Analog Optical Link Technology for the SKA

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INAF

Introduction

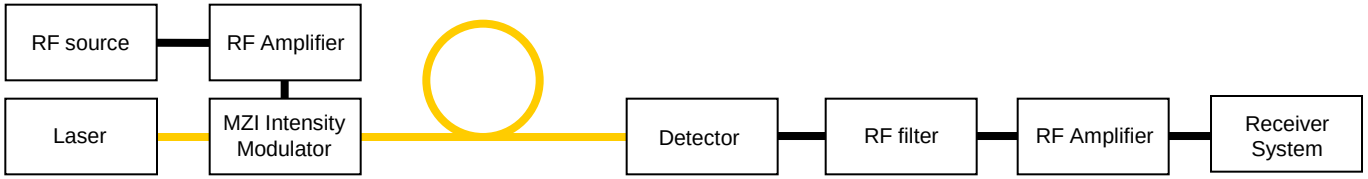
- Analog Optical Links in PrepSKA-STaN
  - Partners
    - ASTRON
    - INAF
    - MPIfR
  - Topics
    - COTS component and system inventory
    - System development
    - System investigation: RF performance and stability

- Analog Optical Link Application Area:
  - Aperture Array Tile Connection
  - PAF / SPF Connection
  - PAF Antenna Element Connection

- Why Photonic Technology
  - Broadband / High Frequency
  - Immunity for RFI
  - Light Weight
  - Small Space Envelope

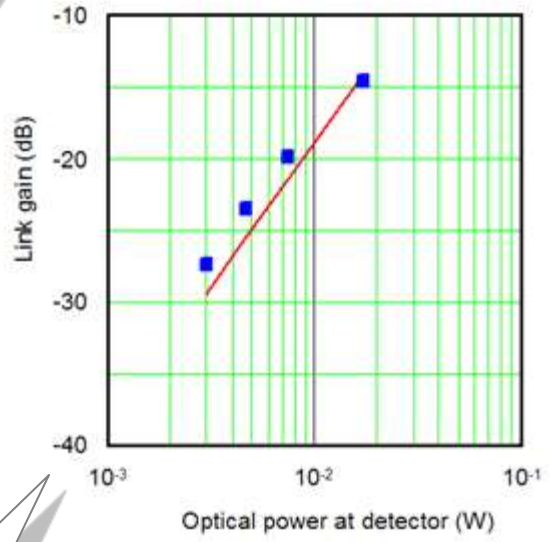
AOL Technology

- External Modulation: Link Gain



- Cost Level: ~ 1 k€

Laser		
	Type	EM4, AA1406
	Optical power	100mW
	RIN level	-170 dB/Hz
Modulator		
	Type	Photline, MXAN LN10
	Insertion loss	4 dB
	V_π at 1 GHz	5.5 V
	Input impedance	50 Ω
Detector		
	Type	Agere, R2560A
	Responsivity	0.8 A/W
	Impedance	50 Ω



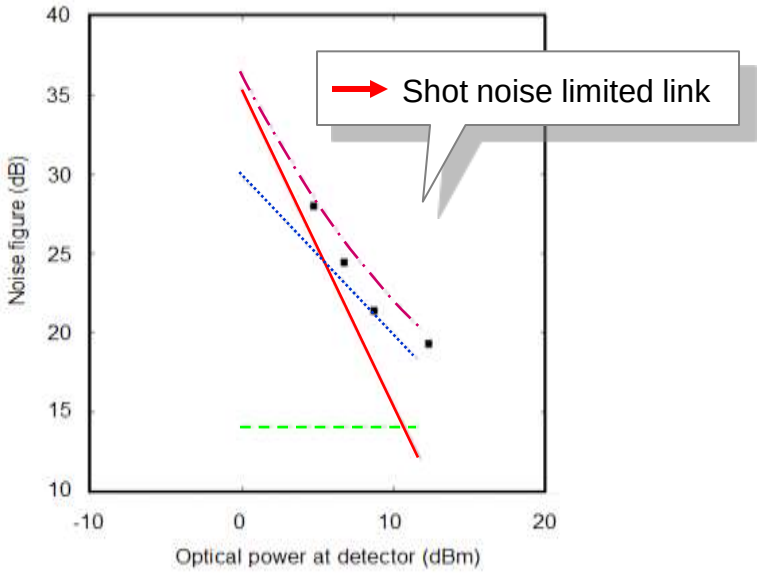
- Link Gain depends on the applied optical power level

AOL Technology

External Modulation: Noise

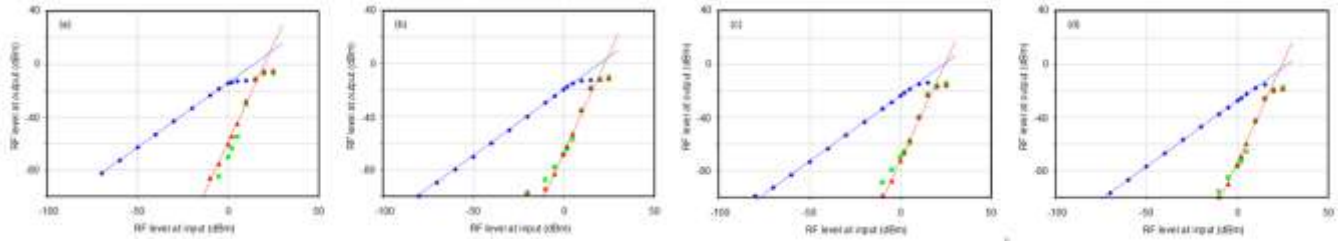
Noise sources:

- Thermal noise $p_{th} = kT$
- Shot noise $p_{shot} = \frac{1}{4} 2qI_D R_L$
- RIN $p_{rin} = \frac{1}{4} \mathrm{RIN}(I_D)^2 R_L$



External Modulation: Distortion

- Only third order spurs!



