Cours LISA : Modèle de Performance

J. Martino

Plan

I/ Objectifs et structure du modèle de performance

II/ Rappels sur la mesure

III/ Quelques bruits en détails

IV/ Limitations

The Consortium LISA Performance Model

GOAL

Link between science specifications in the Science Requirement Document and the instruments noises and parameters values.

- Bottom Up : **Current Best Estimate [CBE]** -> Capture the physics and our best understanding of the instrument.
- Top Down approach: **Allocation** -> Capture our level of confidence.

The Consortium LISA Performance Model

- **Frequency domain model of the LISA constellation** as Amplitude Spectrum Density
- **Hierarchical model** : from strain sensitivity to sub-system noises & parameters

Objectif du modèle de performance

Sous-systèmes
Environnement

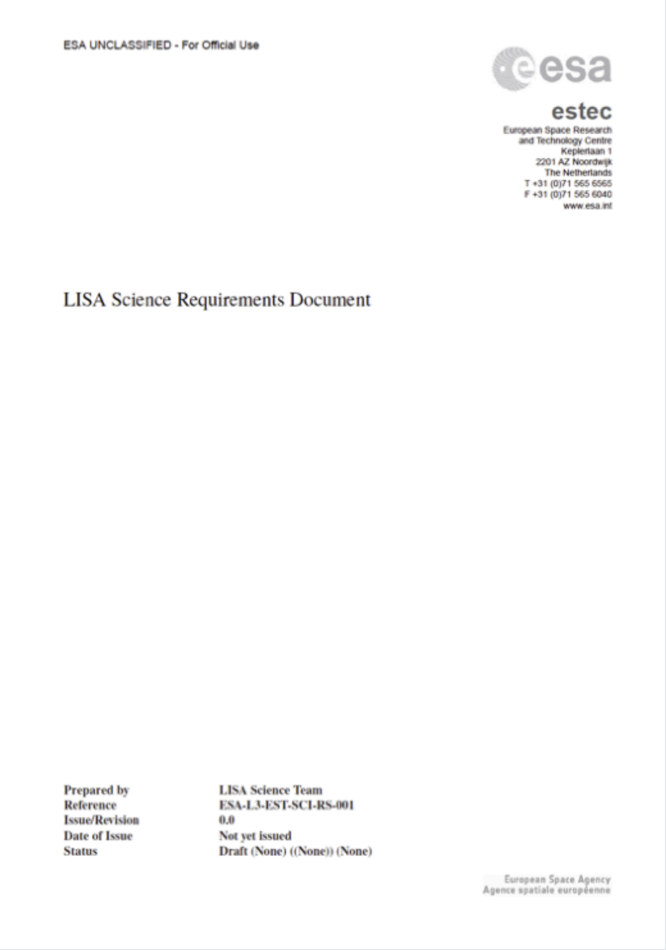
- Stabilité température
- Stabilité plateforme
- Type de matériaux
- Bruit de la photodiode
- etc…

CBE : Current Best Estimate

Modèle quasi-analytique de l'instrument

Allocation

Requirements Scientifiques



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LISA Science Requirements Document

Prepared by	LISA Science Team
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Date of Issue	Not yet issued
Status	Draft (None) ((None)) (None)

European Space Agency
Agence spatiale européenne

October 2020 **Release 1.4 beta - New models/No allocation**

- Stray light main contributors in all IFO's
- SC & MOSA angular jitters coupling to the TM force noise due to SC gravitational imbalance

November 2020 **Data Format & Model sent to primes for interfacing with the performance model**

December 2020 **New « TDI » Performance Model Release (2.0)**

- New TDI 2.0 top level representation
- OMS noises & Test Mass acceleration in TDI variables
- New long arm Tilt-To-Lenght coupling with calibration & drift
- New Laser residuals & Clock residuals and calibration analytical models

January 2020 **Update Release 2.0 with « Consortium » allocation tree**

Produce « primes » version(s) of the Performance Model

Spring 2021 **New performance Model Release (2.1)**

- TDI consolidation
- TDI XY
- DWS & Phasemeter
- … [TBD]

Structure

INPUTS

Multiple versions
Nominal/Cold/Hot

Constants

Parameters

Noise Sources

Transfer Functions

MODELS

LISA
Performance
Model
*[Sum square
Linear Sum
Math Formula]*

- Derived Parameters
- Derived Noises
- Derived Transfer Functions
- Reference Noises

