Deep Space Optical Communication Links Design: Link Budget Tool for Data Rate Estimation

N. K. Lyras[1], A. D. Panagopoulos[2] , P.-D. Arapoglou[3]

e-mails : [1]lyrasnikos@central.ntua.gr, [2]thpanag@ece.ntua.gr, [3]pantelis-daniel.arapoglou@esa.int

Radio & Satellite Communications Group
School of Electrical and Computer Engineering
National Technical University of Athens

European Space Agency

1. Introduction

- **Employment of FSO communications for Deep Space Communication Links:**
  - Science and exploration missions are continuously enlarging the science volume gathered on spacecraft.
  - Demand for returning large data volume from space to earth.
- **Consultative Committee for Space Data Systems (CCSDS)**:
  - Standard for **High Photon Efficiency** (HPE)
    - Specification on coding & synchronization [1].
    - Specification on the physical layer [2].

2. Objectives

- A **tool** for aiding/planning In Orbit Demonstrations (IOD) missions fully relying on the **CCSDS HPE** is presented.
  - The **main elements** that must be taken into account in a deep space link budget analysis in order to the signal and noise photon rates are accurately predicted, are incorporated and presented (see Fig.1).
  - A practical methodology for the **selection of the optimum signaling parameters** (modulation order, code rate, slot width) achieving the higher data rates depending on the signal and noise photon rates without resorting to lengthy coded Bit Error Rate (BER) evaluations that otherwise are needed, is presented and employed in this tool.
- A sensitivity analysis of various hypothetical deep space missions is performed and valuable conclusions are extracted.