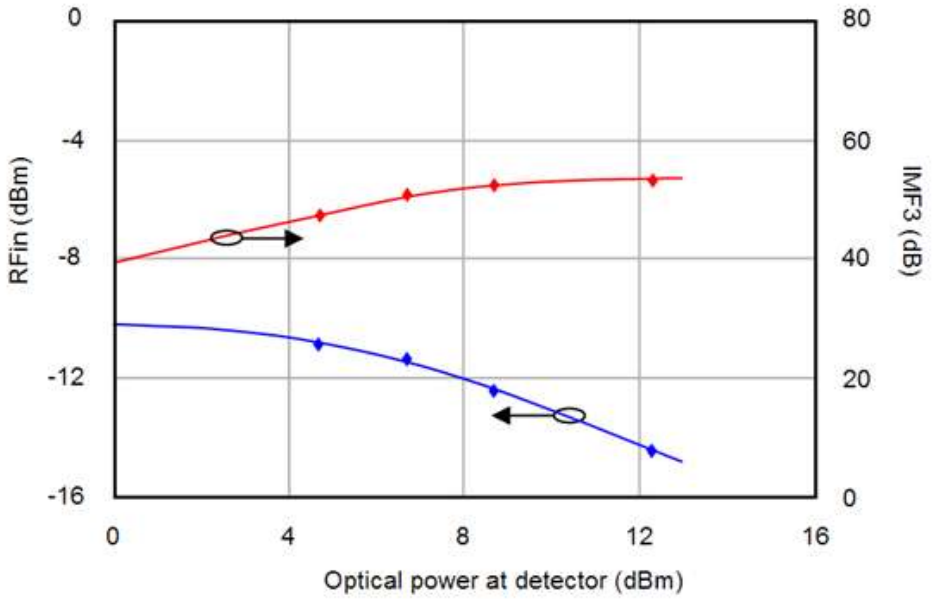
Optical power at detector (dBm)	-1 dB compression point (dBm)	-3 dB compression point (dBm)	IIP3 (dBm)	OIP3 (dBm)
4.7	10.3	15,4	23.1	-4.2
6.7	8.3	12.6	24.4	0.9
8.7	6.0	10.1	24.1	4.3
12.3	-0.7	4.0	23.0	8.4

AOL Technology

- External Modulation: Dynamic Range

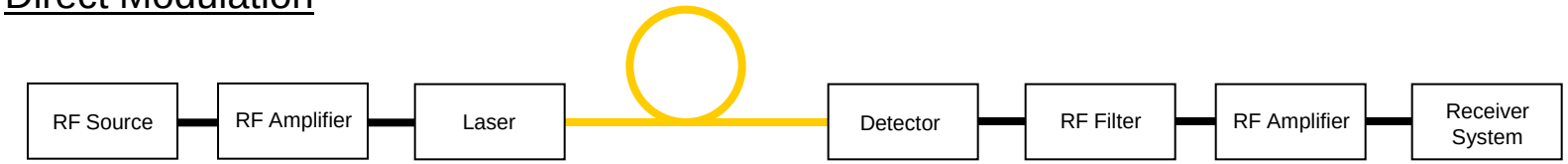
Optical power at detector	Noise level	1 Hz		1 GHz	
		IMF3	RFin	IMF3	RFin
(dBm)	(dBm/Hz)	(dB)	(dBm)	(dB)	(dBm)
4.7	-168.5	107.49	-31.06	47.49	-10.9
6.7	-166.8	110.68	-31.65	50.68	-11.35
8.7	-164.9	112.52	-32.65	52.52	-12.45
12.3	-160.8	113.22	-34.85	53.22	-14.45

$$\text{IMF3} = \frac{2}{3}\cdot\left(\text{OIP3} - P_{noise}\right)$$



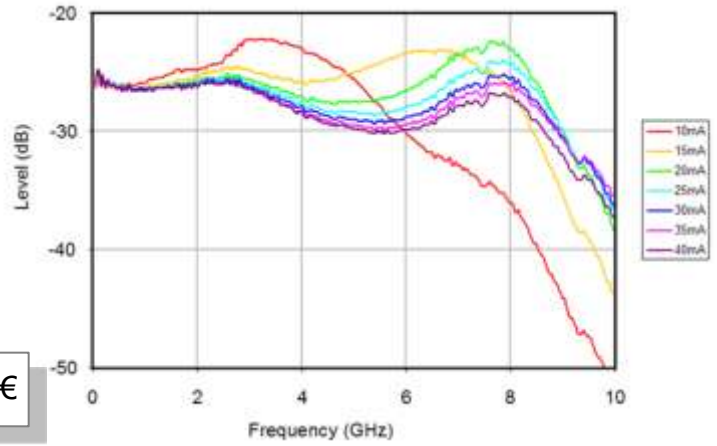
AOL Technology

- Direct Modulation



- Detector: responsivity ~ 0.9 A/W
- Laser: slope efficiency ~ 0.05 – 0.3 W/A

→ Link gains up to -10 dB



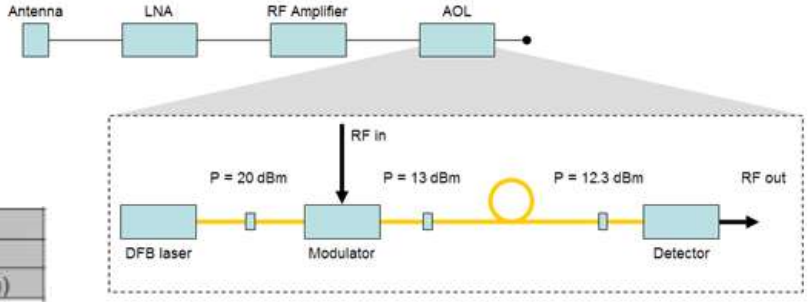
- NF = ~32 dB
- IIP2 = 52 dBm
- IIP3 = 33 dBm
- OIP3 = 6 dBm
- OIP2 = 25 dBm
- IMF2 = 47 dB (1 GHz)
- IMF3 = 49 dB (1 GHz)

- Cost Level: ~ 100 €

Laser		
	Type	Oemarket LDM1550
	Optical power	4 mW
	RIN level	-150 dB/Hz
	Slope Efficiency	0.1 W/A
Detector		
	Type	Oemarket PD-50
	Responsivity	0.8 A/W
	Impedance	50 Ω

