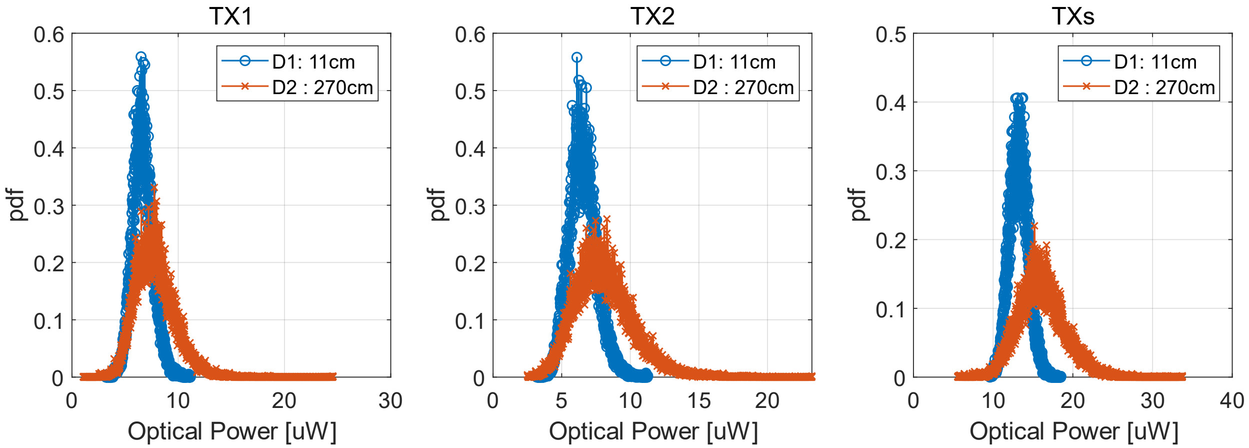
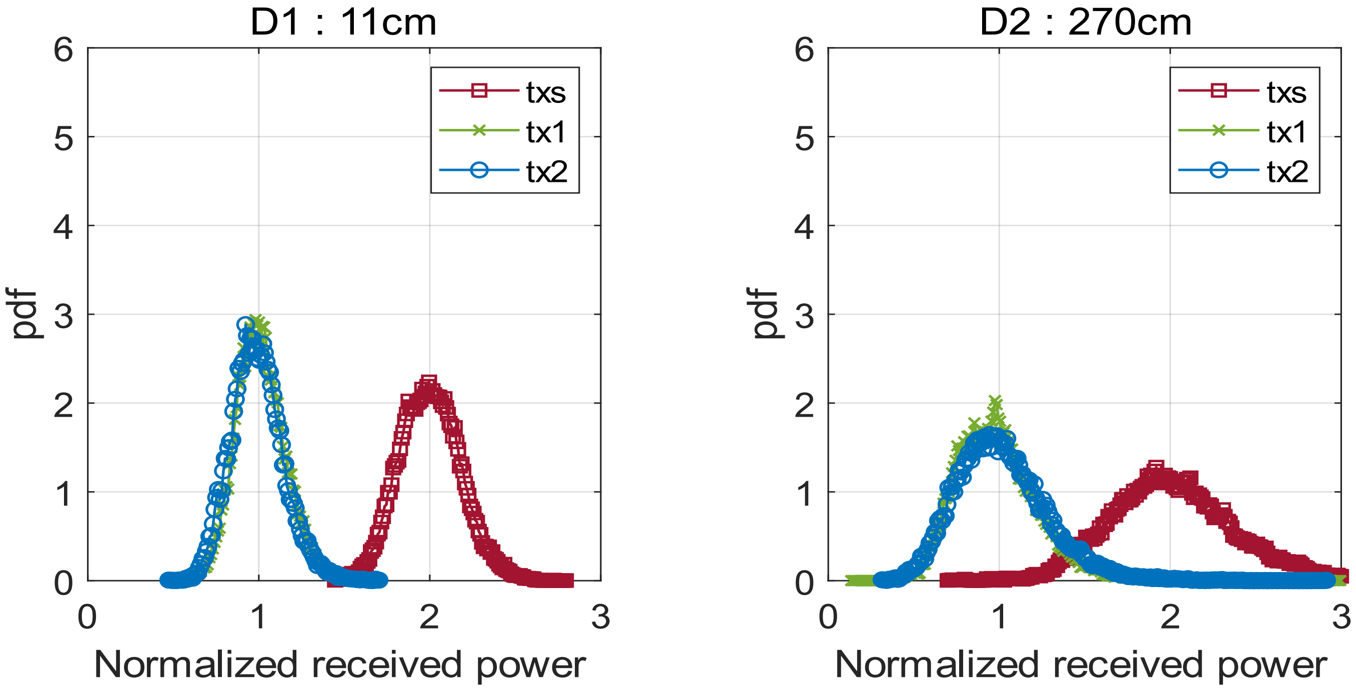
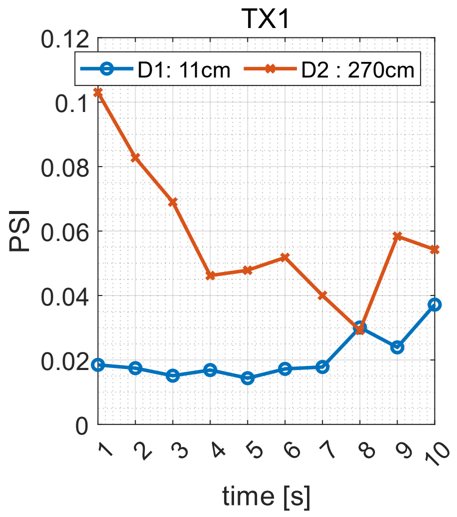
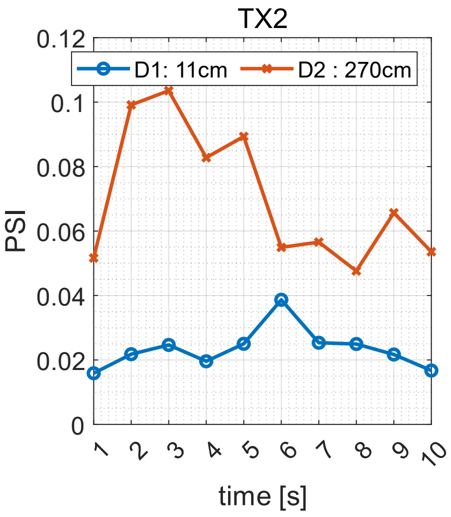
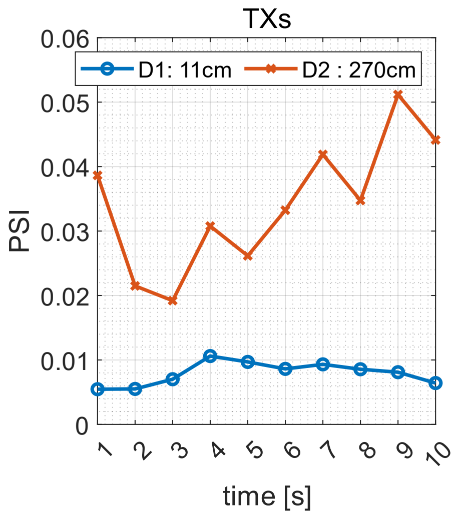