PRODUCTS

- Performance Tree
- Noise Power Spectrum Density
  - CBE breakdown
  - Allocation vs CBE

Structure: Test Mass IFO Electronic Noise

INPUTS

'Noises' :

- **TMI equivalent input current noise density of the electronic**
  description : Equivalent input current noise density of the ele
  type : Source Noise
  varname : s_I_seg_el_tmi

'Parameters' :

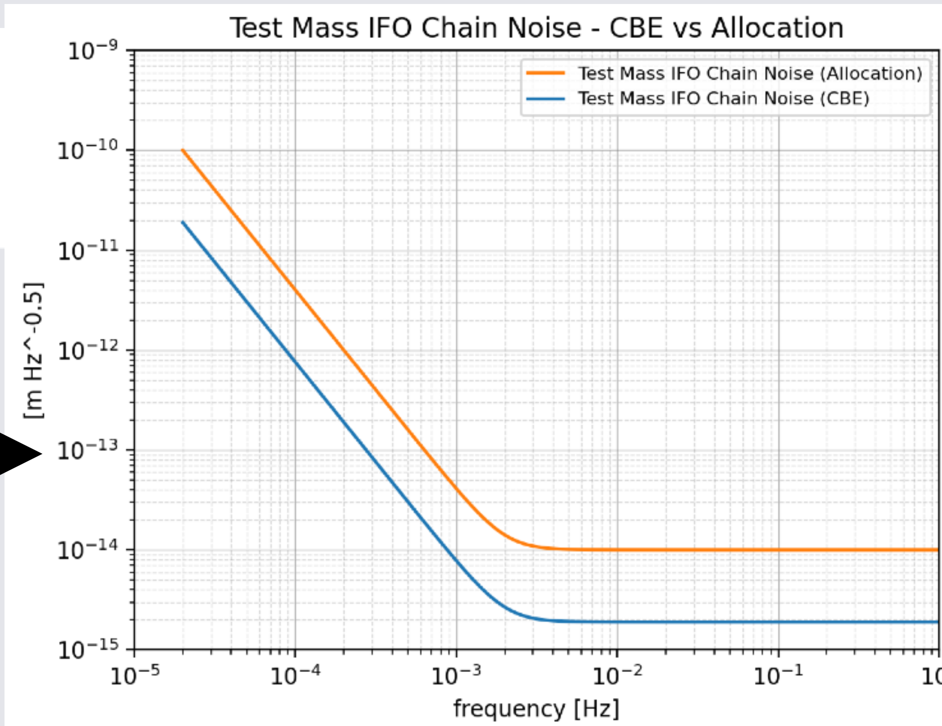
- **lambda** = 1.064e-06 [[m]]
  description : Laser wavelength
  documentation :
- **N_pd_TM** = 4.0 [[]]
  description : Number of photorecievers for the TM IFO
  documentation :
- **N_seg_TM** = 4.0 [[]]
  description : Number of segments per photoreceiver in the TM i
  documentation :
- **eta_car** = 0.81 [[]]
  description : RX power in main carrier signal
  documentation :
- **R_pd** = 0.69 [[A W^(-1)]]
  description : Responsivity of InGaAs
  documentation :
- **HE_loc** = 0.82 [[]]
  description : Heterodyne Efficiency in a Local IFO
  documentation :
- **P_LO_TM** = 5e-06 [[W]]
  description : Local Oscillator power at the photo-receiver in t
  documentation : [Optical Power budget, LISA-UKOB-INST-RP-001]
- **P_TX_TM** = 0.001 [[W]]
  description : TX-beam fraction impinging at the photo-receiver
  documentation : [Optical Power budget, LISA-UKOB-INST-RP-001]

MODEL

Derived Noise

$$\tilde{s}_{\mathrm{TMI,Chain}} = \frac{\lambda}{2\pi} \frac{\tilde{s}_{I_{\mathrm{seg,el}}} \sqrt{N_{\mathrm{Seg,Loc}} \cdot N_{\mathrm{PD,Loc}}}}{R_{\mathrm{PD}} \epsilon_{\mathrm{Carr}} \sqrt{2\eta_{\mathrm{het,Loc}} P_{\mathrm{LO,TM}} P_{\mathrm{TX,TM}}}}$$