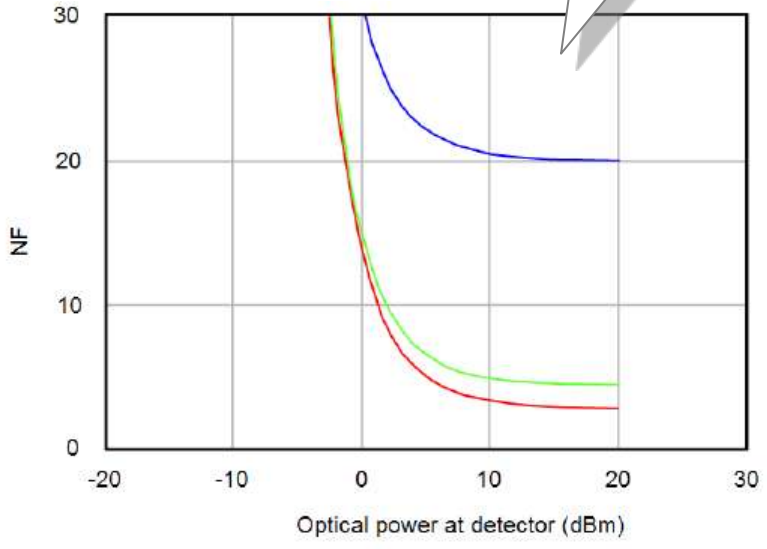
Implementation of AOLs

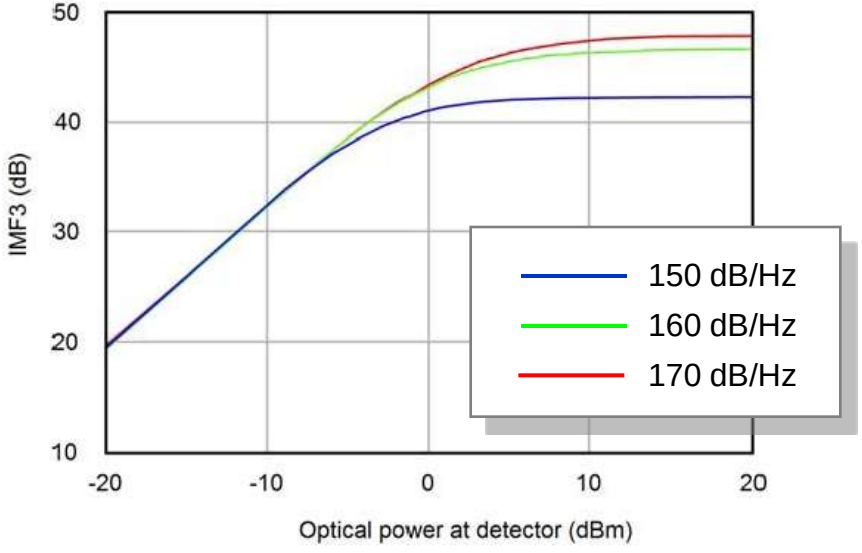
- RF systems with external modulation AOL



	Type	Gain	NF	IP2		IP3	
				In	Out	In	Out
		(dB)	(dB)	(dBm)	(dBm)	(dBm)	(dBm)
Antenna		-0,2					
Low Noise Amplifier	ATF-54143	16	1.5			18.0	36
RF Amplifier	MGA-53543	20	3.3			22	33
AOL		-14.6	19			23	8.4