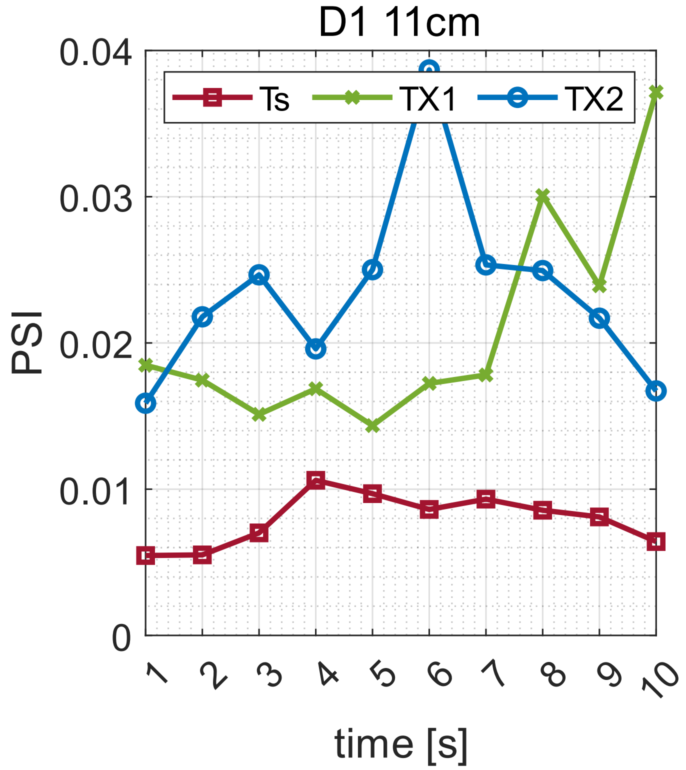


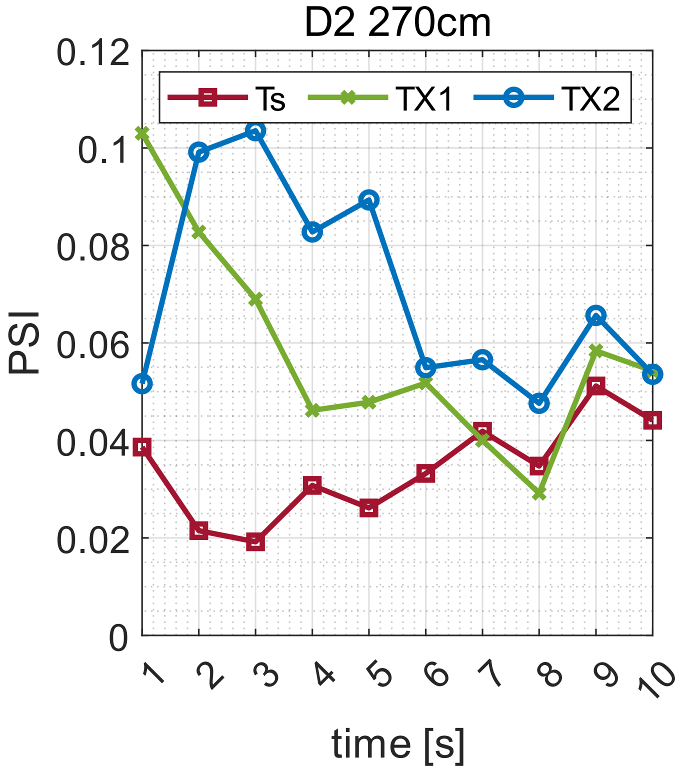
Transmitter Distance





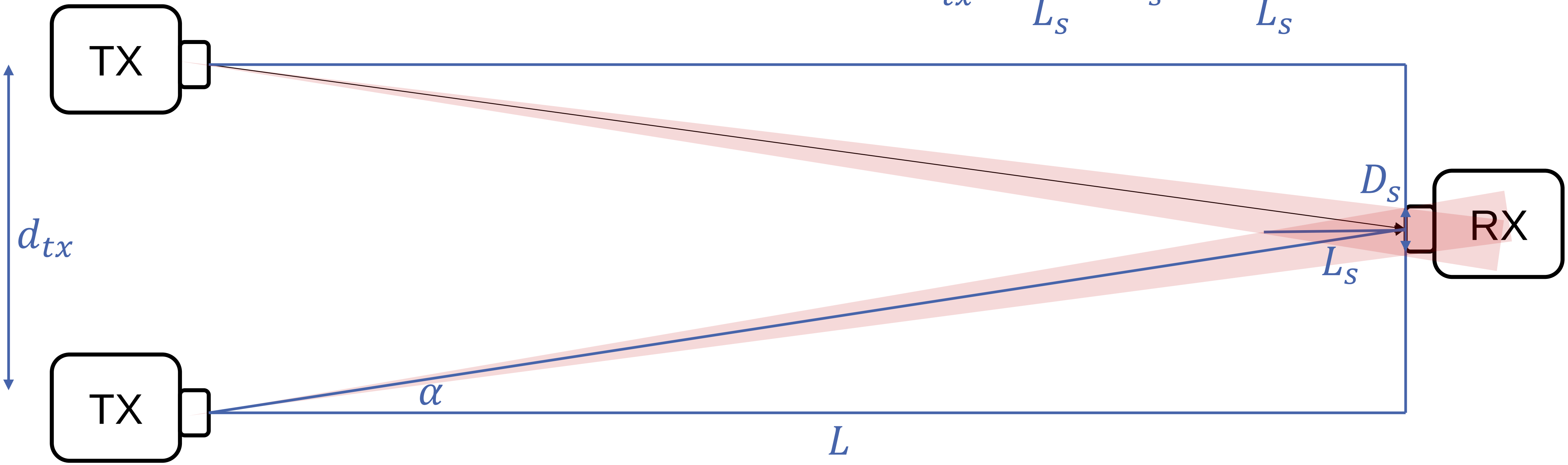






Transmitter Distance

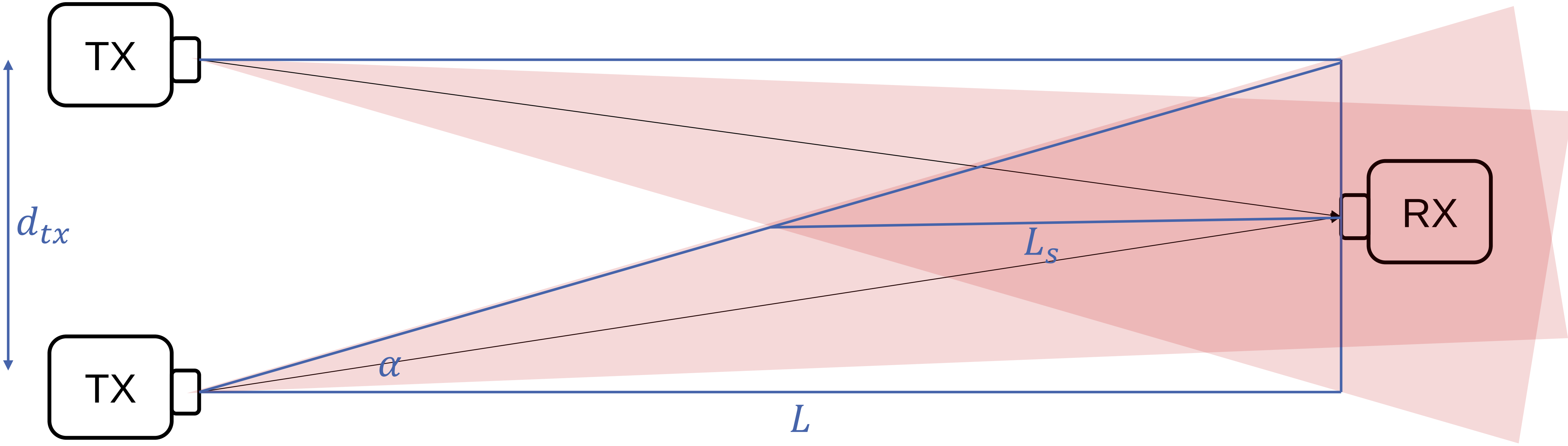
$$d_{tx} = \frac{L}{L_s} \times D_s = \frac{350m}{L_s} \times 25.4mm$$



$$d_{tx} = 2L\tan\alpha$$

$$L_s = \frac{D_s}{2\tan\alpha}$$

Transmitter Distance



Measurement Data cycles

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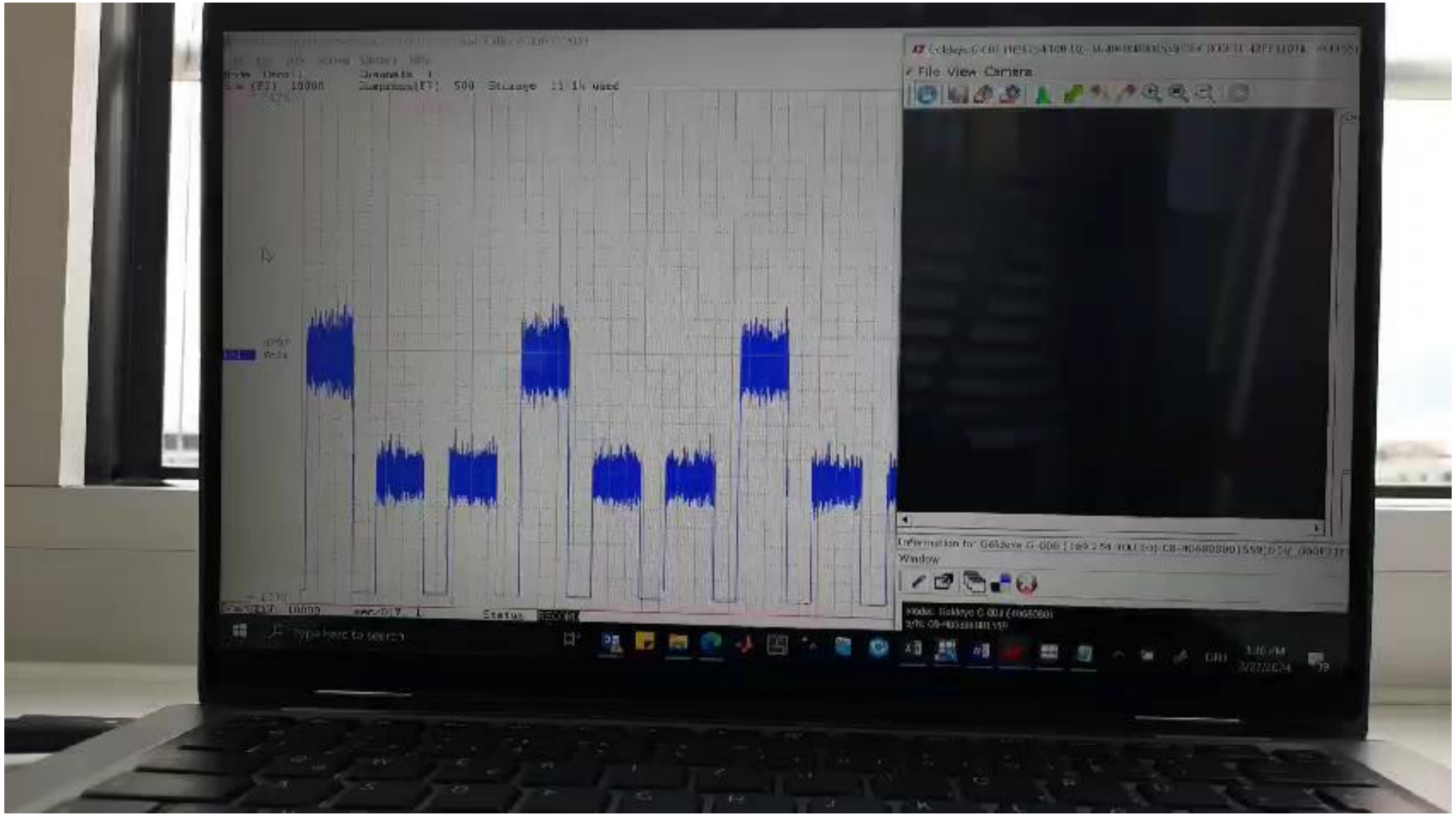
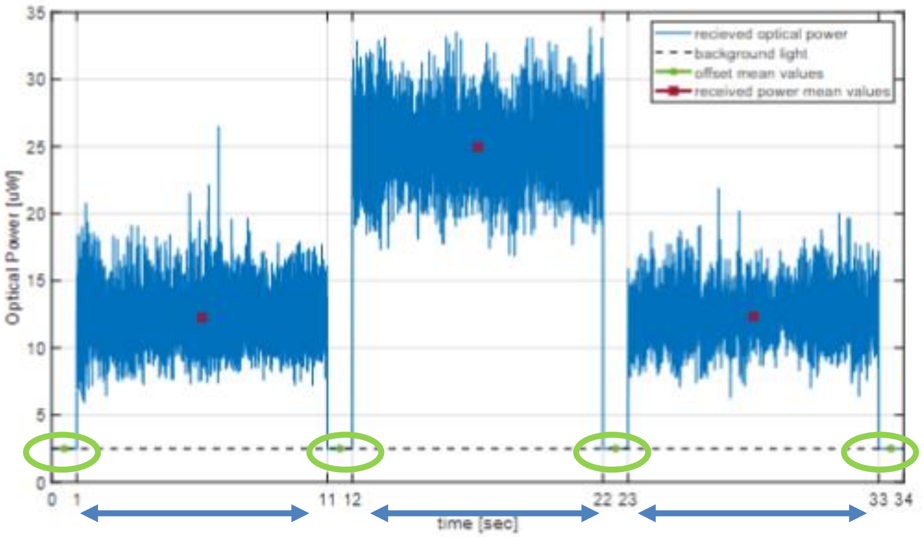
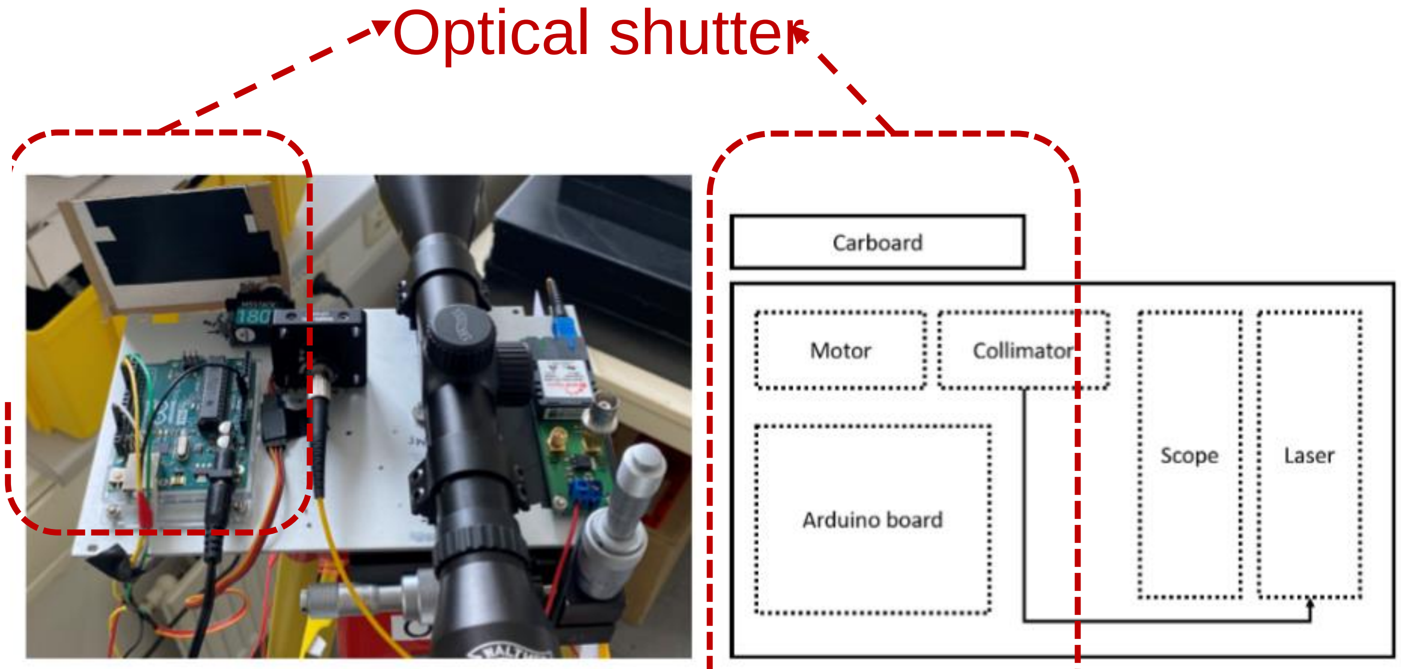


Measurement Data 1cycles



segment	name	mean value (uW)
0-1s	offset1	2.541
1-11s	TX2	12.255
11-12s	offset2	2.539
12-22s	TXs	24.945
22-23s	offset3	2.459
23-33s	TX1	12.348
33-34s	offset4	2.484