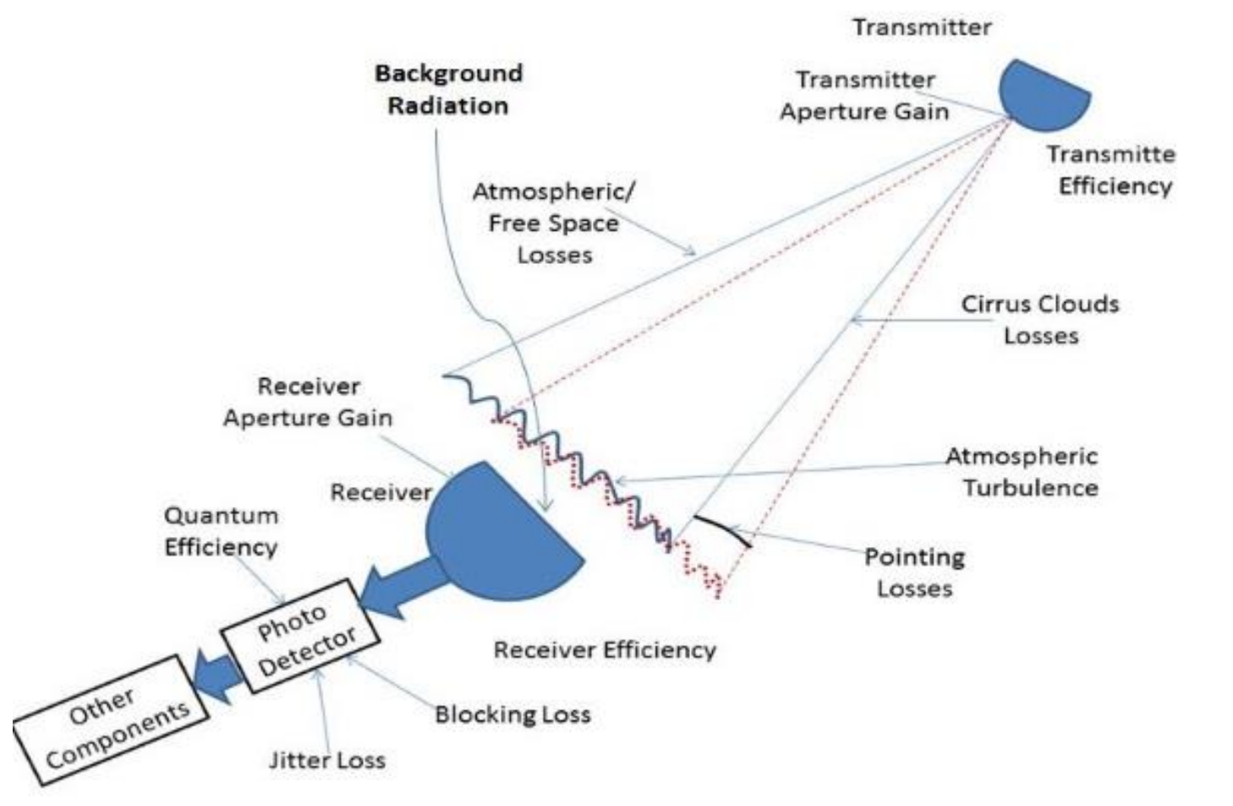

Fig.1: Configuration of Deep Space-Link Budget Design elements

3. Main Assumptions

- Optical downlink operating under cloud free line of sight conditions between an optical terminal on board a deep space spacecraft and an optical ground station.
- A Poisson channel model is assumed.
- Due to the power limited nature of these links intensity modulation (IM) and direct detection (DD) with photon counting detectors are considered for the transmitter and receiver architecture, respectively.
- Pulse Position Modulation (PPM) signaling and a Serially Concatenated-Pulsed Position Modulation (SCPPM) are considered.

4. Link Budget Elements

A. Signaling: Optical Modulation & Coding

- In PPM, $\log_2 M$ bits are modulated by transmitting a single pulse in one of the M possible time slots of a symbol. From a physical layer point of view in each time slot the laser is either "on" or "off".
- $T_s = M \cdot T_{slot} + T_{LR}$. & $T_{LR} = M \cdot T_{slot}/4$
- For coding SCPPM is proposed for deep space missions. Allowed signaling values are presented to [1].

B. Received Power

- **Received power**, before the photo detector:

$$P_{r,ap} = P_t \cdot G_t \cdot G_r \cdot L_{fs} \cdot L_a \cdot L_c \cdot L_s \cdot L_{pt} \cdot \eta_t \cdot \eta_r \qquad (1)$$

- P_t (Watt) is the transmitted power, G_t, G_r are the transmitter and ground receiver aperture gains, respectively, L_{fs} is the free space loss factor, L_c is the cirrus transmittance factor, L_s is the scintillation loss factor, L_{pt} is the pointing loss factor, L_a is the atmospheric loss factor and n_t, n_r are the transmitter and receiver efficiencies respectively.
- A technique used in deep space link budget analysis is the consideration of a power link margin (n_{link_margin}) of some dBs for improved reliability.

C. Detected & Required Power

- **Detected power**:

$$P_{r,\det} = P_{r,ap} \cdot \eta_{\det} \cdot n_{coding} \cdot L_b \cdot L_j \qquad (2)$$

- n_{det} is the detector's quantum efficiency, L_b denotes the blocking loss factor and L_j the jitter loss factor.
- **Required power**:

$$P_r = P_{r,\det} \cdot n_{coding} \qquad (3)$$

- n_{coding} denotes the coding implementation loss and the coding efficiency i.e. "a gap to the theoretical capacity".

D. Blocking & Jitter loss

- Photon-counting detectors become inactive (blocked) for some time after detection event. This blocking leads to losses (blocking losses) relative to an ideal detector, which have to be measured.