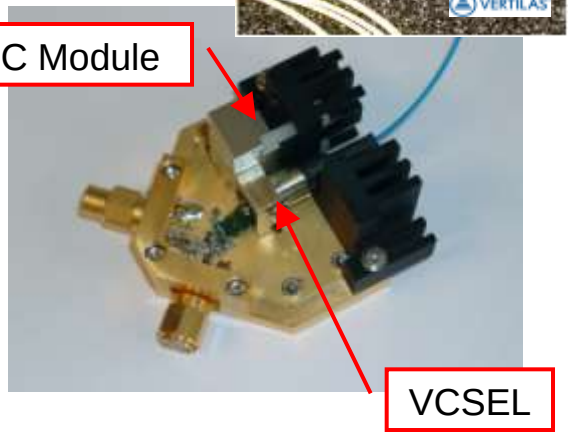
Transmission distance ~ 10 km

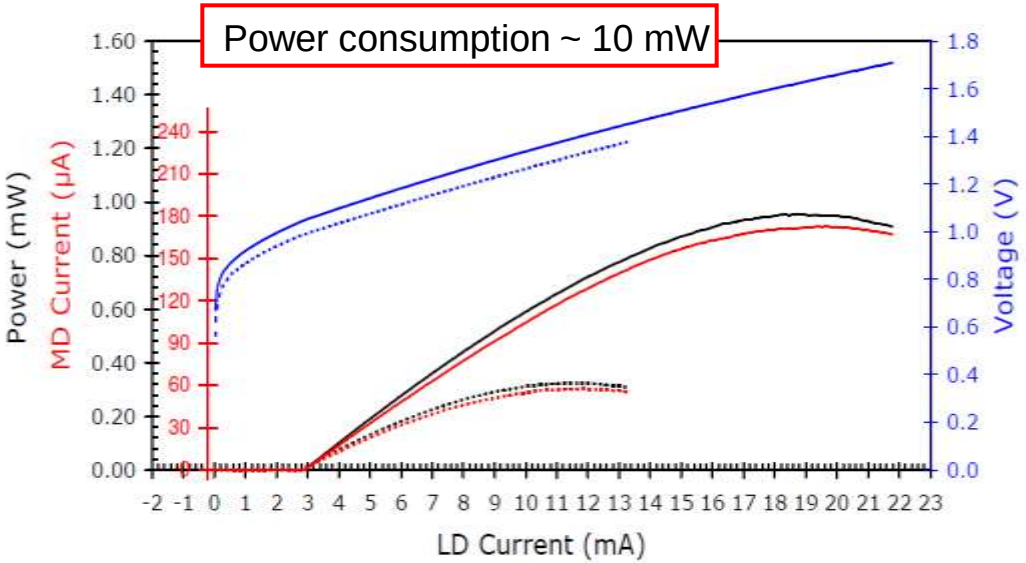




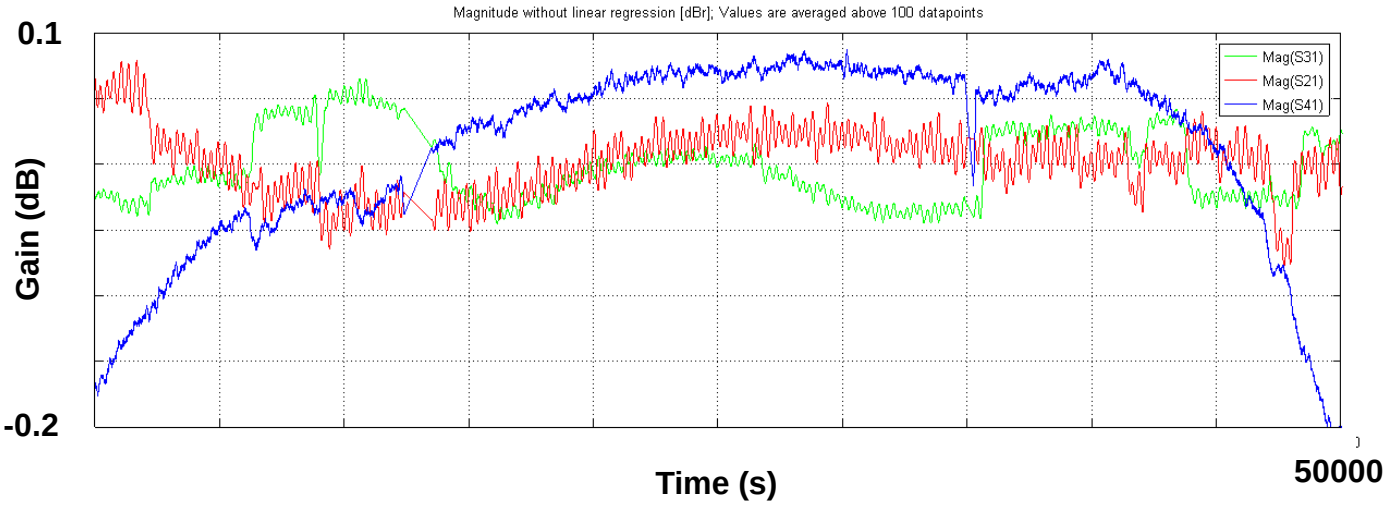
Long Wavelength VCSEL

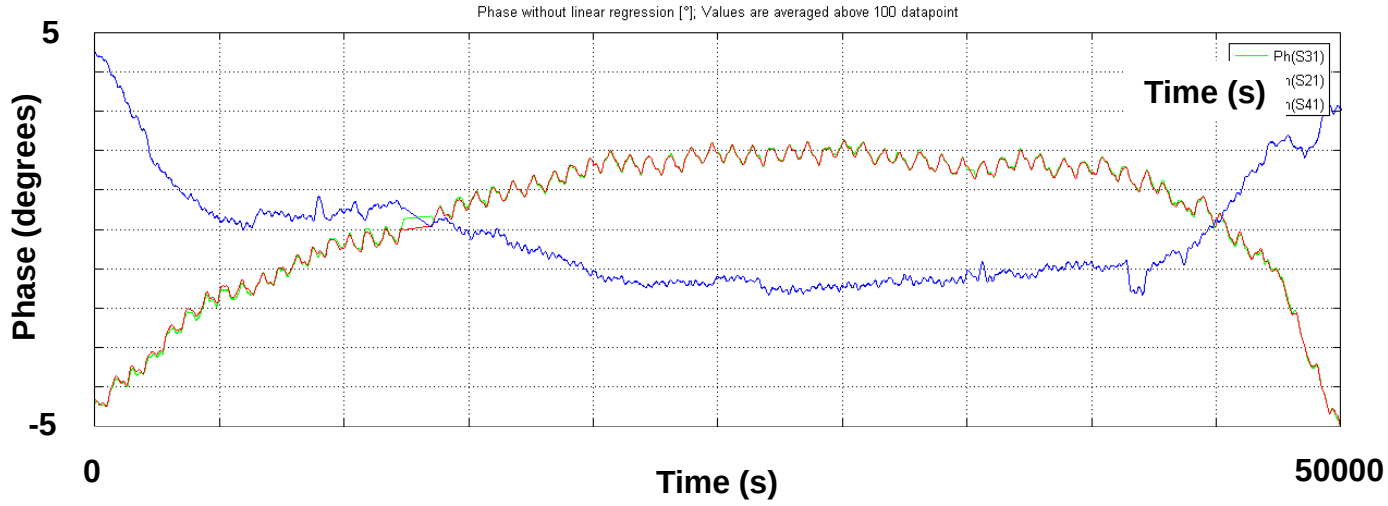
- 10 GBit/s
- Wavelength: 1310nm - 1550nm
- Very low threshold current
  and therefore low power consumption
- P_{out}~ 1 mW