PRODUCTS



Structure: Long Arm Waveplates Thermoelastic

INPUTS

'Noises' :

- **OB Temperature Stability** [K^2 Hz^-1]
  description : This applies to the entire OB basepl
  optical path.
  type : Source Noise
  varname : S_T_OB

'constants' :

- **FOM_Qtz** = 6.1e-07 [[K^(-1)]]
  description : Thermal OPD change of Crystal Quart

'Parameters' :

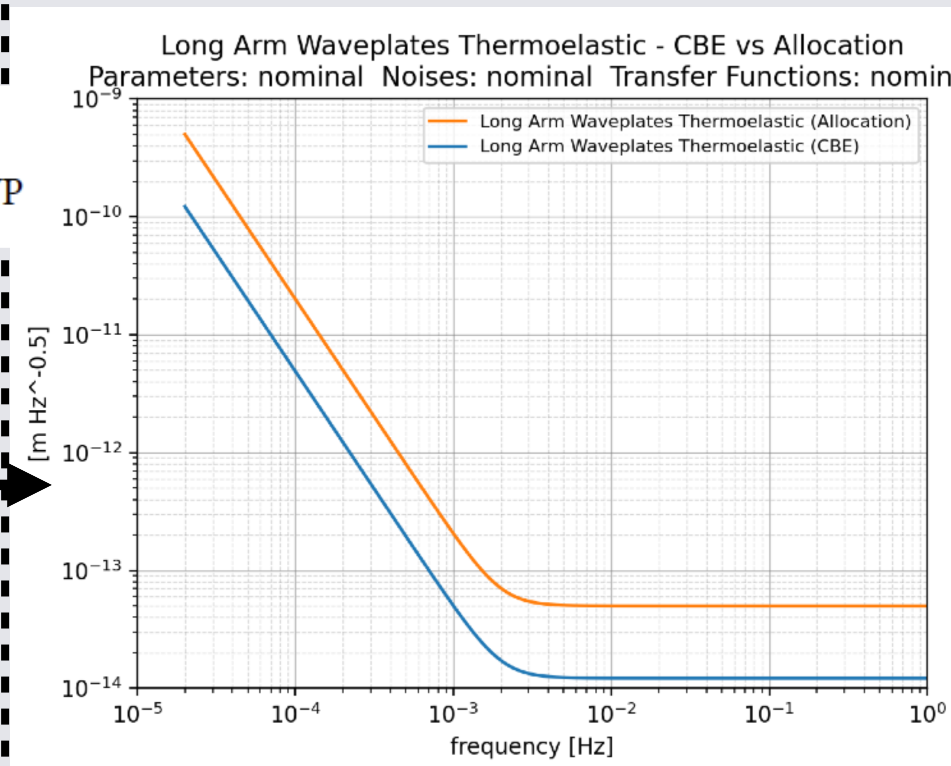
- **D_wp** = 0.001 [[m]]
  description : Thickness of a waveplate
  documentation :
- **N_WP_LA** = 2.0 []
  description : Number of differential transmission
  arm interferometer.
  documentation :