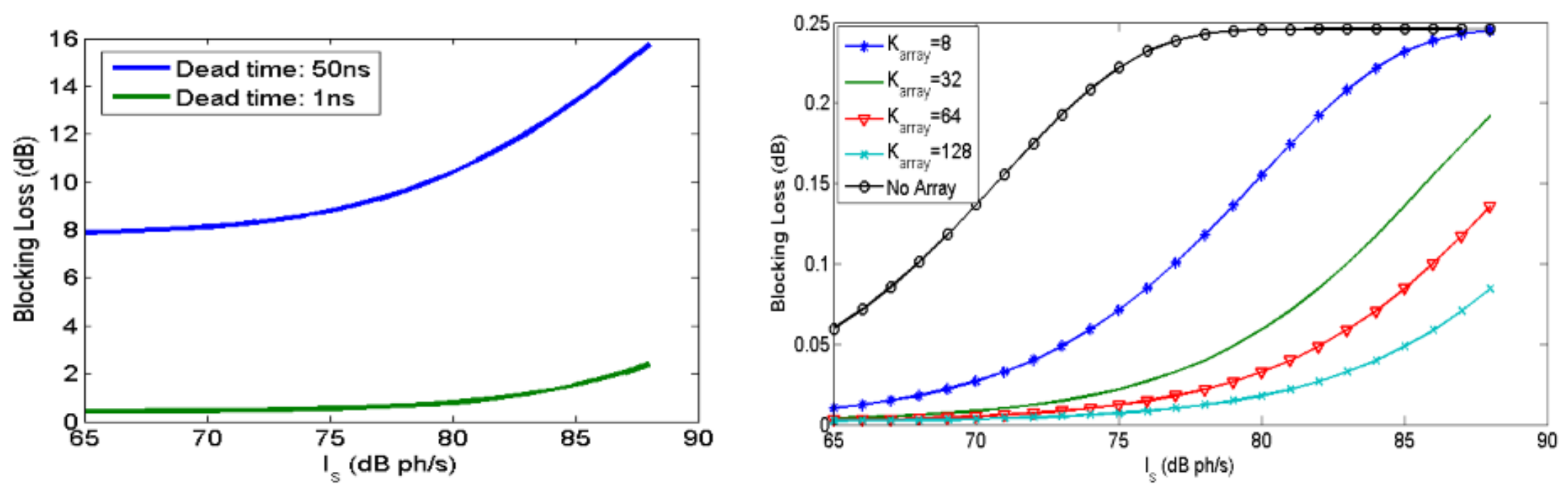

Fig.2 Left:Blocking loss single photon counting detector Right: Blocking loss detector array

- In photon counting detectors there will be a random delay from the time a photon is incident on the detector to the time an electrical output pulse is generated in response to that photon. That random delay, called detector jitter and produces losses.

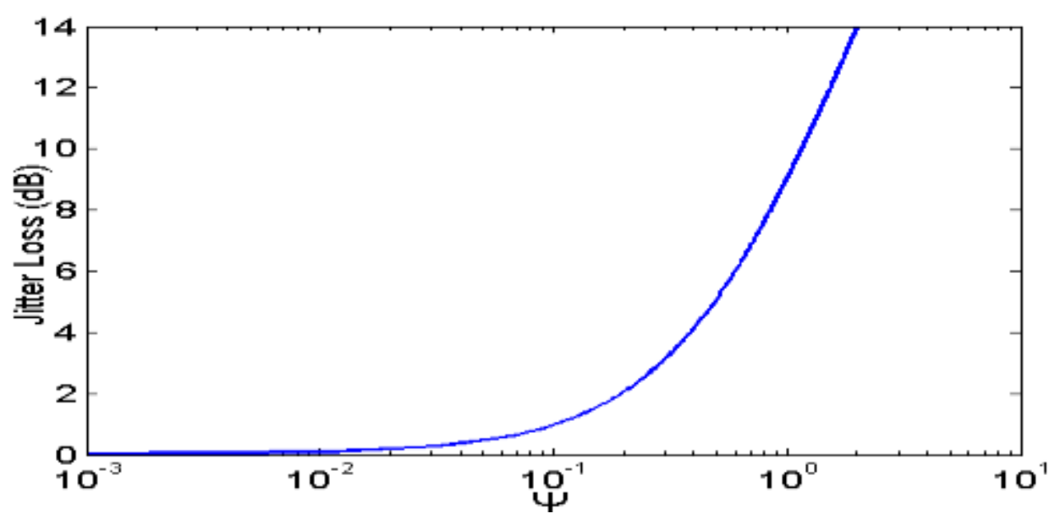

Fig.3 Jitter Loss

E. Noise Contribution

- **Background power**:

$$P_n = n_{\det} \cdot P_b \cdot K_{array} + d^2_{\det ector} \cdot i_d \cdot E_{photon} \cdot K_{array} + n_{leakage} \cdot P_{r,ap} \cdot n_{\det} \qquad (4)$$

- where i_d $(e/s/m^2)$ is each detector's dark rate, $n_{leakage}$ is the leakage ratio, P_b (W) is the Background Power per detector,(m) is the diameter of each detector. If only one detector is assumed $K_{array}=1$.

$$P_b = (H_{b,sky} + H_{b,stray} + H_{b,planets})\Omega_{fov} n_r A_r B_f + N_{b,stars} n_r A_r B_f \qquad (5)$$

- n_r is the efficiency of the receiver H_b $(W/m^2/Sr/\mu m)$, N_b $(W/m^2/\mu m)$ are the background radiance and irradiance energy densities respectively, B_f is the receiver's band pass optical filter width (μm), A_r is receiver area (m^2) and Ω_{fov} is the field of view of the receiver's aperture (sr). $P_b = P_b * n_{reduction}$ where is the background reduction factor.