Phase and Amplitude Stability





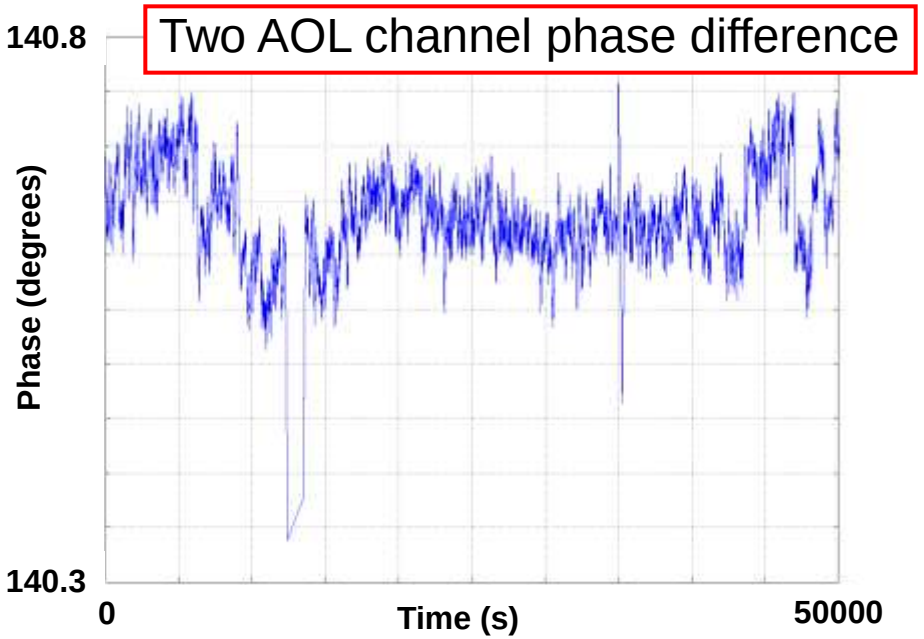
AOL1
AOL2
COAX

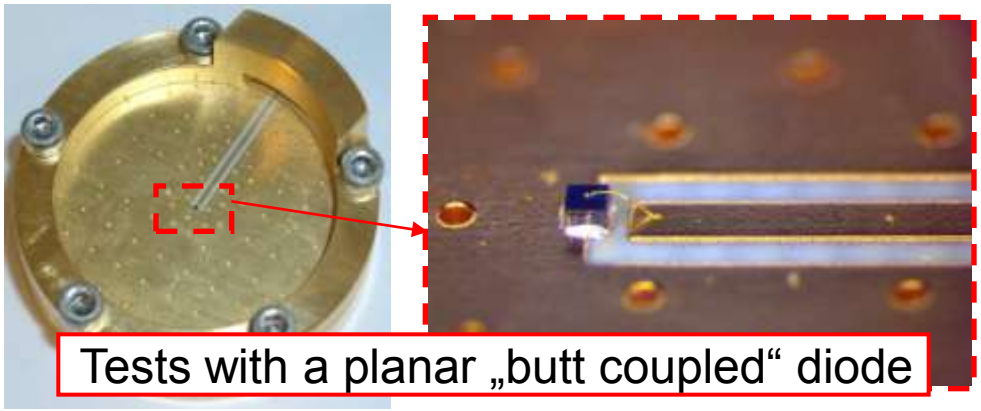
ΔT_{room} = 1.5 ºC

$\Delta T_{outside}$ = 9 ºC

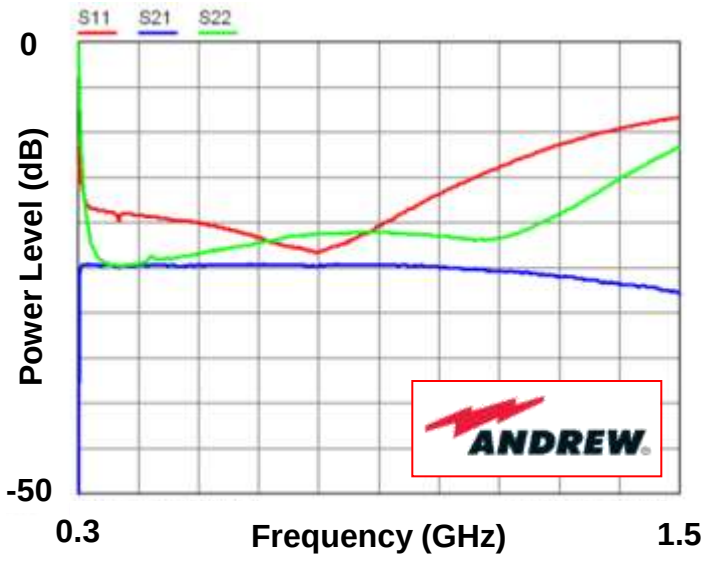
Phase and Amplitude Stability

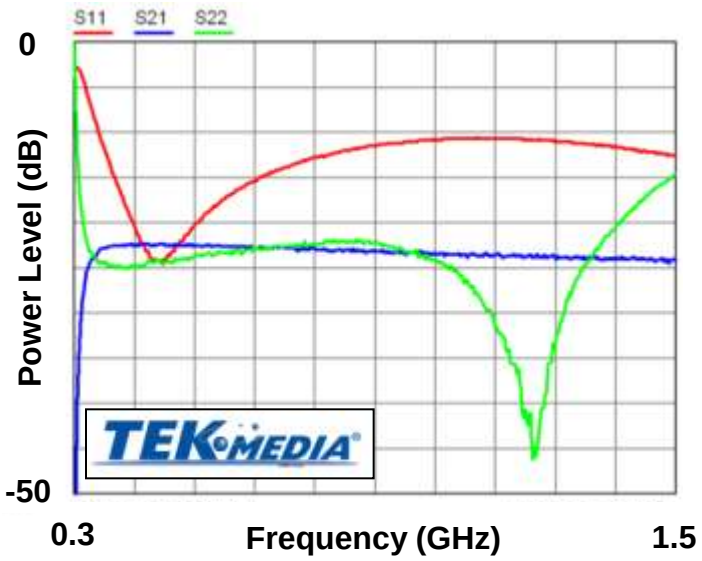
- Phase of link strongly influenced by temperature
  (length and refractive index changing of the fibre)
- Gain of link depends on telescope azimuth position
  (possibly due to birefringence of the fibre and a polarisation sensitive photodiode)