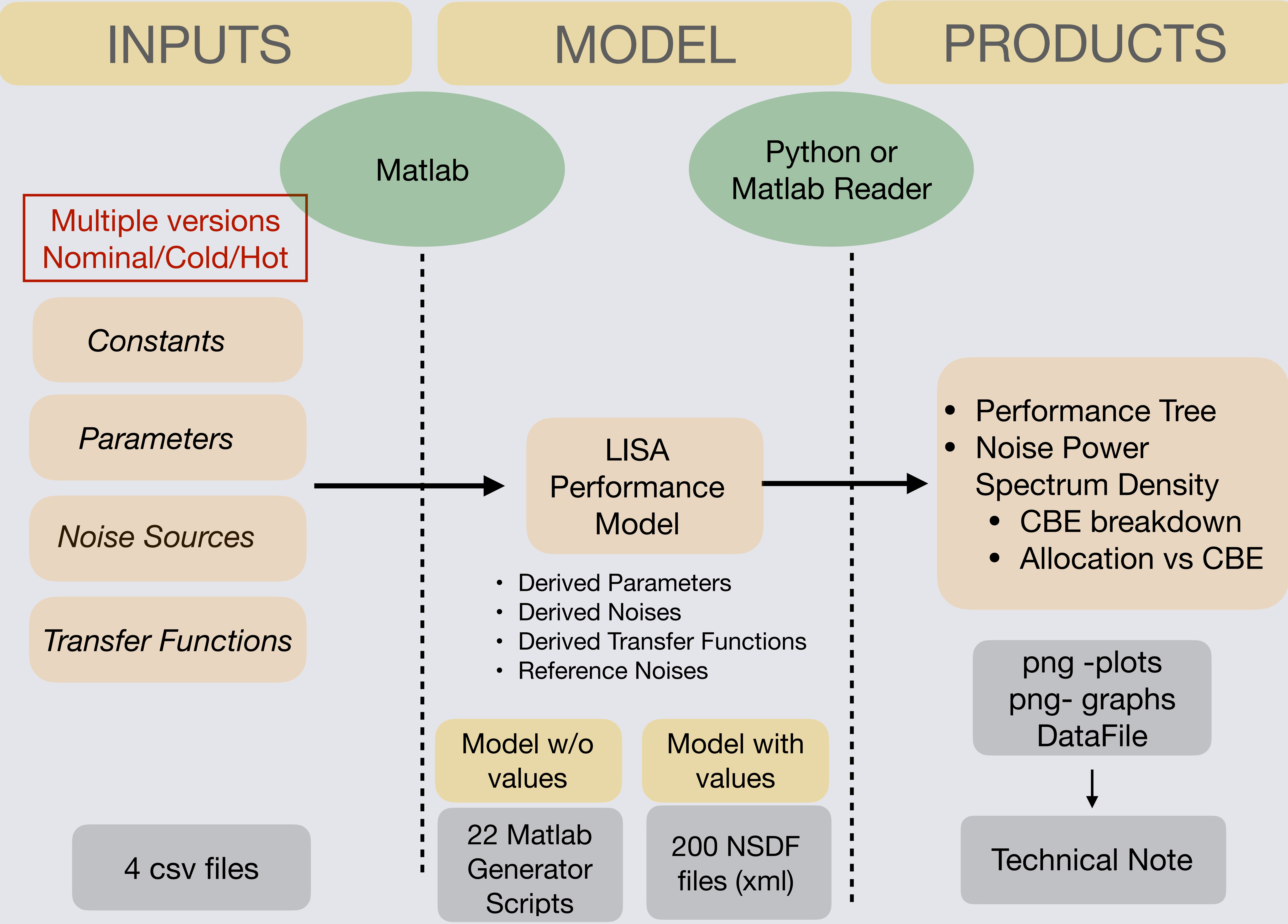
MODEL

Derived Noise

$$\tilde{s}_{\text{Therm,LA,WP}} = \text{FOM}_{\text{Qtz}} \cdot \tilde{s}_{T_{\text{OB}}} \cdot N_{\text{WP,LA}} \cdot D_{\text{WP}}$$

PRODUCTS




INPUTS
MODEL
PRODUCTS
Matlab
Python or Matlab Reader
Multiple versions Nominal/Cold/Hot
Constants
Parameters
Noise Sources
Transfer Functions
LISA Performance Model
• Performance Tree
• Noise Power Spectrum Density
• CBE breakdown
• Allocation vs CBE
• Derived Parameters
• Derived Noises
• Derived Transfer Functions
• Reference Noises
Model w/o values
Model with values
png -plots png- graphs DataFile
4 csv files
22 Matlab Generator Scripts
200 NSDF files (xml)
Technical Note