F. Capacity

$$C = \frac{1}{\ln 2 \cdot E_{photon}} \left(\frac{P^2_r}{\frac{P_r}{\ln(M)} + P_{n\_\det} \frac{2}{M-1} + P^2_r \frac{M \cdot T_{slot}}{\ln(M) \cdot E_{photon}}} \right) \qquad (6)$$

5. Signaling Parameters Selection

- A practical methodology for the optimum selection of the best combination of parameters allowed by the CCSDS HPE standard in order to the data rate is maximized, is presented.
- Main steps:
  - All the available combinations of coding rates R_{ECC}, PPM order M, and slot duration T_{slot} , $(R^i_{ECC}, M^j, T^k_{slot})$ are considered.
  - The data rate of a coded SCPPM signal for all the available combinations is computed (but without taking into account the guard slot duration).

$$R^{i,j,k}_b = \frac{R^i_{ECC} \log_2(M^j)}{M^j \cdot T^k_{slot}} \qquad (7)$$

  - All the combinations are sorted beginning from the one with the higher data rate.
  - The received signal power and the detected noise power are estimated.

- For all $(R^i_{ECC}, M^j, T^k_{slot})$ combinations and received noise/signal power computed in the previous step, the blocking/jitter/coding losses (as factors $L^{i,j,k}_{blocking}$, $L^{i,j,k}_{hitter}$ $n^{i,j,k}_{coding}$) are computed respectively.
- For all $(R^i_{ECC}, M^j, T^k_{slot})$ combinations the required power is defined as

$$P^{i,j,k}_r = P_{r,ap} \cdot L^{i,j,k}_{jitter} \cdot L^{i,j,k}_{blocking} \cdot n^{i,j,k}_{coding} \cdot n_{\det} \qquad (8)$$

- Assuming the noise power computed in step 5, for each $P^{i,j,k}_r$ the soft capacity is calculated.
- The combination of $(R^i_{ECC}, M^j, T^k_{slot})$ with the highest data rate is selected given that