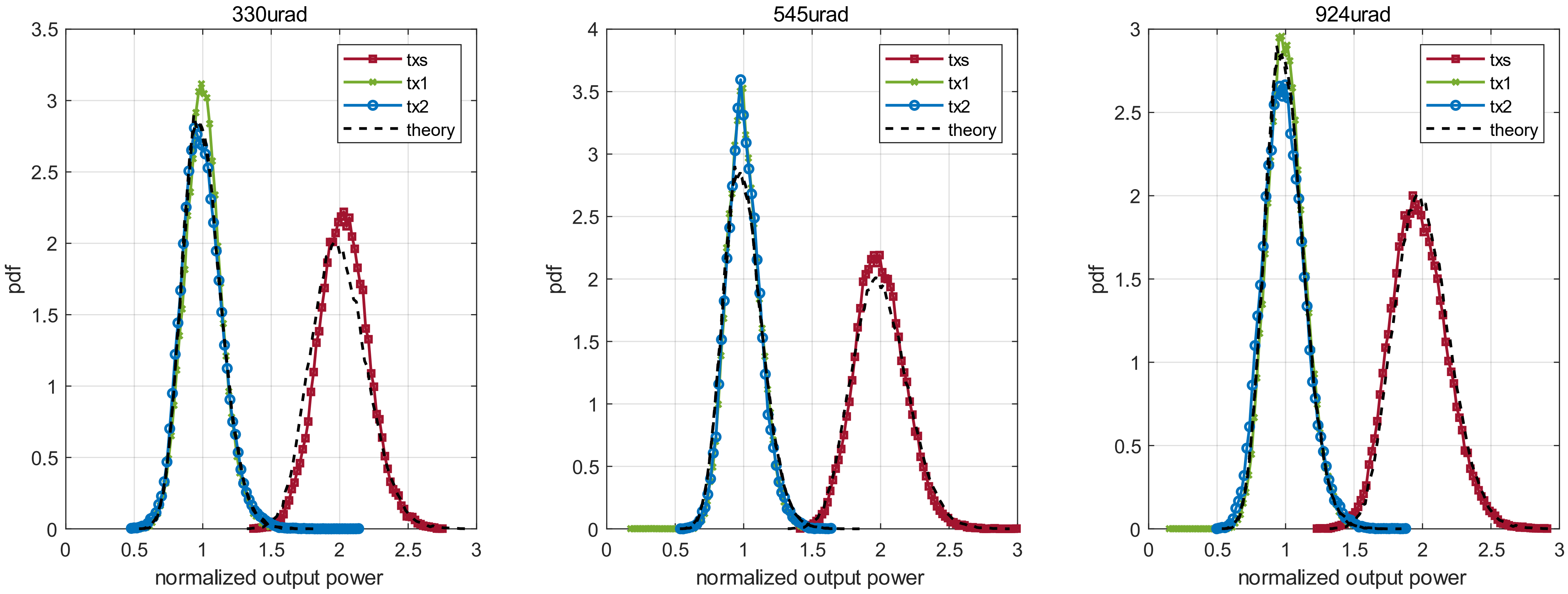
[Figure 10] Cycle structure



(a) picture (b) diagram

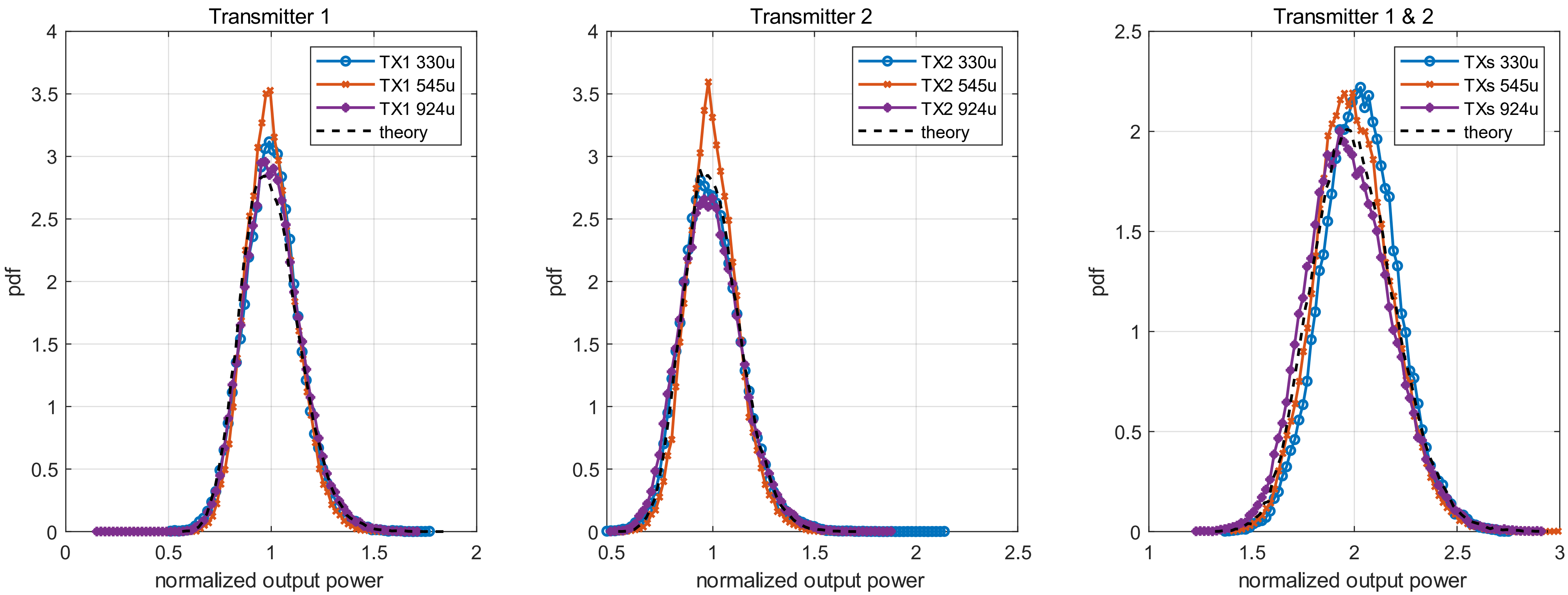
[Figure 11]Tranmitter assembly

Normalized PDF for 1 cycle – 330urad / 545urad / 924urad



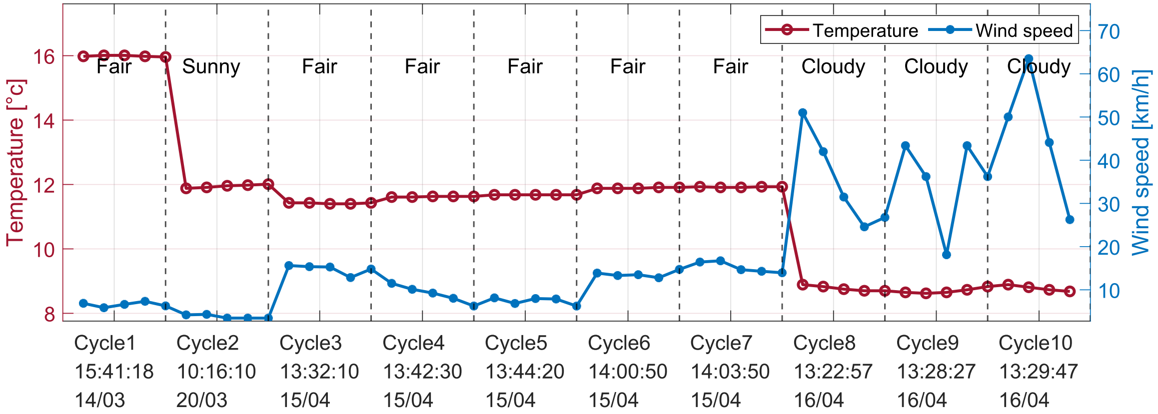
[Figure 12]PDF

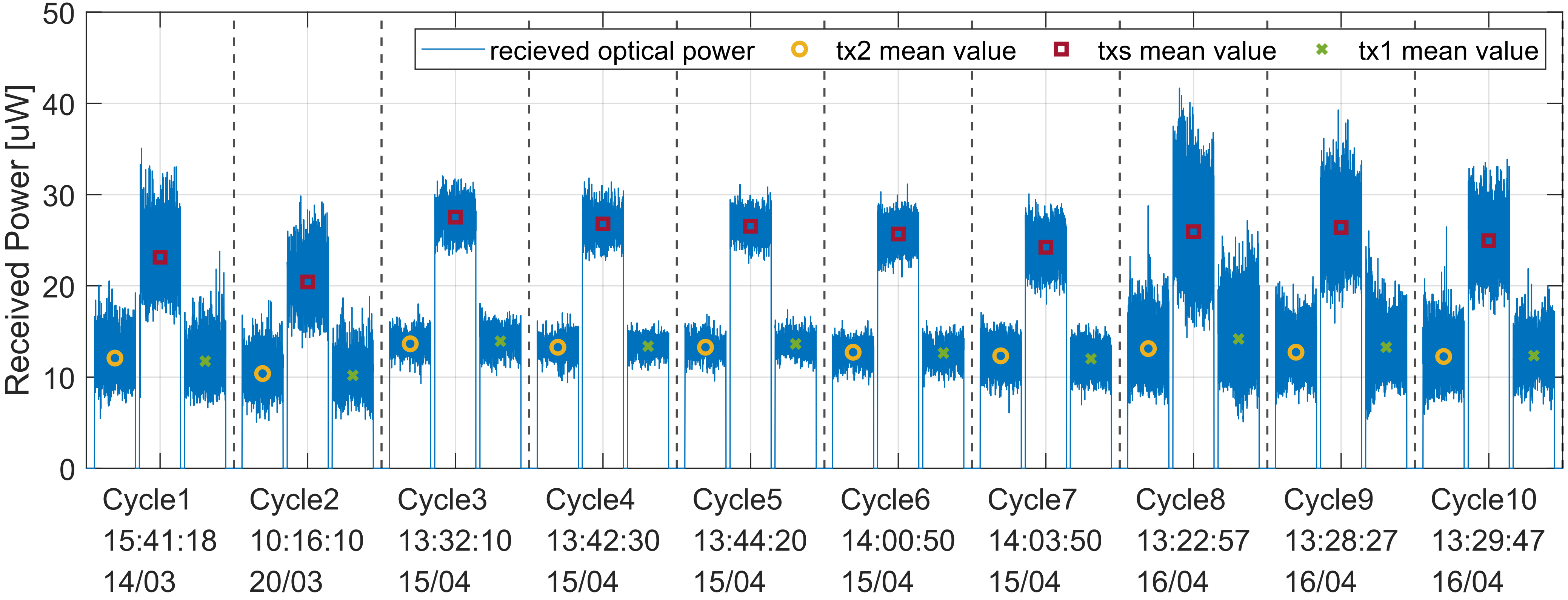
PDF for 1cycle – 330urad / 545urad / 924urad