Parameters - CSV files

LISA_PerfModel_Parameters

name	description	unit	documentation	allocation	nominal	cold	hot
lambda	Laser wavelength	[m]		1.064E-06	1.064E-06	1.064E-06	
L_arm	Arm Length	[m]		2500000000	2500000000	2500000000	
D_tel	Telescope Diameter (clear aperture)	[m]		0.30000000000000000	0.30000000000000000	0.30000000000000000	0
P_L	Laser Power from MOPA	[W]		2	2	2	
R12	Vector from TM1 to Tm2	[m]		0.42000000000000000	0.42000000000000000	0.42000000000000000	0
L_MSS	Effective length of MSS	[m]	[LISA-ADSF-INS	0.30000000000000000	0.30000000000000000	0.30000000000000000	0
R_pd	Responsivity of InGaAs	[A W^(-1)]		0.69000000000000000	0.69000000000000000	0.69000000000000000	0
D_pd	QPD Diameter	[m]		0.001	0.001	0.001	
TMsize	TestMass size	[m]		0.046000000000000000	0.046000000000000000	0.046000000000000000	0.0
TMmass	TestMass mass	[kg]		1.9300000000000000	1.9300000000000000	1.9300000000000000	
VacuumPressure	Vacuum Enclosure Pressure	[Pa]		1E-06	1E-06	1E-06	
T_GRS	GRS Temperature	[K]		293	293	293	
alphanoise	Noise amplification factor	[]		13	13	13	
DCX_DX_GRS1	Cx to TM derivative with respect to x for GRS1	[F m^(-1)]		2.91385358345786E-10	2.91385358345786E-10	2.91385358345786E-10	2.
DCXH_DX_GRS1	Cx to EH derivative with respect to x for GRS1	[F m^(-1)]		-6.96752395467991E-11	-6.96752395467991E-11	-6.96752395467991E-11	-6.
CEL_GRS1	Total TM to electrodes capacitance for GRS1	[F]		1.53958921869247E-11	1.53958921869247E-11	1.53958921869247E-11	1.
CTOT	Total TM capacitance	[F]		3.42E-11	3.42E-11	3.42E-11	
D2CTOT_DX2_GRS1	Total TM to ground capacitance second derivative with respect to x^2 for (	[F m^(-2)]		1.36515242625754E-06	1.36515242625754E-06	1.36515242625754E-06	1.
R_star	Electrodes Effective Armlength between x-face electrodes	[m]		0.033000000000000000	0.033000000000000000	0.033000000000000000	0.0
eta_car	RX power in main carrier signal	[]		0.81000000000000000	0.81000000000000000	0.81000000000000000	0
HE_la	Heterodyne Efficiency in the Long Arm IFO	[]		0.75	0.75	0.75	
HE_loc	Heterodyne Efficiency in a Local IFO	[]		0.82000000000000000	0.82000000000000000	0.82000000000000000	0
eta_fibre	Optical efficiency of the OB feed fibres (insertion loss of 0.3 dB)	[]		0.93300000000000000	0.93300000000000000	0.93300000000000000	0
eta_fios	Optical efficiency of the OB FIOS (loss at FIOS PBS + output polariser	[]		0.95693838400000000	0.95693838400000000	0.95693838400000000	0
eta_OB_TX	Optical Efficiency of the OB TX Path	[]		0.941417218	0.941417218	0.941417218	
eta_Tel_TX	Optical Efficiency of the Telscope TX Path	[]		0.94715284900000000	0.94715284900000000	0.94715284900000000	0
alpha_fact	Optimum transmission factor for gaussian beam through two apertures.	[]		0.40726436345010700	0.40726436345010700	0.40726436345010700	0
eta_Tel_RX	Optical Efficiency of the Telscope RX Path	[]		0.81366680900000000	0.81366680900000000	0.81366680900000000	0
eta_OB_RX	Optical Efficiency of the OB RX Path up to Long Arm QPDs	[]		0.77987120200000000	0.77987120200000000	0.77987120200000000	0