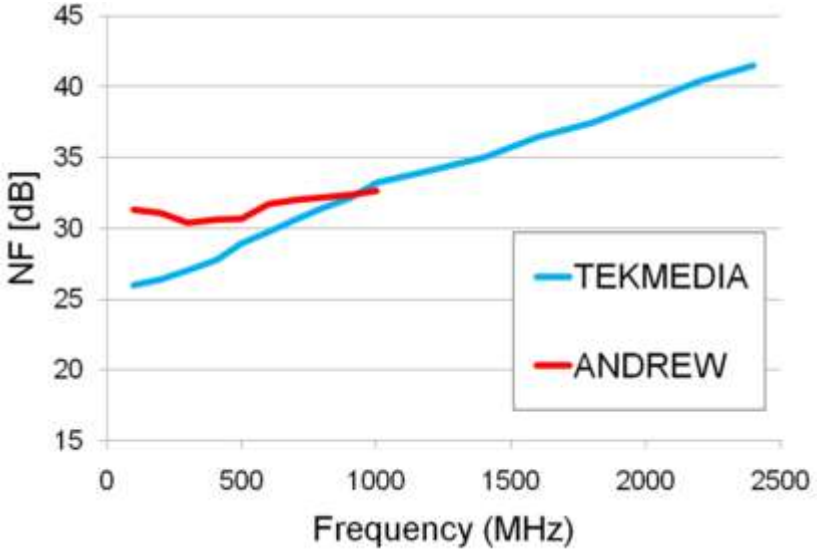


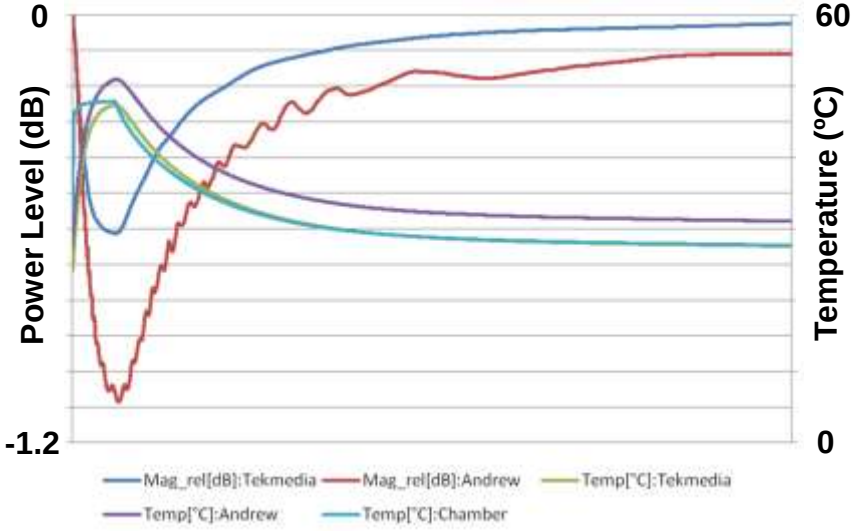


COTS Analog Optical link: TX & RX









Stability: fiber / coax comparison

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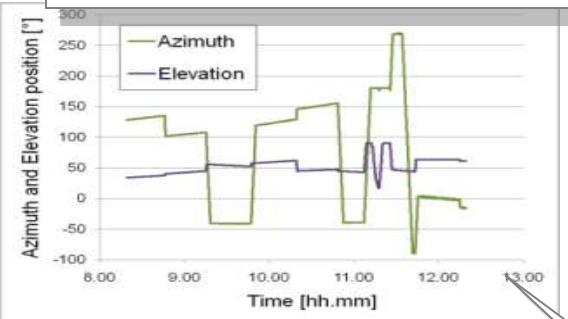
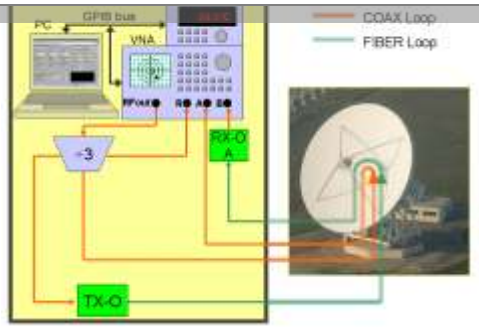
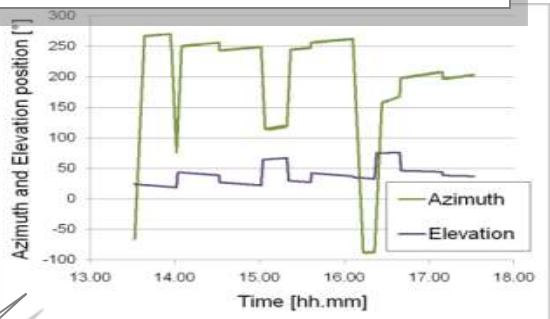
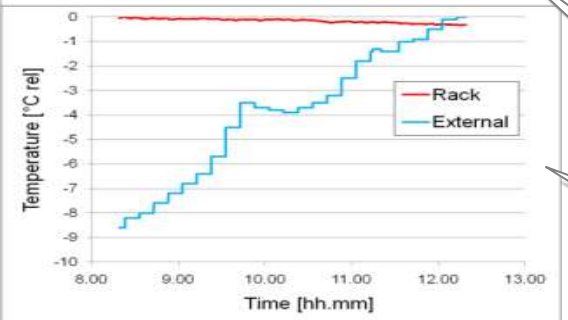


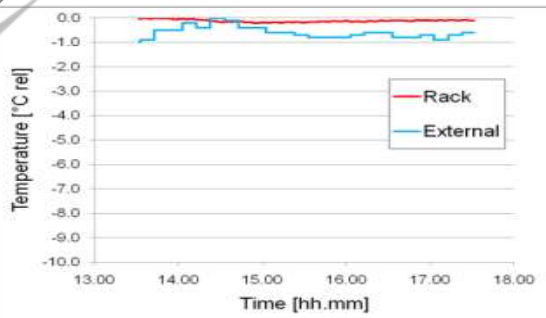


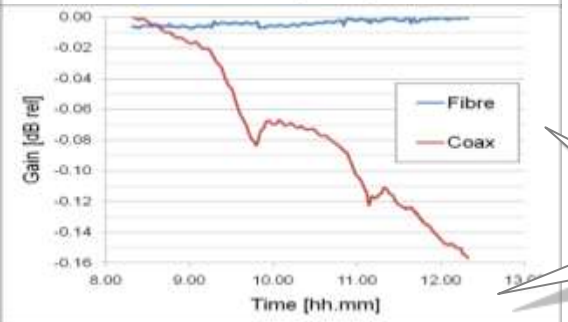


Similar antenna movement scenarios

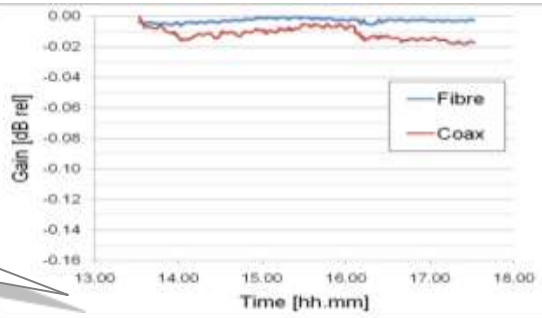


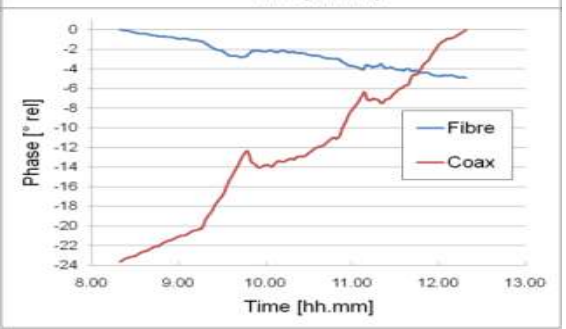
Different external (air) temperature scenarios