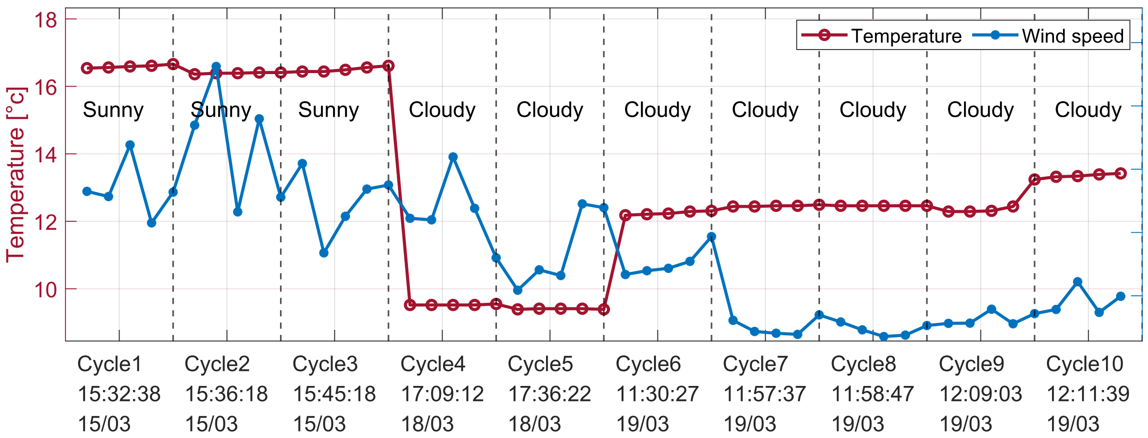
[Figure 13]PDF-TX

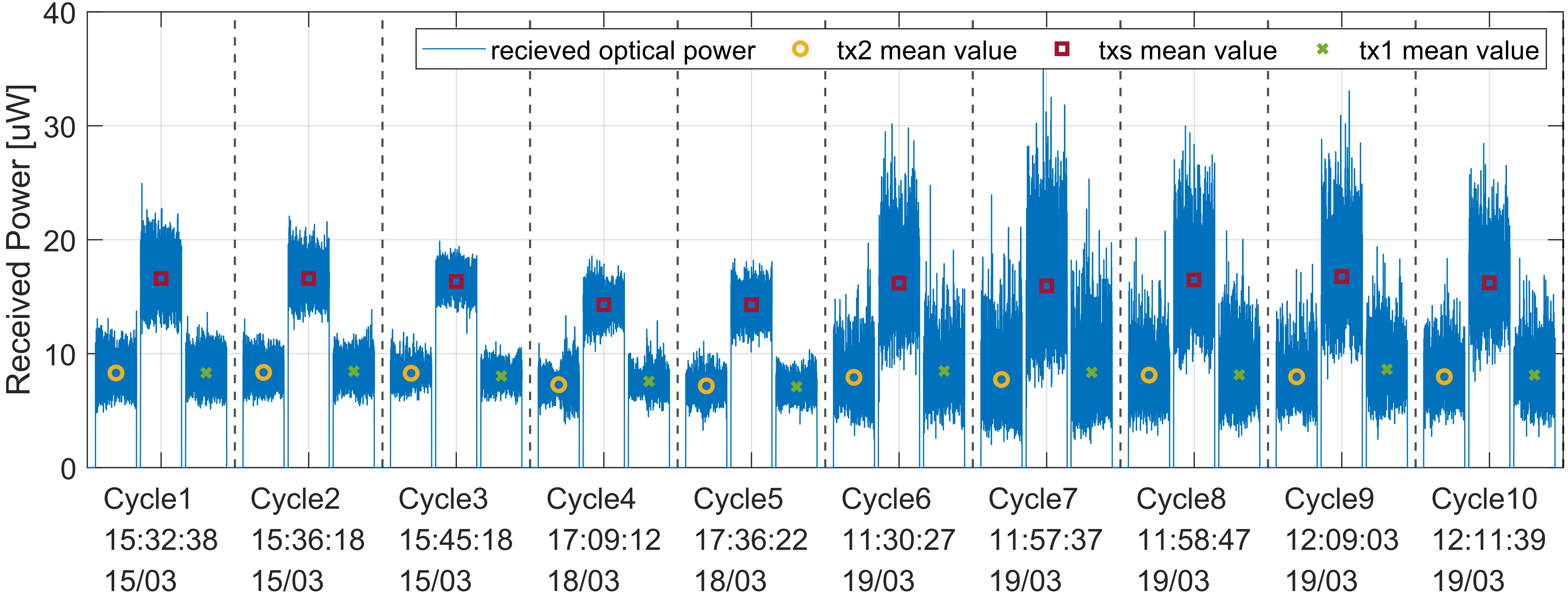
Overall measurement – 330urad



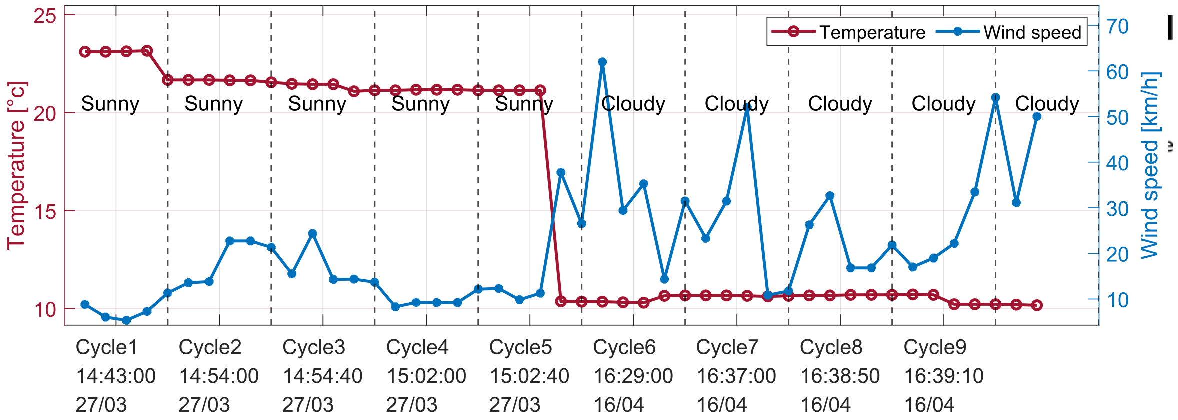


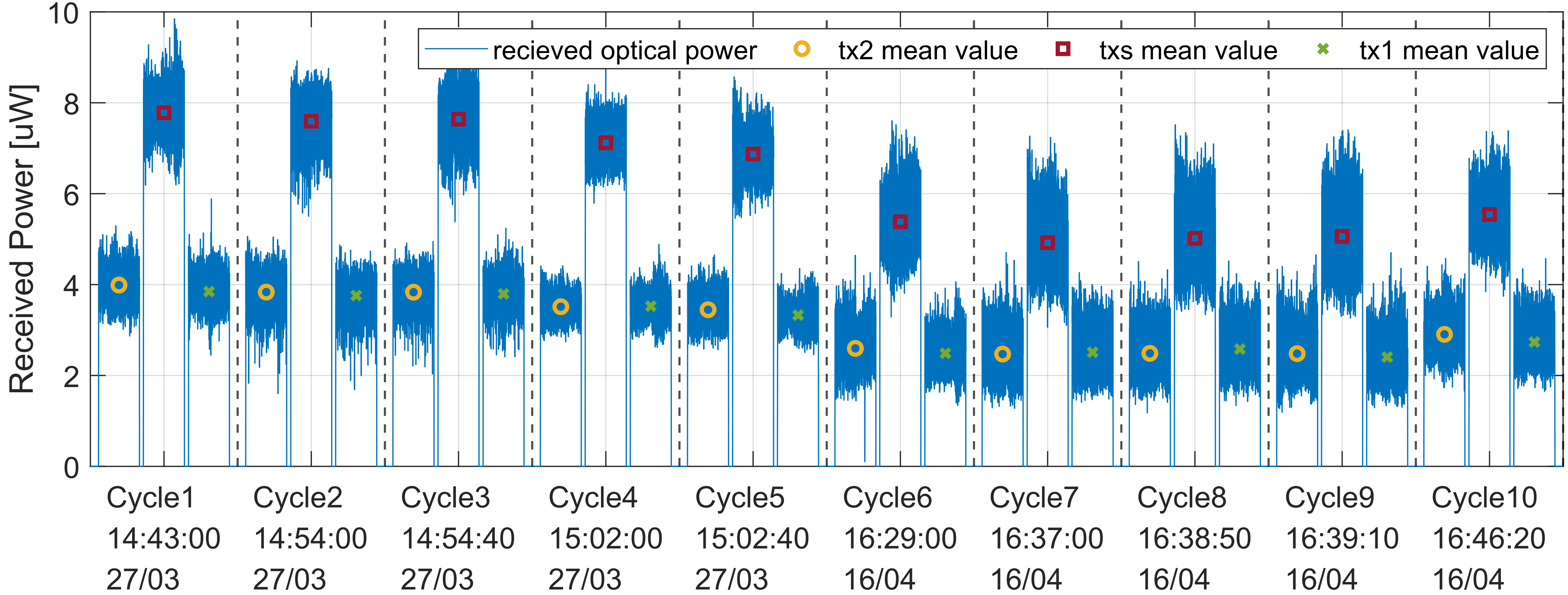
Overall measurement – 545urad



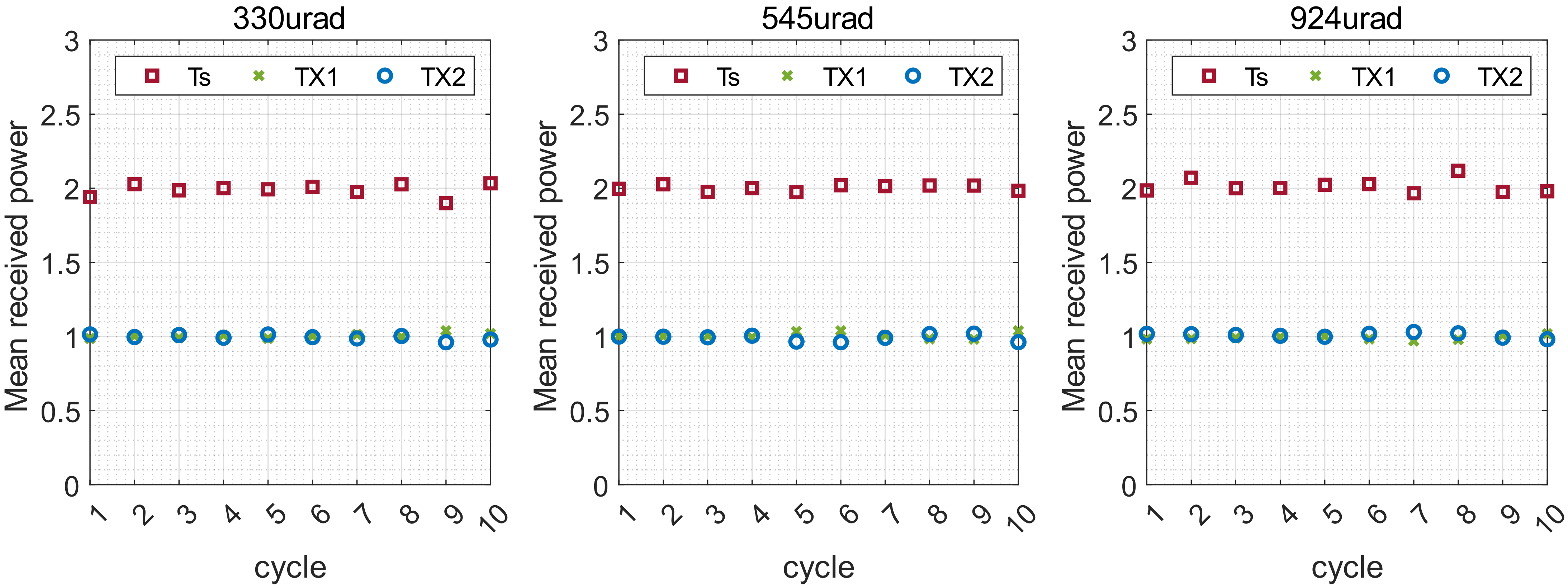


Overall measurement – 924u

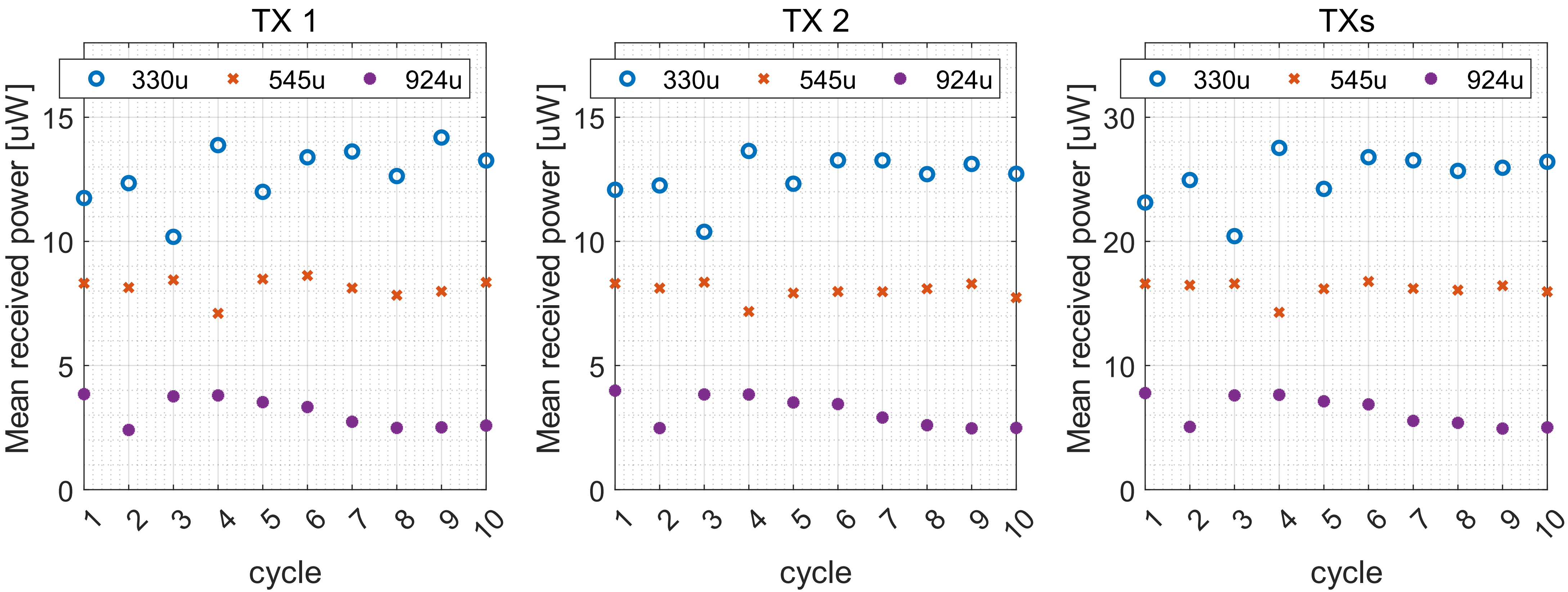




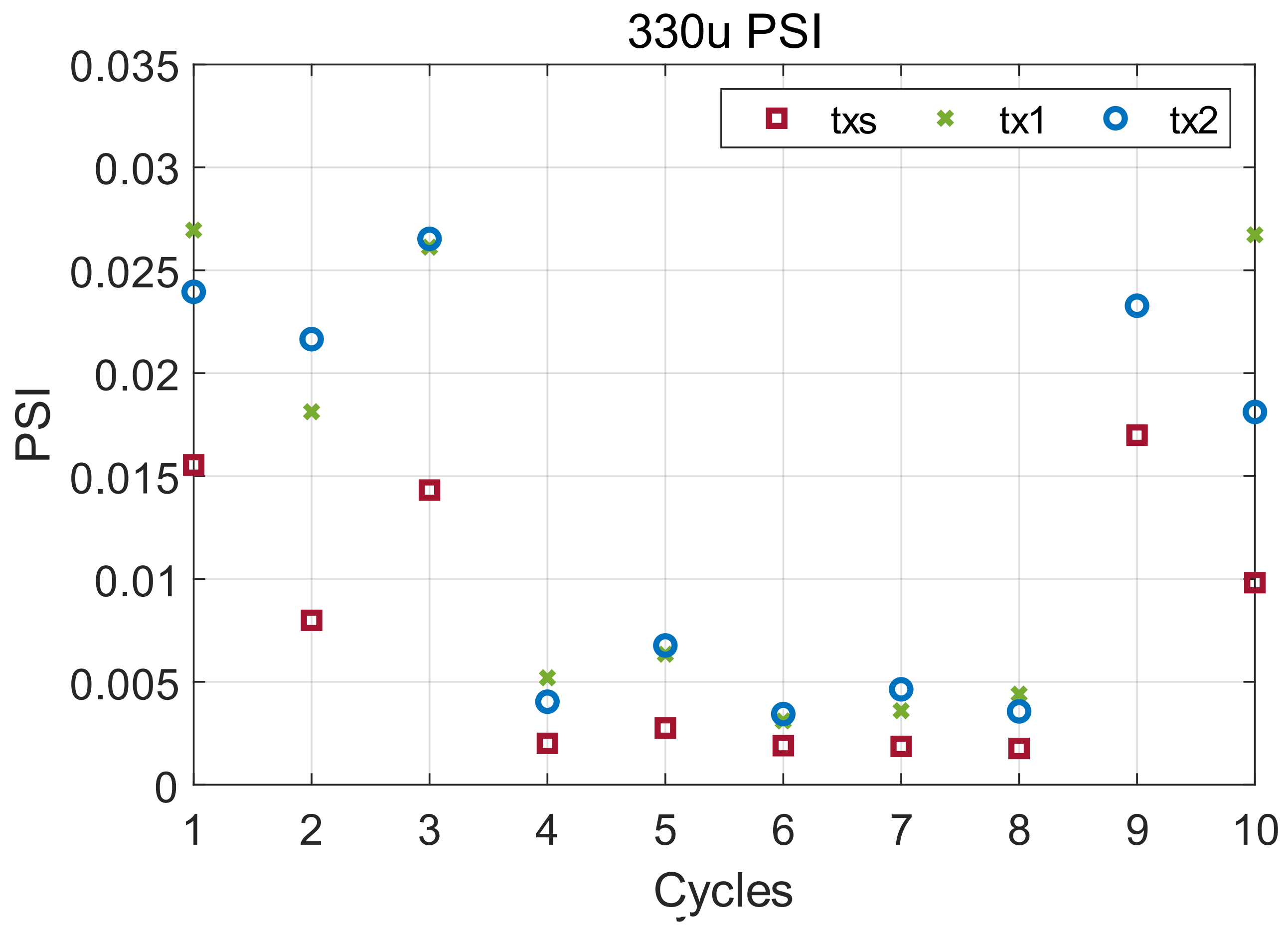
Overall measurement – Normalized mean received power