Parameters - CSV files

LISA_PerfModel_Parameters

D_ob	Characteristic scale of the OB for path stability	[m]		1	1
D_ob_grs	Dimension between GRS and OB	[m]		0.25	0.25
D_path	Possible path mismatch error on OB	[m]		1	1
D_comp_tol	Tolerence on the thickness of a Beam Splitter	[m]		0.0001	0.0001
D_mir	One Mirror Thickness	[m]		0.008	0.008
D_win	Thickness of the Optical Window on the GRS	[m]		0.00635	0.00635
D_wp	Thickness of a waveplate	[m]		0.001	0.001
D_paam	Offset from PAAM mount to reference mirror	[m]		0.007	0.007
C_RX	Total Rx TTL Coupling Factor	[m rad^(-1)]		0.005	0.005
C_TX	Total Tx TTL Coupling Factor	[m rad^(-1)]		0.004	0.004
C_TM	Total TM TTL Coupling Factor	[m rad^(-1)]		4E-05	4E-05
TTL_Cal	TTL Calibration Accuracy	[]		1	1
los	Alignment tolernace between TM Normal and RX Direction	[rad]		7E-05	7E-05
CTE_MSS_OBTel	Coefficient of thermal expansion of the MSS averaged over the structural materi	[K^(-1)]		9E-06	9E-06
dx_sc_pp	Residual SC Translation Per Axis. Infer from LPF o1 measurement	[m]		1E-08	1E-08
dL	Expected Ranging Bias	m		1	0.1
L_dot	Average SC speed	m s^(-1)		8	8
kF	Anti-aliasing filter property	Hz^-2	This is an approximation shape at	3.38.*f.^2	3.38.*f.^2
fhet	Maximal beatnote frequency	Hz		25000000	25000000
fmod	Modulation frequency	Hz		2400000000	2400000000
P_incidentTM	laser power incident on the TM	W		0.001	0.001
T_OB	Optical Bench Temperature	K		293	293
D_hole	laser hole diameter on the EH +X face	m		0.006	0.006
epsilon	TM reflectivity			1	1
dg_dT_mean	Electro-Housing mean temperature fluctuation coupling coefficient to differentia	m s^-2 K^-	Measured at the end of LPF missic	1E-12	1E-12
dg_dDT	Electro-Housing temperature gradient fluctuation coupling coefficient to differen	m s^-2 K^-1		2E-11	2E-11
omegasquarexx	Test Mass x-axis stiffness	s^-2		-8E-07	-8E-07
omegasquareGRSxx	Test Mass x-axis stiffness due to GRS	s^-2		-7E-07	-7E-07
omegaxysquare	TestMass y to x cross-stiffness	s^-2		-6E-08	-6E-08
omegaxzsquare	TestMass z to x cross-stiffness	s^-2		-6E-08	-6E-08
omegaxphisquare	TestMass phi to x cross-stiffness	m/s^2		-1.012E-09	-1.012E-09
omegaxetasquare	TestMass eta to x cross-stiffness	m/s^2		-4.6E-10	-4.6E-10
omegaxthetasquare	TestMass theta to x cross-stiffness	m/s^2		-4.6E-10	-4.6E-10