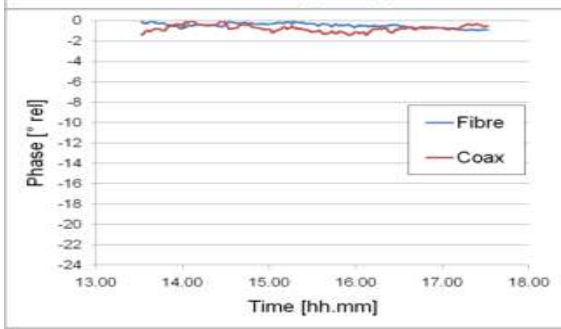


Optical fiber is always more stable than coax cable (both gain and phase)





The main influence factor is the external temperature variation rather than the antenna movements



AOL: discussion and conclusion

- Measured performance:

	Link Gain (dB)	IMF2 @ 1 GHz (dB)	IMF3 @ 1 GHz (dB)
External modulation AOL	-14.6	-	53
Direct modulation AOL	-27	47	49

- Higher frequencies / longer distances: AOLs most attractive
- AOLs are have a have a better phase and gain stability compared to coax cable links
- AOL noise figure
  - High with respect to *kTB*
  - Thanks to the high gain in front of the AOL, system noise figure is much lower.
- Further work:
  - Lower power consumption component (VCSELs) tests
  - Lower cost AOLs
  - Continued testing of novel AOLs in existing radio telescope systems

AOL costs

- Lasers

Supplier	Component ID	$P_{opt.\ max}$ (mW)	RIN (dB/Hz)	λ (nm)	Linewidth (MHz)	Costs Euro	Costs US Dollar	Type	Comment
Oclaro	LC95A76ULR	250		976	4500			CW	
CIP	DFB-080-XXX	80	-150	1550	1			CW	CIP gets its DFBs from EM4
EM4 Inc.	EM253	100 - 120	-170	1550	1	974	1550	CW	
Ortel / Emcore	1772-NM-63-02-FC-PM	63	-163	1550	1	1485		CW	
Lumics	LU1064M150	150		1064	30			CW	
Toptica	DFB	60		1550	5			CW	Reseller of these components
Toptica	DFB	140		970	5			CW	

Supplier	Component ID	$P_{opt.\ max}$ (mW)	RIN (dB/Hz)	λ (nm)	Bandwidth (GHz)	Costs Euro	Costs US Dollar	Type	Comment
OEQuest	LDM5S515-005	2	-150	1550	2.5		125	DML	
OEmarket	LDM1550	4	-150	1550	2		199	DML	Measured bandwidth 9 GHz
	LDM-C	3	-150	CWDM grid	2.5		239	DML	CWDM laser

AOL costs

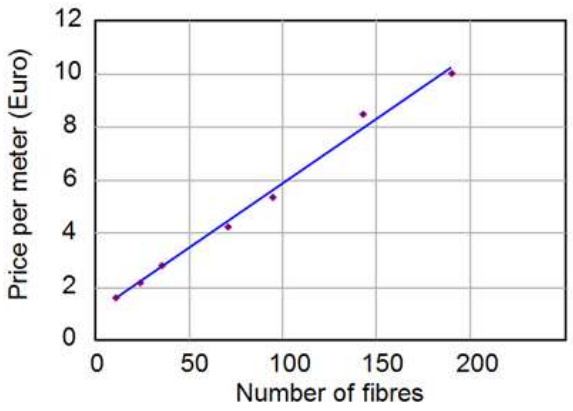
- Modulators

Supplier	Component ID	Vπ		Pop-in		Prf-in		Δν	IL	Wavelength	LinkGain	Price
		(V)	@ ν	(dBm)	(mW)	(dBm)	(mW)	(GHz)	(dB)	(nm)	(dB)	(Euro)
Photline												
	MXAN-LN-10	5.1	50kHz	23	200	28	631	12	4 dB	1480 - 1600	0,4	1680
	NIR-MX-LN	4.0	50kHz	20	100	28	631	12	5.0 dB	980 - 1064	-5,5	
JDSU												
	APE Microwave Anolog Intensity Modulator	6.0	1 GHz		200	27	500	9	5.0 dB	1540 - 1560	-3	2615
	2.5 Gbps bias free Miniaturized Modulator	3.7	100 kHz		100*	24	250	3	5.0 dB	1535 - 1565	-4,8	
	2.5 Gbps Bias-free Modulator w. Attenuator	3.7	100 kHz		100*	24	250	3	6.5 dB	1535 - 1565	-7,8	
Crisel Instruments												
	Standard, 1550nm, 18GHz	5.0	1 kHz		300		300	20	5.0 dB	1530 - 1570	2,1	3750
	Standard, 1060nm, high extinction ratio	4.1	1 kHz		100		300	5	4.5 dB	1040 - 1070	-4,7	
	Linearised modulator	5.5	1 kHz		100*			20	7 dB	1530 - 1570	-12,3	
	Custom AM1550	3.5	2 GHz		150			2	4	1550		
EOSpace	10-20 Gb/s Z-cut Modulator	3	1 GHz		100*			12.5	3 dB	1550	0.9	
	10-20 Gb/s X-cut Modulator	4	1 GHz		100*			12.5	4 dB	1550	-3,5	
Sumitomo												
	2.5Gbps Bias Free IM	4.5	2 Gb/s		20				5.5 dB	1530 - 1570	-21,5	
Covega												
	LN058	3.5	20GHz		100*				5.5 dB	1525 - 1605	-5,3	
Avanex												
	PowerLog FA-20	4	1 kHz		100	28		12	3.5 dB	1525 – 1615*	-2,5	
	PowerLog AM-20	5	1 kHz		100	25		20	4.5 dB	1525 – 1615 *	-6,4	
Lumera												
	20Gbps polymer IM	1.1	3 kHz		100*			16	11 dB	1528 – 1610	-6,3	