Overall measurement – mean received power comparison

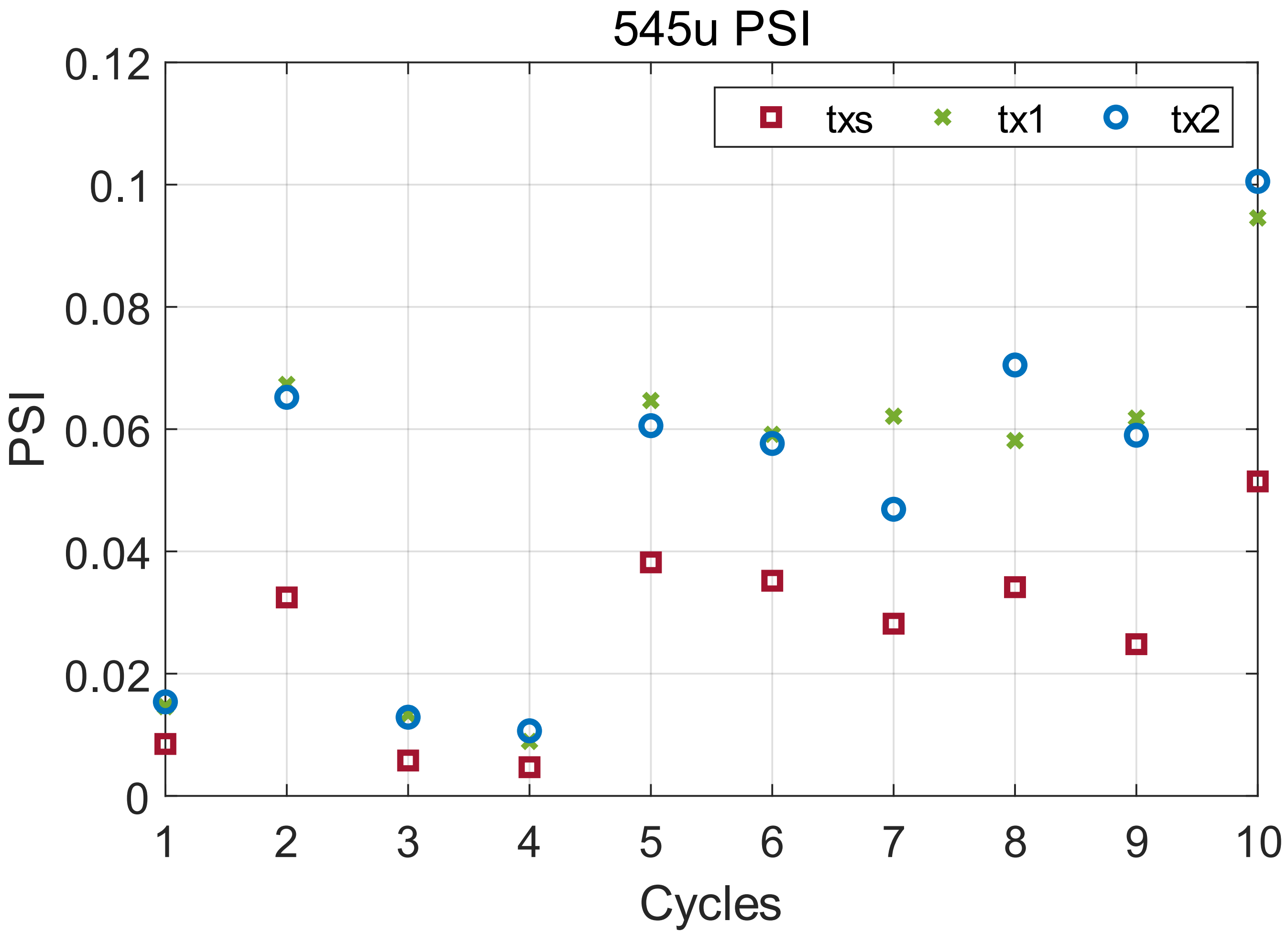


PSI analysis – 330urad



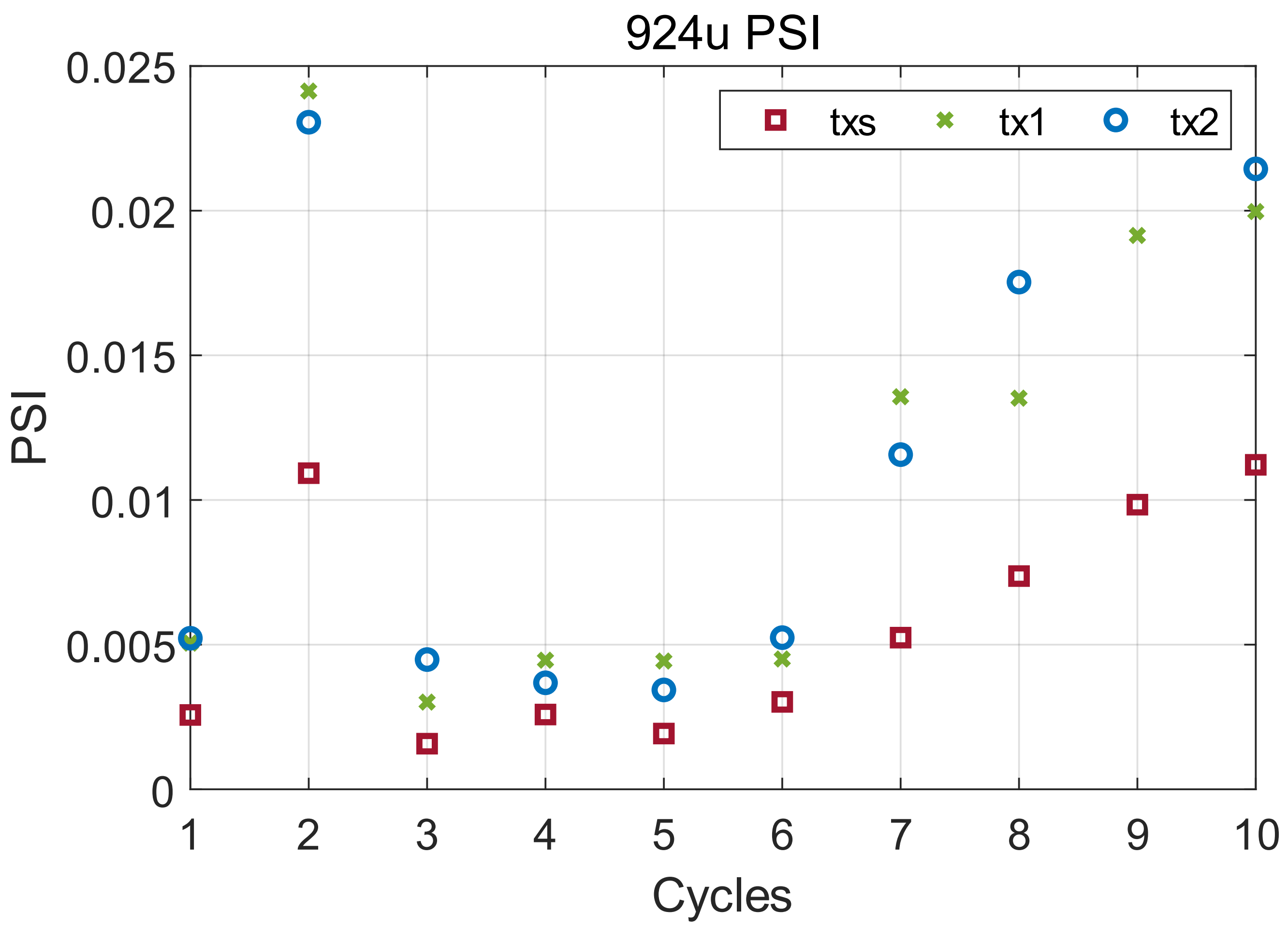
Cycle	TX1	TX2	TXs
1	0.0270	0.0240	0.0155
2	0.0181	0.0217	0.0080
3	0.0261	0.0265	0.0143
4	0.0052	0.0040	0.0020
5	0.0063	0.0068	0.0028
6	0.0031	0.0034	0.0019
7	0.0036	0.0046	0.0019
8	0.0044	0.0036	0.0018
9	0.0323	0.0233	0.0170
10	0.0267	0.0181	0.0098

PSI analysis – 545urad



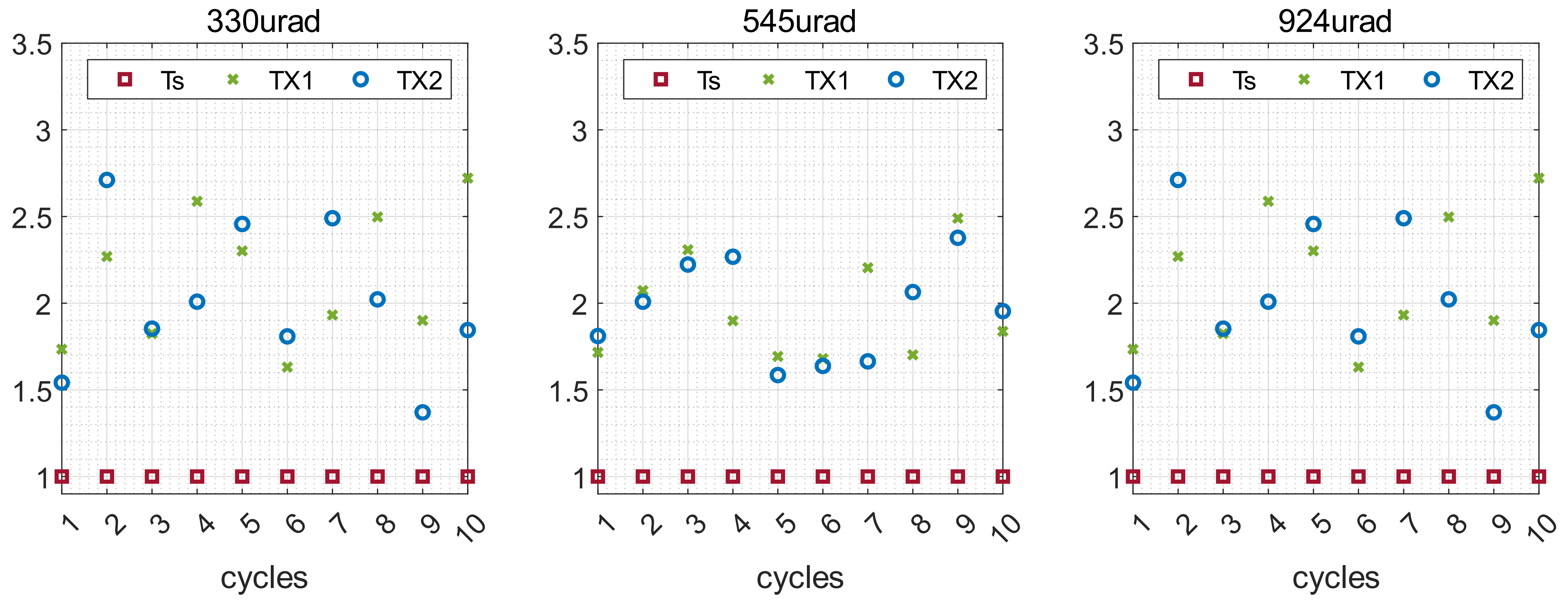
Cycle	TX1	TX2	TXs
1	0.0146	0.0154	0.0085
2	0.0673	0.0652	0.0325
3	0.0134	0.0129	0.0058
4	0.0089	0.0106	0.0047
5	0.0647	0.0606	0.0382
6	0.0591	0.0577	0.0352
7	0.0621	0.0469	0.0282
8	0.0581	0.0705	0.0342
9	0.0618	0.0590	0.0248
10	0.0946	0.1005	0.0514