$$C^{i,j,k}(P^{i,j,k}_r) > R^{i,j,k}_b \qquad (9)$$

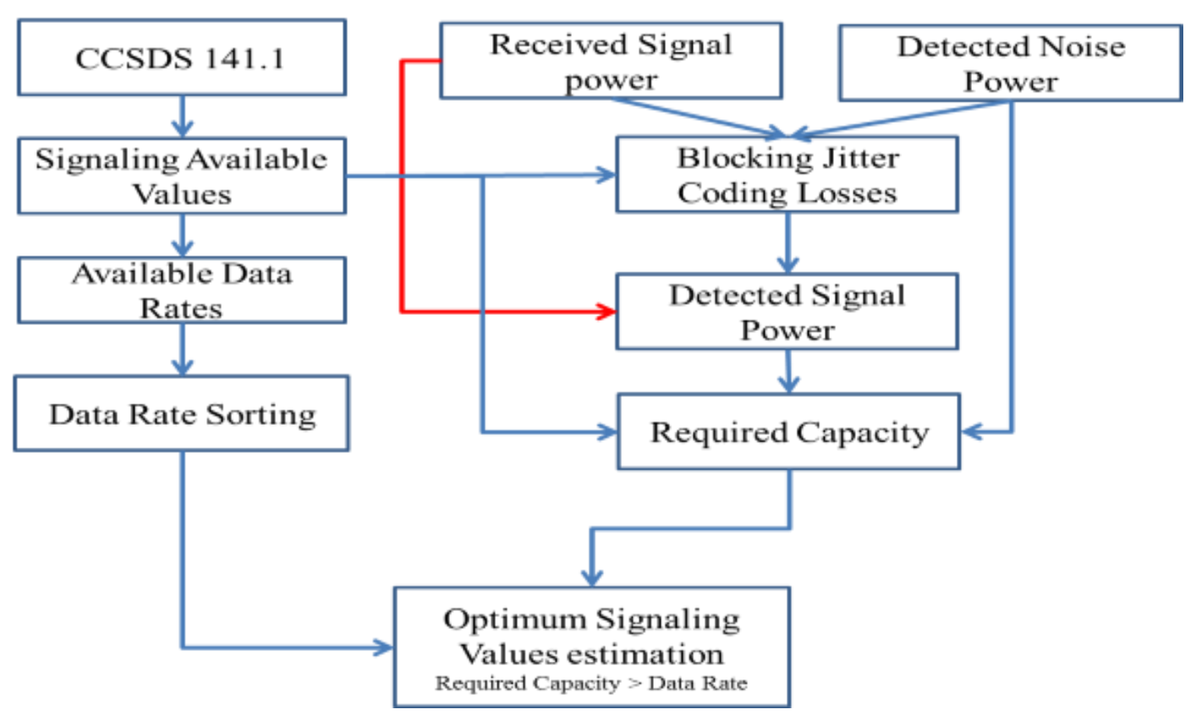

Fig.4 Signaling Values Estimation

6. Numerical Results

Table: Deep Space Link Budget Inputs-Outputs-4m receiver, 0.3/0.7/1.3 AU range, $15W/m^2/\mu m/sr$ radiance.- One Single detector and Detector Array 32

Variables	INPUTS	Variables	OUTPUTS (Single)	OUTPUTS (32Array)
Wavelength (nm)	1550nm	Transmitter Gain (dB)	112.9	112.985
Range link	0.3/0.7/1.3AU	Receiver Gain (dB)	138.1	138.178
Elevation angle (deg)	20 deg	Free Space Losses (dB)	-351.3 / -358.6 / -363.9	-351.2 / -358.6 / -363.9
Transmit Power (W)	4W	Atmospheric Transmittance	0.943	0.943
Transmitter Diameter (m)	0.22m	Scintillation Loss (dB)	0.01	0.01
Transmitter Sec. Diam.(m)	0m	Pointing Loss (dB)	1.95	1.95
Transmitter Efficiency	0.6	Cirrus Loss (dB)	0.5	0.5
Receiver Aperture diameter	4/6/8/10m	**Signaling**		
Receiver secondary aperture	0	PPM order	128 / 64 / 256	64 / 256 / 256
Receiver efficiency	0.4	Slot duration (ns)	0.25 / 2 / 1	0.25 / 0.25 / 1
Receiver quantum efficiency	0.5	ECC code rate	1/3 - ½ - 1/3	1/3 – 1/3 – 1/3
Focal length of receiver	16m	Symbol duration (ns)	40 / 160 / 320	20 / 80 / 320
Detector diameter	30e-6 m	**Blocking/Jitter Losses**		
Optical filter	0.2e-3μm	Blocking Loss (dB)	3.9 / 1.25 / 0.54	0.5
Atmospheric eff. Vertical	0.98	Jitter Loss (dB)	1.7 / 0.285 / 0.31	2.15
Link Margin	4.0 dB	**Received Signal Power**		
Pointing RMS Error Value	0.7*μrad*	Received Signal Power (W)	2.02e-11 / 3.7e-12 / 1e-12	2.02e-11 / 3.7e-12 / 1e-12
Probability Level	10^{-4}	Received Signal flux (Ph/s)	1.57e+8 / 2.9e+7 / 8.38e+6	1.57e+8 / 2.9e+7 / 8.38e+6
Modulation	M-PPM	Received Photons/symbol	6.29 / 4.6 / 2.68	3.15 / 2.32 / 2.68
Guard Slots	M/4	**Required Signal Power**		
Back. noise red. factor	0.5	Detected Signal Power (W)	2.2e-12 / 1e-12 / 3.54e-13	4.38e-12 / 1e-12 / 3.97e-13
Coding efficiency	0.8	Detected Signal flux (Ph/s)	1.7e+7 / 8e+6 / 2.76e+6	3.4e+7 / 8.3e+6 / 3.1e+6
Radiance of planets + Sky	$15/85W/m^2/\mu m/sr$	Detected Photons/symbol	0.692 / 1.3/ 0.88	0.68 / 0.66 / 0.99
Leakage Ratio	0	**Received Background Power**		
Detector Array size	1	Received Background Power (W)	2.1e-14	6.66e-13
Detector Dark Rate	$10^{12}e/s/m^2$	Received Background flux (Ph/s)	162227	5.2e+6
Blocking time	50ns	Received Background Photons/slot	4e-5 / 3e-4 / 1.6e-4	0.0013 / 0.0013 / 0.0052
Jitter time	240ps	**Detected Noise Power**		
		Detected Noise Power (W)	1.05e-14	3.37e-13
		Detected Noise flux (Ph/s)	82013.6	2.63e+6
		Detected Photons/slot	2.05e-5 / 1.6e-4 / 8.2e-5	6.6e-4 / 6.6e-4 / 0.0026
		Capacity/Data Rate /BER/SER		
		Soft Capacity(Mbits/s)	78.33 / 23.87 / 12.9	131.5 / 43 / 13.52
		Hard Capacity(Mbits/s)	63.7 / 20.7 / 11.3	98.84 / 33.5 / 10.12
		Data Rate (Mbits/s)	58.33 / 18.75 / 8.33	100 / 33.3 / 8.33
		SER	0.49 / 0.3 / 0.43	0.5 / 0.54 / 0.47
		BER	0.248 / 0.15 / 0.21	0.256 / 0.27 / 0.236