Noise Sources - CSV files

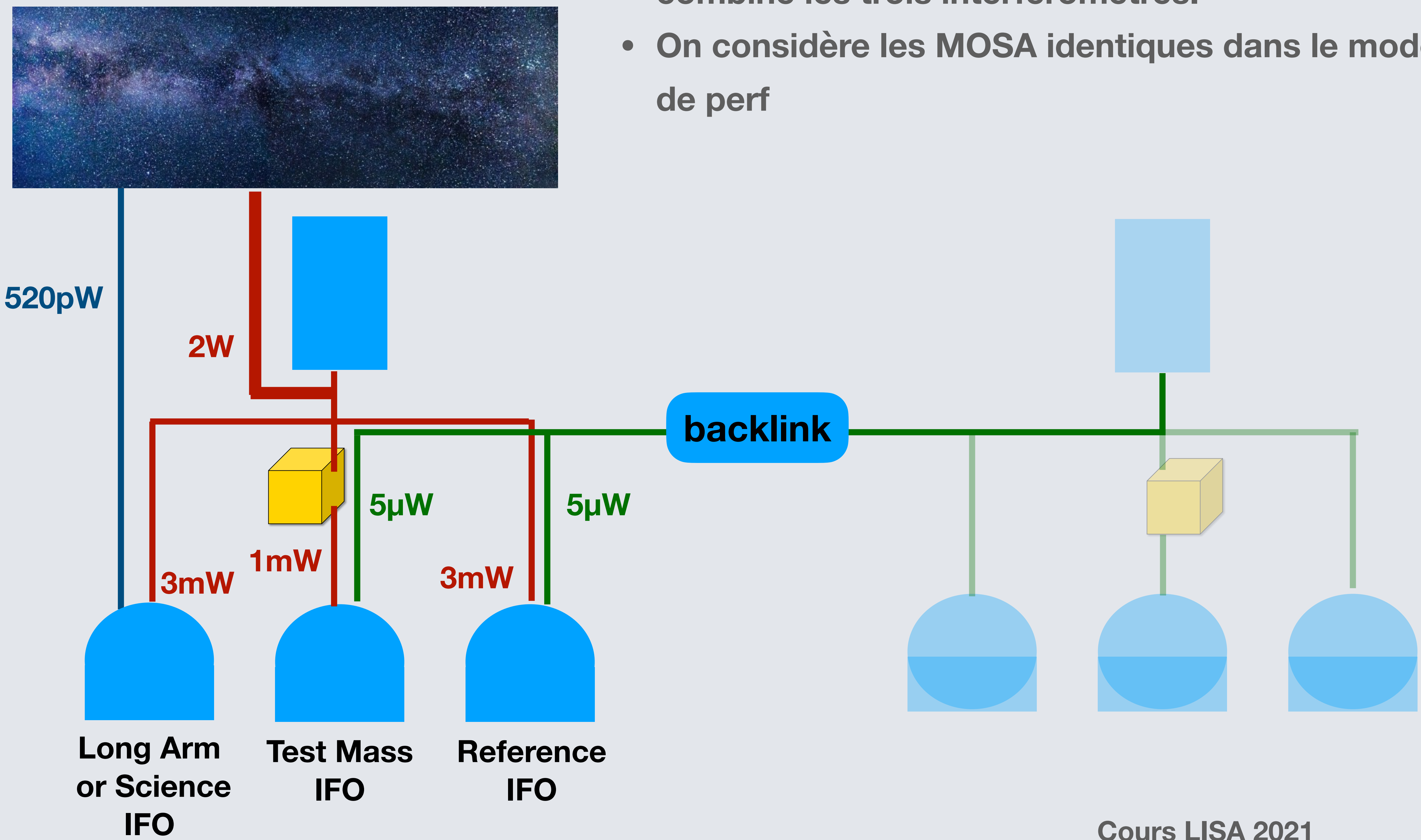
LISA_PerfModel_NoiseInputs

name	type	varname	description	documentation	unit	allocation
TMI equivalent input current noise density of the electr	Source Nois	s_I_seg_el_tmi	Equivalent input curr	Value from GSFC measuren	A Hz^-0.5	3.5E-12.*sqrt(1+(2E-3./f).^4)
LA equivalent input current noise density of the electro	Source Nois	s_I_seg_el_LA	Equivalent input curr	Value from GSFC measuren	A Hz^-0.5	3.5E-12.*sqrt(1+(2E-3./f).^4)
Long Arm PMS	Source Nois	longArmPmsNoise	Apparent displaceme	Currently these are both top	m Hz^-0.5	2E-12.*sqrt(1+(2E-3./f).^4)
Test Mass IFO PMS	Source Nois	tmiPmsNoise	Apparent displaceme	For now these are both top-	m Hz^-0.5	1E-12.*sqrt(1+(2E-3./f).^4)
Laser Frequency Stability	Source Nois	laserFreqStab	The required laser fre	SCI-F ESA ESA-LISA-EST-I	Hz Hz^-0.5	30.*sqrt(1+(2E-3./f).^4)
Reference PMS	Source Nois	refPmsNoise	Apparent displaceme	For now these are both top-	m Hz^-0.5	1E-12.*sqrt(1+(2E-3./f).^4)
REF equivalent input current noise density of the electr	Source Nois	s_I_seg_el_ref	Equivalent input curr	Value from GSFC measuren	A Hz^-0.5	3.5E-12.*sqrt(1+(2E-3./f).^4)
MSS Temperature Stability	Source Nois	S_T_MSS	This applies to the e	This applies to the elements	K^2 Hz^-1	(10e-6).^2.*(1+(2e-3./f).^4)
OB Temperature Stability	Source Nois	S_T_OB	This applies to the e	Technically we could allow	K^2 Hz^-1	(10e-6).^2.*(1+(2e-3./f).^4)
Telescope Temperature Stability	Source Nois	S_T_Tel	This applies to the entire telescope.		K^2 Hz^-1	(10e-6).^2.*(1+(2e-3./f).^4)
Test Mass temperature stability	Source Nois	S_T_TM	Required stability of	Since this effects only the C	K^2 Hz^-1	(0.25E-6).^2.*(1+(2E-3./f).^4)
OW temperature stability	Source Nois	S_T_OW	This applies to the O	Note that this could be mer	K^2 Hz^-1	(10e-6).^2.*(1+(2e-3./f).^4)
Fibre Temperature Stability	Source Nois	S_T_fibre	Expected fibre temp	eLISA-AEI-PRDS-2019-04-1	K^2 Hz^-1	(1.4e-3).^2.*(1+(2e-3./f).^4)
Unmodelled Local Oscillator TTL	Source Nois	thermoRefTTL	Allow for in-band thermla jitter of the local oscilla		m Hz^-0.5	0.1e-12.*sqrt(1+(2E-3./f).^4)
mean temperature fluctuations of the GRS head	Source Nois	S_T_GRS	Assumed levels of m	Currently an allocation only	K^2 Hz^-1	(43e-6).^2 .* (100e-6./f).^7 + (5e-6).^2