PSI analysis – 924urad

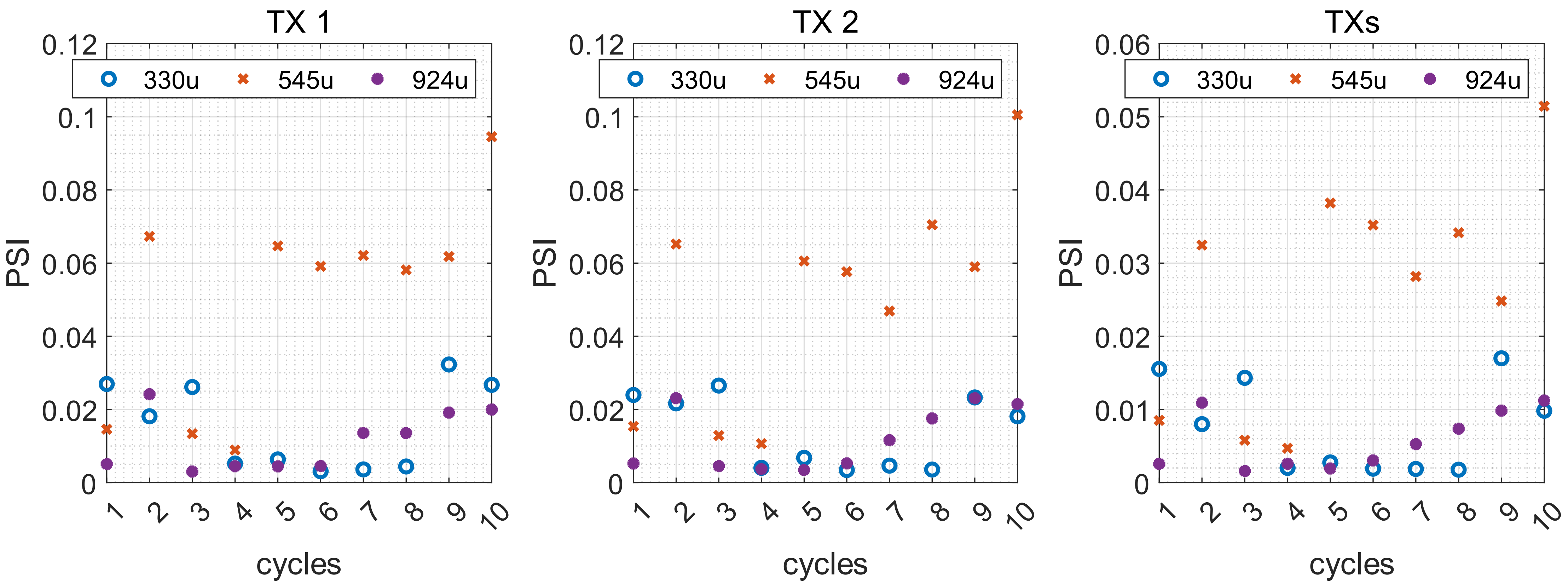


Cycle	TX1	TX2	TXs
1	0.0051	0.0052	0.0026
2	0.0241	0.0231	0.0109
3	0.0030	0.0045	0.0016
4	0.0045	0.0037	0.0026
5	0.0044	0.0034	0.0019
6	0.0045	0.0052	0.0030
7	0.0136	0.0116	0.0052
8	0.0135	0.0175	0.0074
9	0.0191	0.0231	0.0098
10	0.0200	0.0214	0.0112

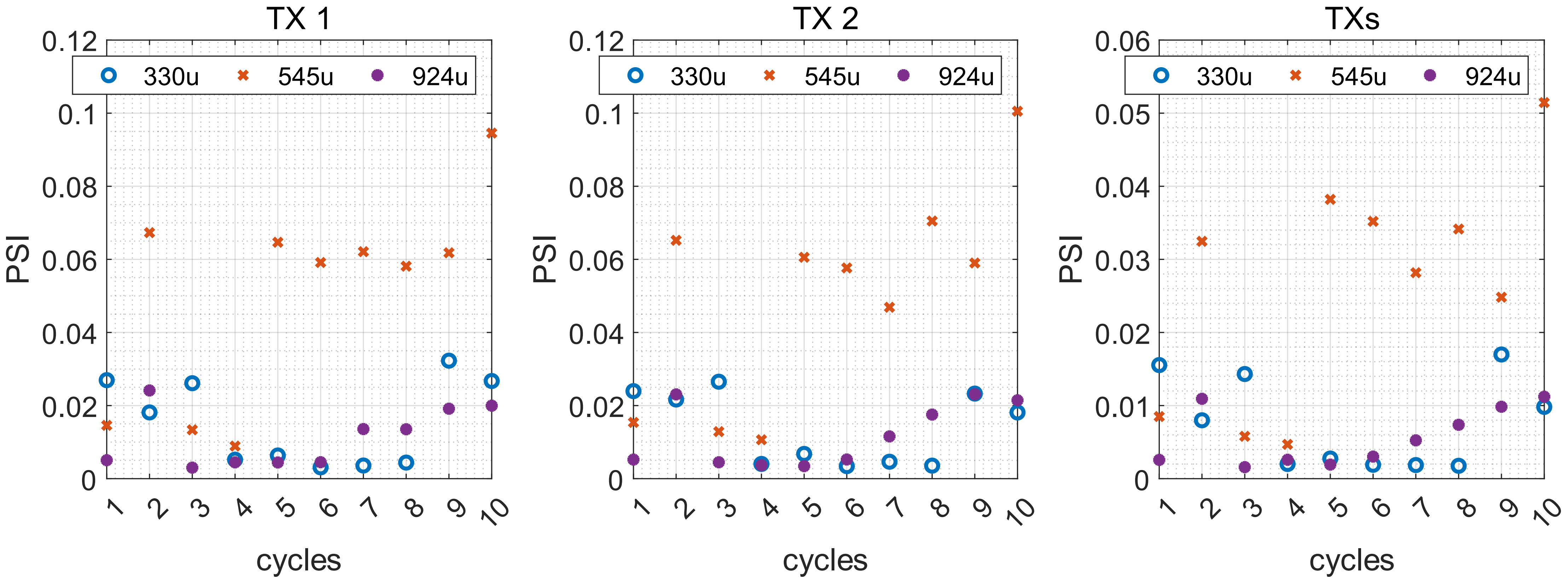
PSI analysis



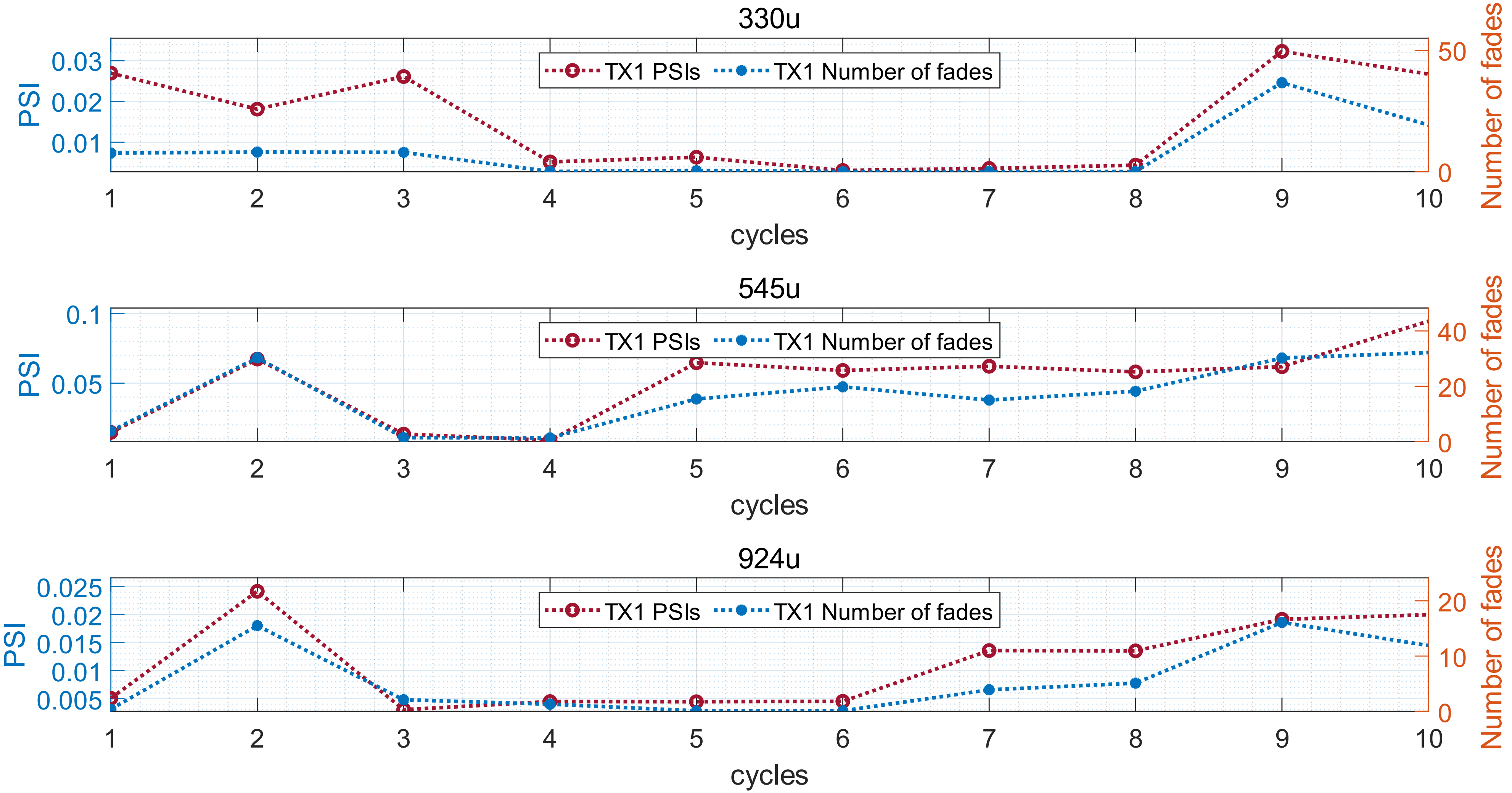
PSI analysis- PSI values comparison



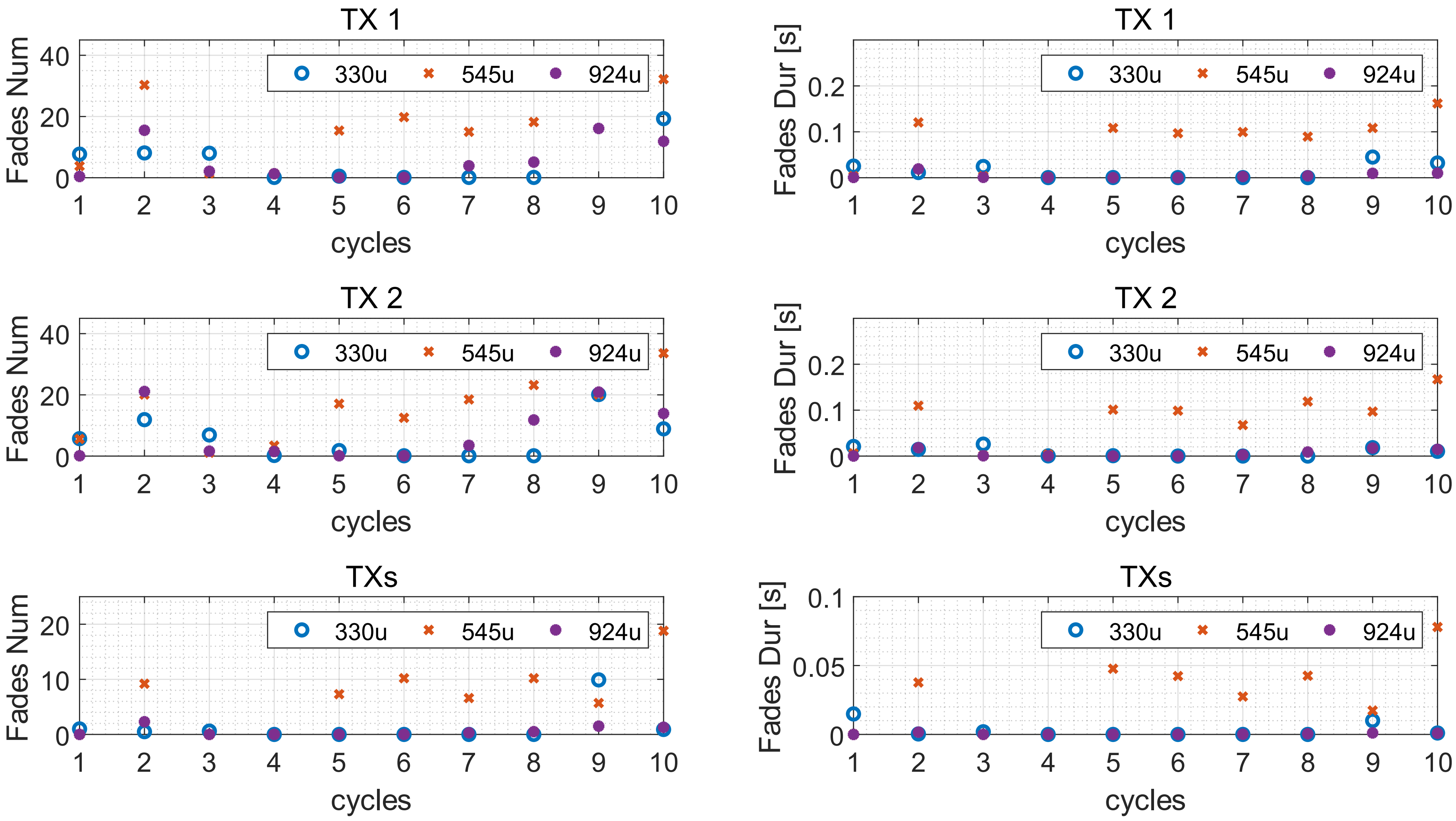
PSI analysis- PSI values comparison



Fades analysis



Fades analysis



Conclusion

Transmitter Diversity with three divergence angles

- Double mean power
  - ➔ Smaller divergence has more power
- Approximately half PSI
  - ➔ Limited to compare relation with divergence angle
  - ➔ Significantly related to weather conditions
    - ➔ some key factors
    - ➔ Impacted by combinations of all factors
- Higher PSI created more fades effects
- Decreased Fades effects
  - ➔ more measurements are needed with long distance

Stand-alone low weighted receiver

- Low-weight (approx. 750g)
- Small dimension (160mm*100mm*100mm)

Questions

Backgrounds explanation

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Sums of Random Variables

In many applications, we need to work with a sum of several random variables. In particular, we might need to study a random variable Y given by

$$Y = X_1 + X_2 + \cdots + X_n.$$

The linearity of expectation tells us that

$$EY = EX_1 + EX_2 + \cdots + EX_n.$$

We can also find the variance of Y based on our discussion in Section 5.3. In particular, we saw that the variance of a sum of two random variables is

$$\mathrm{Var}(X_1 + X_2) = \mathrm{Var}(X_1) + \mathrm{Var}(X_2) + 2\mathrm{Cov}(X_1, X_2).$$

If X_1, X_2,…,X_n are independent, $\mathrm{Var}\left(\sum_{i=1}^{n} X_i\right) = \sum_{i=1}^{n} \mathrm{Var}(X_i)$.