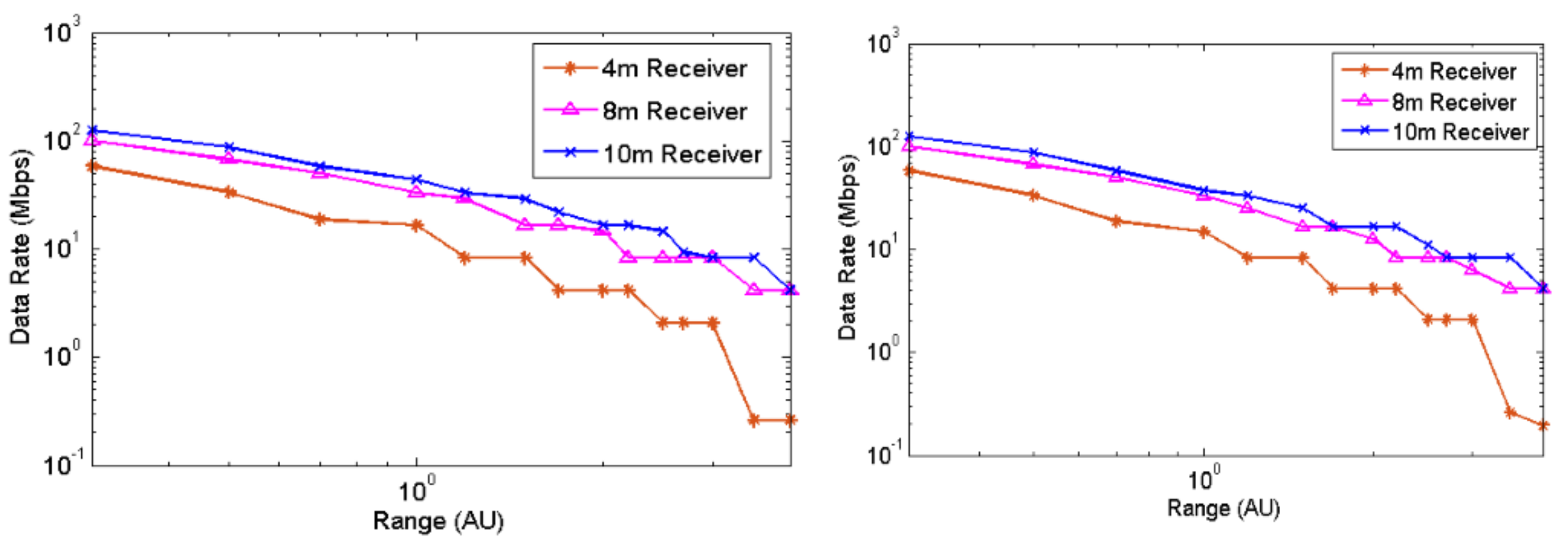

Fig.5 Data Rate vs Range, Different Receivers, No Array,
Left: H_b=15 $W/m^2/\mu m/sr$, Right: H_b=85 $W/m^2/\mu m/sr$