AOL costs

- Detectors

Supplier	Component ID	$P_{opt,\ max}$ (mW)	Responsivity (A/W)	λ (nm)	Bandwidth (GHz)	Costs Euro	Costs Dollar	Comment
OEmarket	PD-20	2	0.85	1250 - 1600	2	35		
	PD-A-30		0.95	1100 - 1650	3	32		
	Bookham PT10G	10	0.8	1310 - 1575	11.5		590	With transimpedance amplifier
	PD-50	3	0.95	1100 - 1650	5	56		
Go4Fiber	GDCS985	3	0.90	1100 - 1650	3		80	
	Emcore R2860E	2.5	0.8	1280 - 1580	9		99	With transimpedance amplifier
	Agere R2560A	16	0.8	1500 - 1600	13		900	



- Fiber: 0.06 Euro / meter

AOL Power Consumption

- External modulation AOL

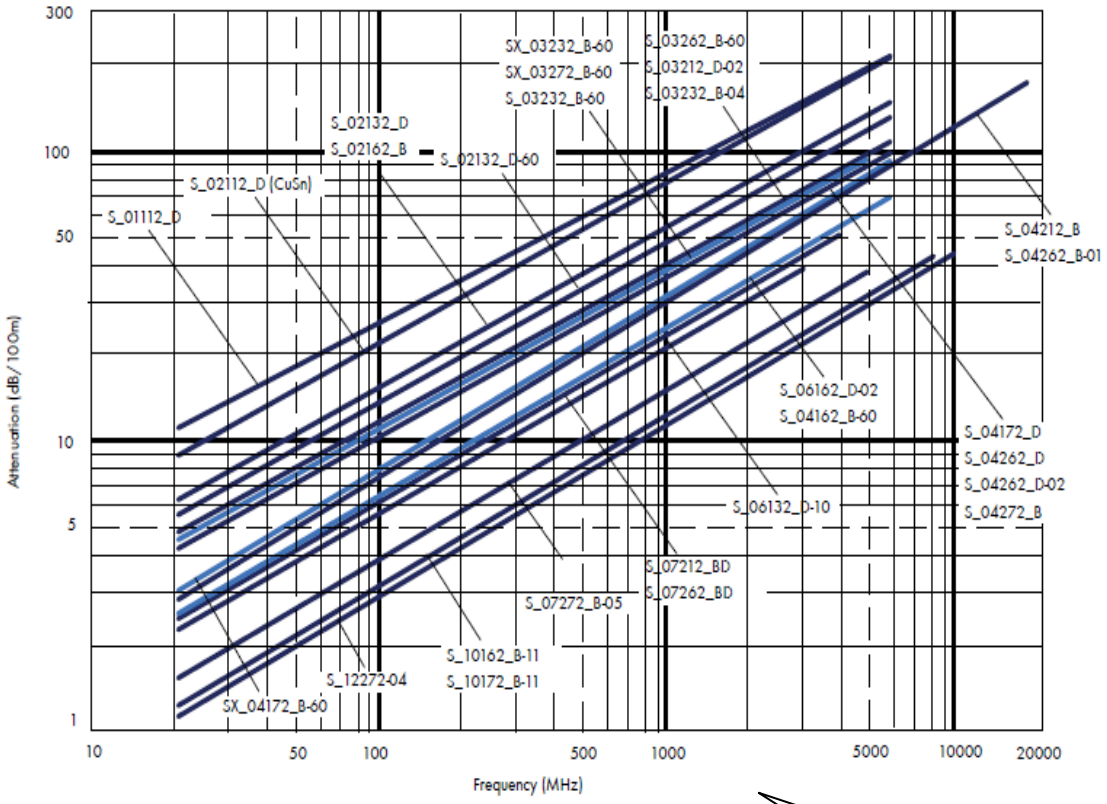
Component	Type	Subsection	Voltage	Current	Power	Comment
			(V)	(A)	(W)	
CW Laser	EM4, AA1406					
		Laser Chip	3	0.55	1,65	
		TEC	< 3	< 3	9	
		Thermistor	< 5	< 0.0005	< 0.0025	
Modulator	Photline, MXAN LN10					
		Modulator Chip	< 20	< 0.0002	< 0.0004	
		Monitor Diode	< 5	< 0.0035	< 0.02	
Detector	Agere, R2560A		15	< 0.013	0	
RF amplifier	MGA-53543		3.3	0.03	0.1	

- Direct modulation AOL

Component	Type	Subsection	Voltage	Current	Power	Comment
			(V)	(A)	(W)	
Laser	LDM1550		1	0.02	0.02	
Detector	PD-50		3	0.001	0	
RF amplifier	MGA-53543		3.3	0.03	0.1	Two amplifiers are needed

Comparison electronic / photonic

- Performance comparison: attenuation vs. frequency



Huber+Suhner low loss, 50 Ohm, coax

Comparison electronic / photonic

- Performance comparison

Coax

	Unit			
Manufacturer		Radiall	Huber & Suhner	Micro-coax
Type		SHF5OD low loss	S04212_B low loss	UFF092F low loss
Material		Silver, copper, PTFE	Silver, copper, SPE	Silver, copper, PTFE
Insertion loss at 1/5/15 GHz	dB/m	0.26 / 0.61 / 1.1	0.3 / 0.8 / 1.5	0.76 / 1.7 / 3.2
Connection type		connector	connector	connector/soldering
Cable diameter	mm	6.25	5.30	2.34
Static bend radius	mm	25	53	3.18
Dynamic bend radius	mm	-	106	
Weight	g/m	78	41	16.4
Loss vs. temperature	%/°C	0.2		
Phase change vs. bending	°/360°	< 0.4		< 2
Phase stability vs. temperature		< 1 °/m/GHz (0°C - 90°C)		< 1500 PPM (0°C - 70°C)

Fiber

	Unit		Remark
Insertion loss	dB/km	0.25	@ 1550 nm
Connection type		Connector, splice	
Cable diameter	mm	0.125	Without mantle
Bend radius	mm	10	Spec.: ITU-T G.657
Weight	g/m	0.1	ρ_{glass} = 2500 kg/m^3
Loss vs. temperature	%/°C	0	
Phase change vs. bending	°/360°		
Phase stability vs. temperature	PPM	< 595	between 0°C - 70°C, α_{glass} = 8.5 °C^{-1}