Gaussian Beam

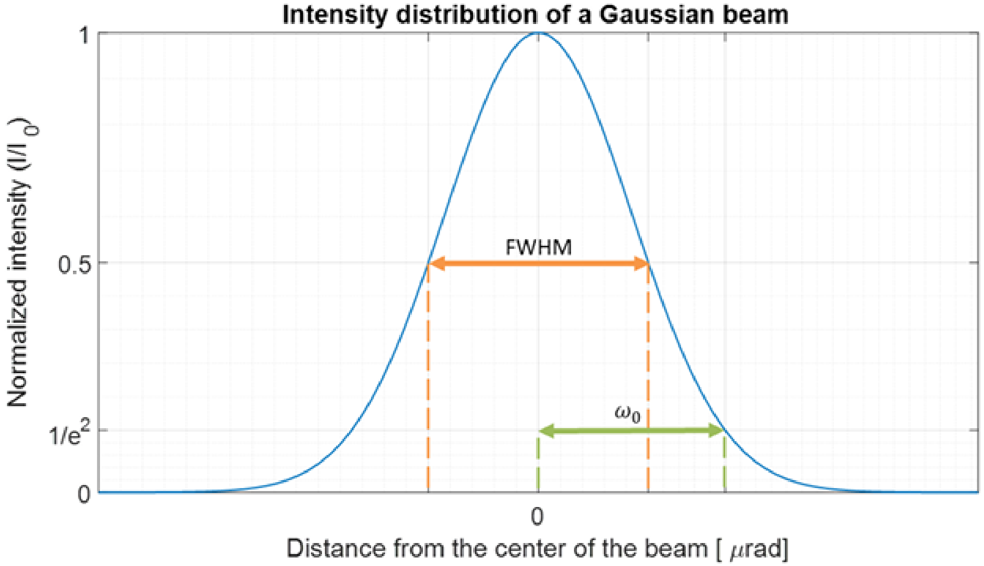

Figure 2. Intensity distribution of a Gaussian beam (TEM_{00}).

In link-budget calculations for FSO communication applications, the divergence angle of the transmitted Gaussian beam is often expressed as the full width at half maximum (FWHM) value. The FWHM value (ω_{FWHM}) is defined as twice the angular distance from the center of the beam to the point where the intensity drops to half the value of I_0. For Gaussian beams, ω_{FWHM} and ω_0 are related by

$$\omega_0 = \frac{\omega_{FWHM}}{\sqrt{2\ln 2}} \approx 0.849\ \omega_{FWHM} \quad [\text{rad}] \tag{2}$$

2022-Carrillo-Effects of Pointing Errors on Intenstiy Losses in the Opt LEO Uplink_CNF.pdf

Transmitter Distance

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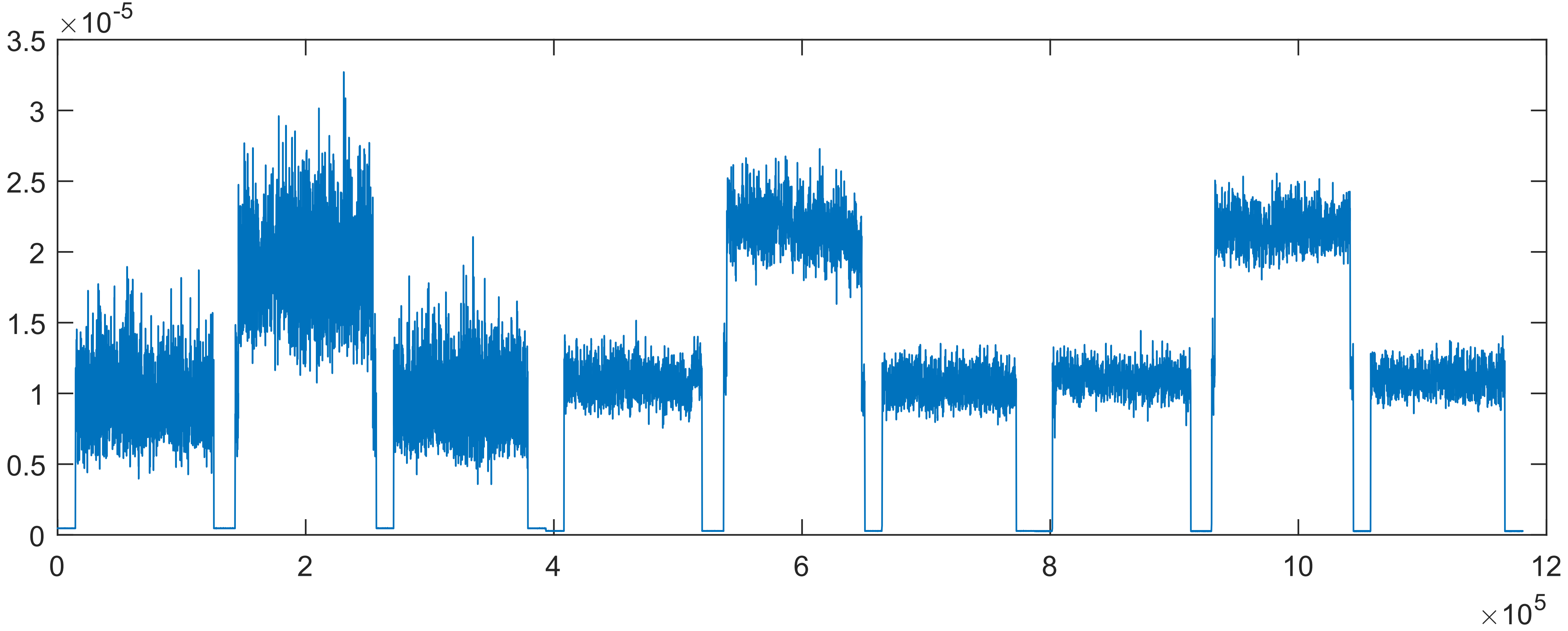

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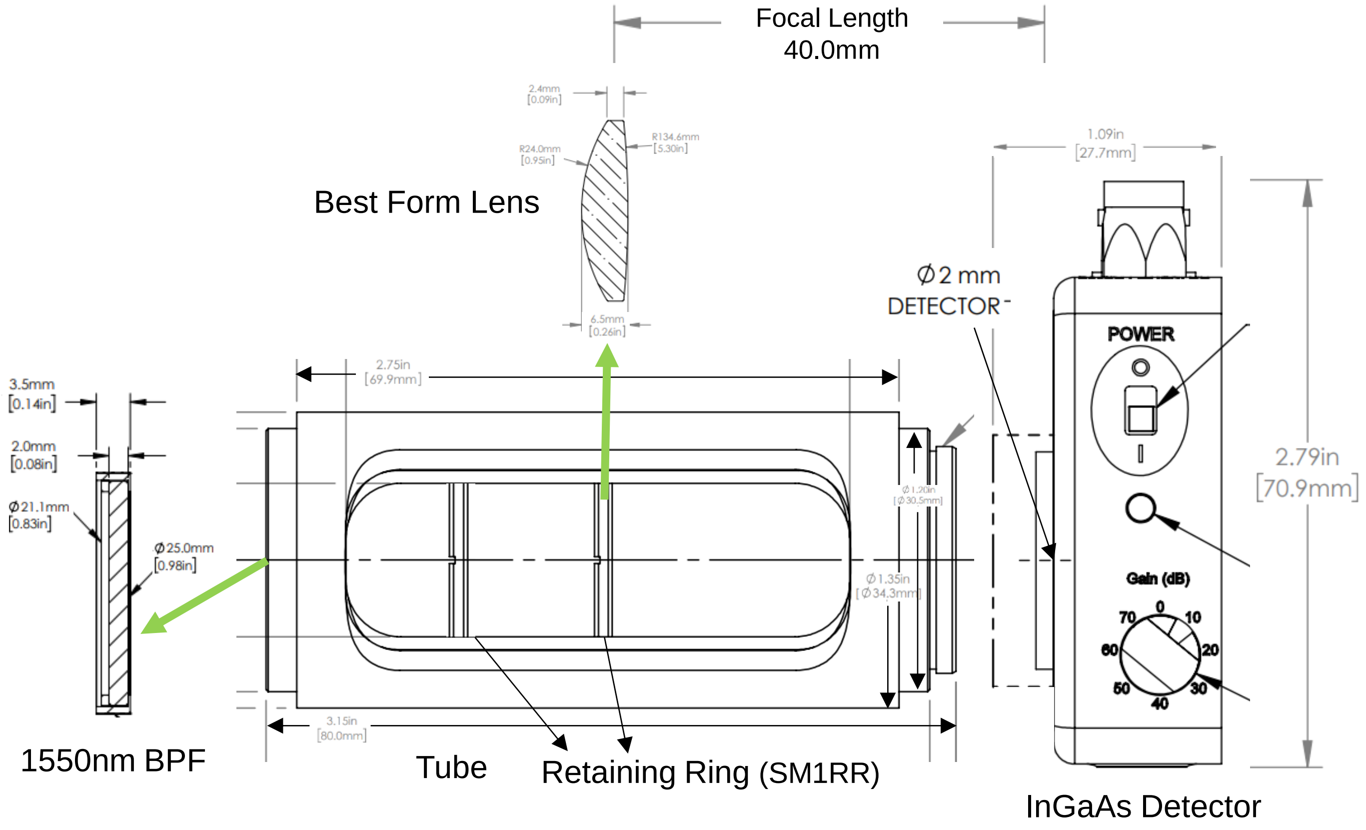
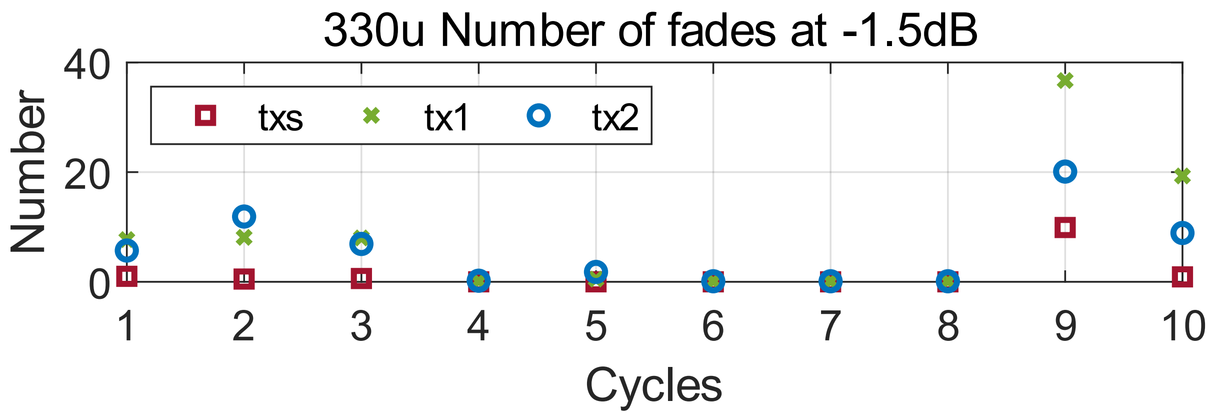
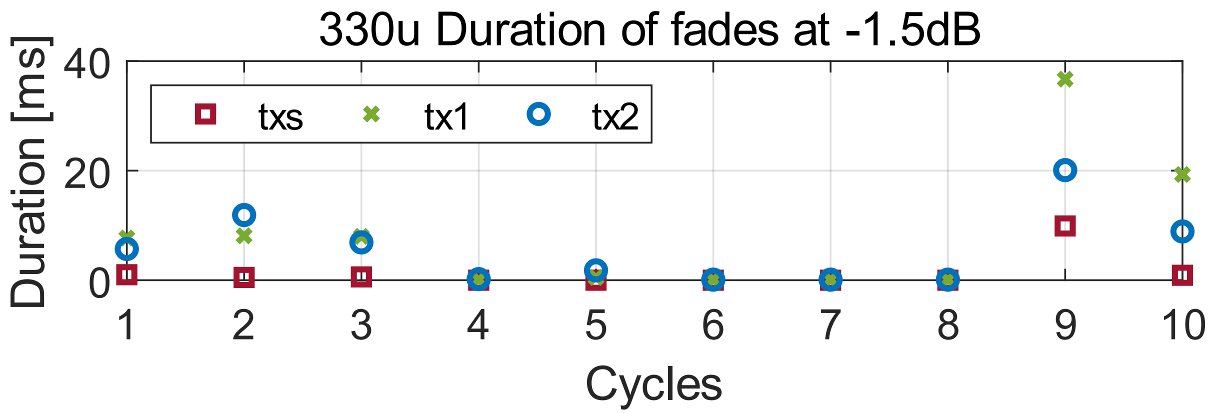
Hardware - receiver