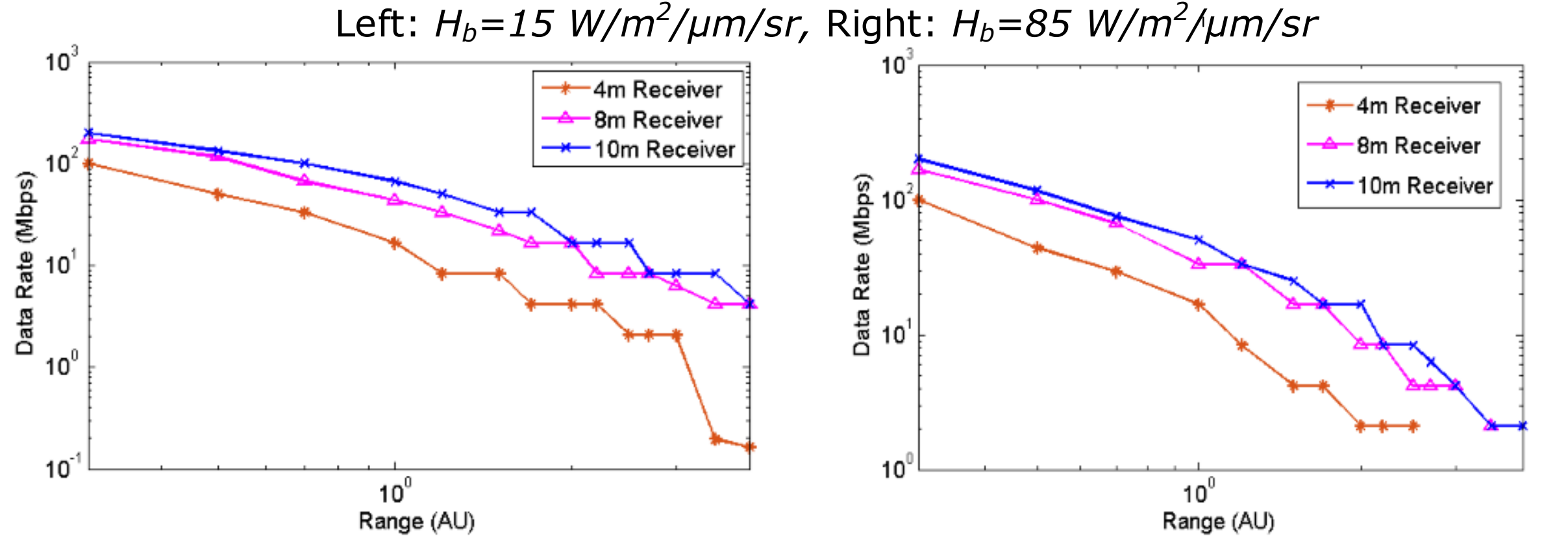

Fig.6 Data Rate vs Range, Different Receivers, 32 Detector Array,
Left: H_b=15 $W/m^2/\mu m/sr$, Right: H_b=85 $W/m^2/\mu m/sr$

Comparing the data rates achieved with a single detector and the 32 detector array it can be pinpointed that the achieved data rates with the detector array are higher for distances up to 1 AU. **For longer distances it can be shown that equal or even higher data rate can be achieved with only one detector. When detector arrays are employed, on one hand the blocking loss is minimized but on the other hand the noise increases. Therefore, for longer distances, the received power is extremely low and, in case of the detector array, the noise photon rate is higher than the signal photon rate.**

ACKNOWLEDGEMENT
The work presented in this paper was carried out under the ESA funded project "Development of a link budget tool for deep space communication optical links" with ESA Contract Nr. 4000121821/17/NL/FE .

[1] CCSDS Red Book, Recommendation for Space Data System Standards "Optical Comm. Coding & Synch. Sub layer.2017.
[2] CCSDS HIGH PHOTON EFFICIENCY OPTICAL COMMUNICATIONS PHYSICAL LAYER. 2019
[3] Moision B. & Hua X. "An approximate link equation for the direct-detected optical PPM link." Int. Net. Prog. Rep199.27, 2014
[4] N.K. Lyras et al. "Deep Space Optical Communication Link Engineering: Sensitivity Analysis", IEEE Aerospace & Electonics Systems Magazine*, September 2019*