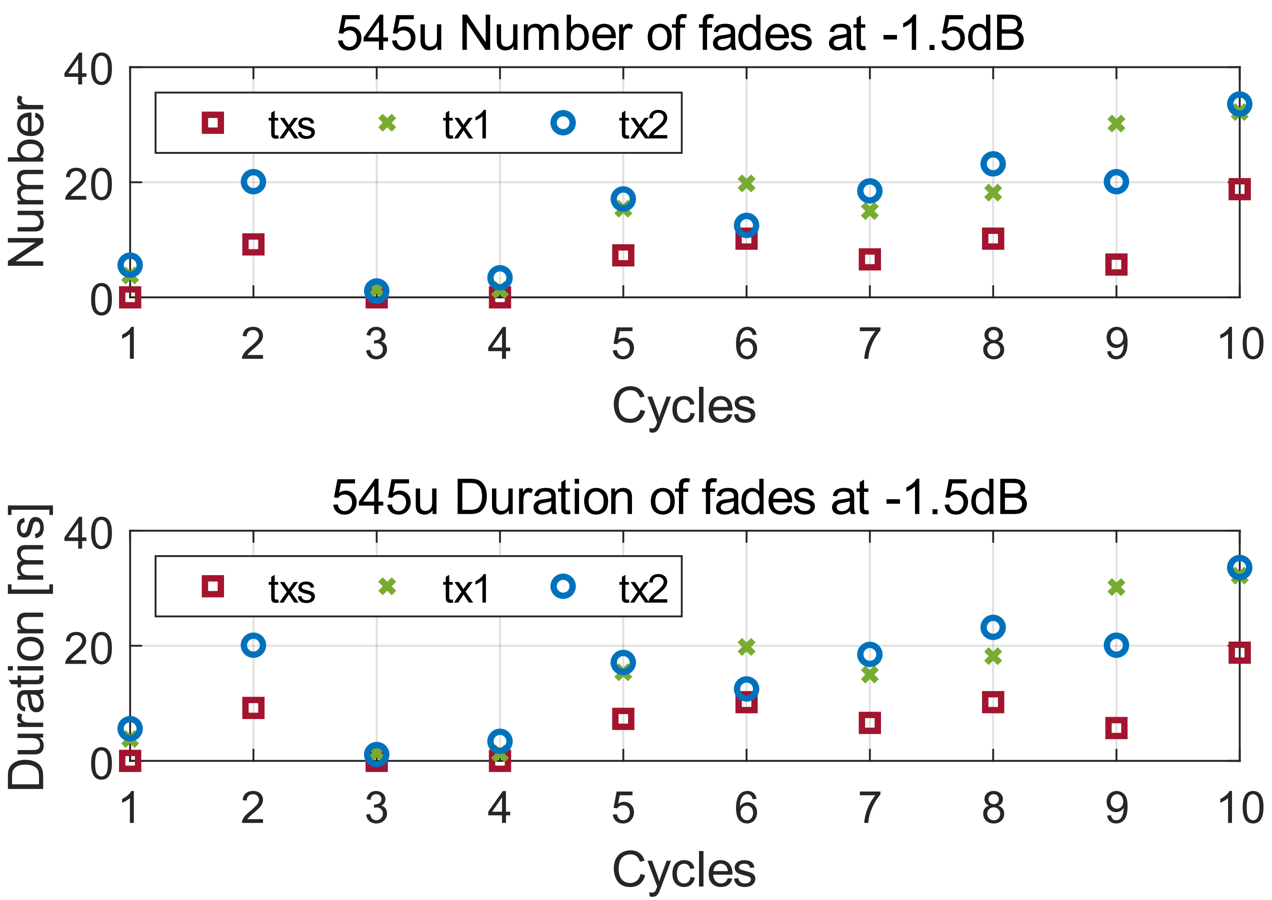
Fades analysis – 330urad





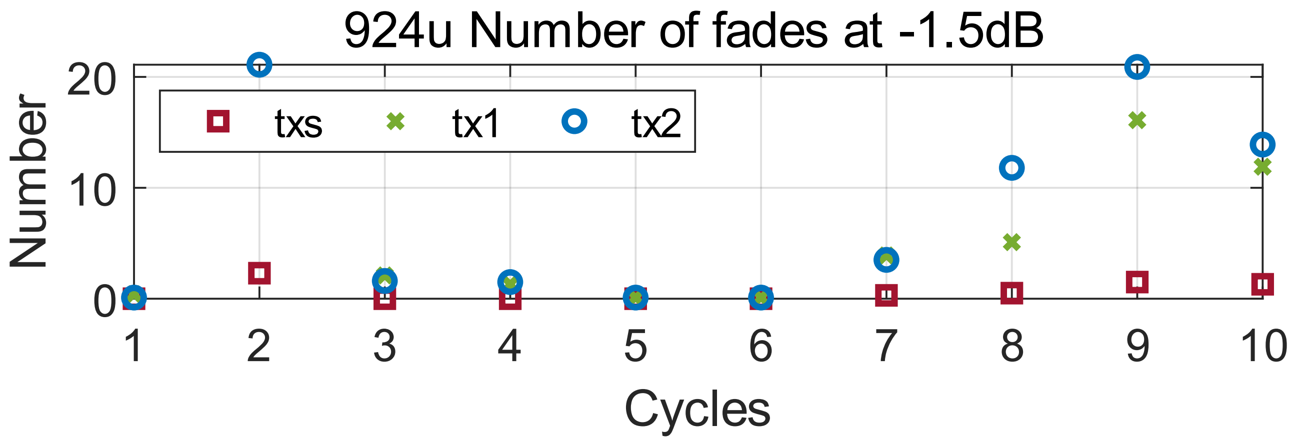
Cycle	TX1	TX2	TXs
1	7.7	5.7	1
2	8.1	11.9	0.5
3	8	6.9	0.6
4	0.1	0.2	0
5	0.5	1.8	0
6	0.1	0.1	0
7	0.1	0.1	0
8	0.1	0.1	0
9	36.7	20.1	9.9
10	19.3	8.9	0.9

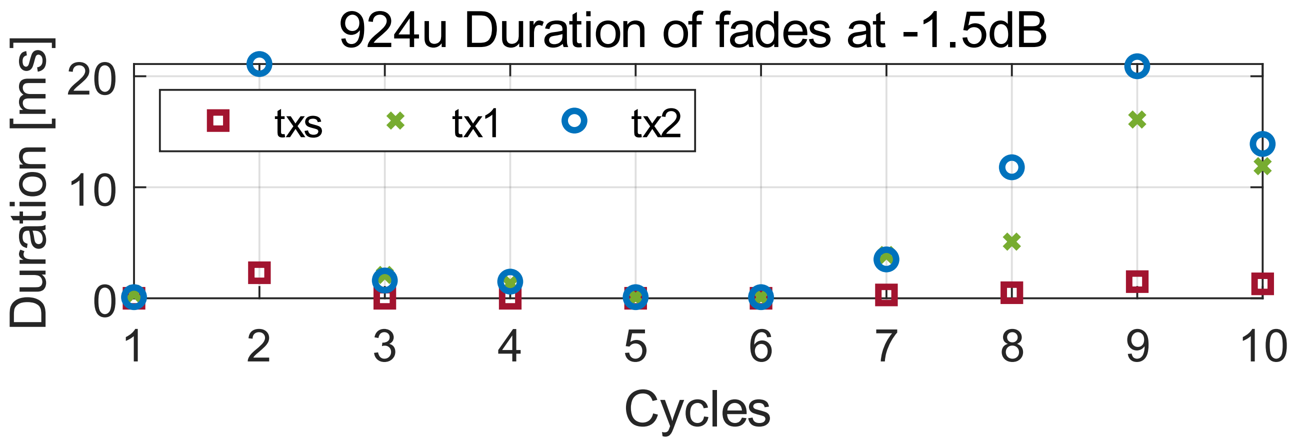
Fades analysis – 545urad



Cycle	TX1	TX2	TXs
1	3.8	5.6	0
2	30.3	20.1	9.2
3	1.4	1.1	0
4	1.3	3.4	0
5	15.4	17.1	7.3
6	19.8	12.5	10.2
7	15	18.5	6.6
8	18.2	23.2	10.2
9	30.2	20.1	5.7
10	32.2	33.6	18.8

Fades analysis – 924urad





Cycle	TX1	TX2	TXs
1	0.4	0.1	0
2	15.5	21.1	2.3
3	2.1	1.6	0
4	1.3	1.5	0
5	0.1	0.1	0
6	0.1	0.1	0
7	3.9	3.5	0.3
8	5.1	11.8	0.5
9	16.1	20.9	1.5
10	11.9	13.9	1.3

Introduction : Link Budget

Deutsches Zentrum für Luft- und Raumfahrt
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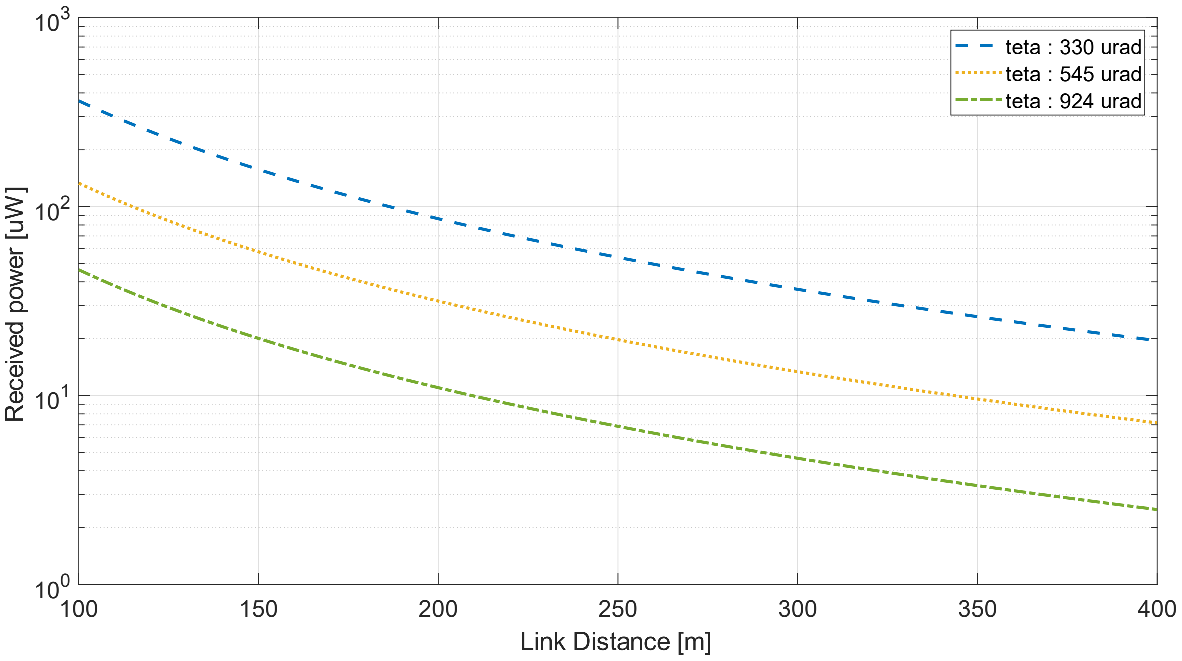

* PD NEP : 0.213 nW

[Figure 5] Link Budget in log-scale in [uW]]

$$P_{Rx} = P_{Tx} + a_{Tx} + g_{Tx} + a_{bw} + a_{fsl} + a_{atm} + a_{sci} + g_{Rx} + a_{Rx} \quad [dBm]$$

P_{Rx} received optical power [dBm]
P_{Tx} transmit optical power [dBm]
a_{Tx} tranmitter optical loss [dB]
g_{Tx} transmitter antenna gain [dB]
a_{bw} beam wander loss [dB]
a_{fsl} free-space loss [dB]
a_{atm} atmospheric attenuation loss [dB]
a_{sci} scintillation loss [dB]
g_{Rx} receiver antenna gain [dB]
a_{Rx} receiver optical loss [dB]

Divergence Angle	@350m
330urad	29.41 uW
545urad	10.78 uW
924urad	3.75 uW

[Table 1] Estimated received power [uW]]