temperature difference fluctuations aross the Electrod	Source Nois	S_DT_EH	Assumed levels of th	Currently an allocation only	K^2 Hz^-1	(1e-5).^2 .* (1e-4./f).^4 + (5e-6).^2
mean temperature fluctuations as seen by the TM thro	Source Nois	S_T_TM_VIEW	Assumed levels of th	Currently an allocation only	K^2 Hz^-1	(1e-3).^2 .* (1e-4./f).^3 + (5e-6).^2
Test Mass DWS Noise	Source Nois	s_DWS_Loc	Local or Test Mass D	Currently an allocation only	rad Hz^-0.5	5E-9.*sqrt(1+(0.7E-3./f).^4)
Jitter y TM wrt MOSA	Source Nois	Sy_tm	TestMass Jitter along y with respect to MOSA		m^2 Hz^-1	(5e-9).^2 .* (1 + (1e-3./f)) .* (1 + (f/8e-3).^4) ./ (1 + (f./8e
Jitter z TM wrt MOSA	Source Nois	Sz_tm	TestMass Jitter along	Currently an allocation only	m^2 Hz^-1	(5e-9).^2 .* (1 + (1e-3./f)) .* (1 + (f/8e-3).^4) ./ (1 + (f./8e
Jitter x TM wrt MOSA	Source Nois	Sx_tm	TestMass Jitter along	Currently an allocation only	m^2 Hz^-1	(0.95e-9).^2 .* (1 + (2e-4./f).^2) .* (1 + (f/8e-3).^4) ./ (1
Jitter x TM wrt GRS	Source Nois	S_x_GRS	GRS-OB baseline de	Currently an allocation only	m^2 Hz^-1	(0.3e-9).^2 .* (1 + (1.5e-3./f).^2)
Jitter phi TM wrt MOSA	Source Nois	S_phi_grs	Tm phi angular jitter	Currently an allocation only	rad^2 Hz^-1	(10e-9).^2 .* (1 + (5e-4./f).^4 + (2e-3./f).^2)
Jitter eta TM wrt MOSA	Source Nois	S_eta_grs	TM eta angular jitter	Currently an allocation only	rad^2 Hz^-1	(10e-9).^2 .* (1 + (5e-4./f).^4 + (2e-3./f).^2)
Jitter theta TM wrt MOSA	Source Nois	S_theta_grs	TestMass Jitter along	Currently an allocation only	rad^2 Hz^-1	(200e-9).^2 .* (1 + (1e-3./f))
Jitter angular S/C wrt IS.	Source Nois	SCang_SC_IS	Residual SC angular	Currently an allocation only	rad Hz^-0.5	10E-9.*sqrt(1+(0.8E-3./f).^4)
Jitter phi MOSA wrt IS.	Source Nois	MOSA_phi_IS	Residual MOSA jitter	Currently an allocation only	rad Hz^-0.5	10E-9.*sqrt(1+(0.8E-3./f).^4)
Jitter eta MOSA wrt IS.	Source Nois	MOSA_eta_IS	Residual MOSA jitter	Currently an allocation only	rad Hz^-0.5	1E-9.*sqrt(1+(0.8E-3./f).^4)
Jitter phi MOSA wrt S/C	Source Nois	sphi_MOSA_SC	Residual MOSA Jitte	Currently an allocation only	rad Hz^-0.5	10E-9.*sqrt(1+(0.8E-3./f).^4)
Jitter Uncontrolled MOSA wrt S/C	Source Nois	su_MOSA_SC	Residual uncontrolle	Currently an allocation only	rad Hz^-0.5	10E-9.*sqrt(1+(0.5E-3./f).^4)

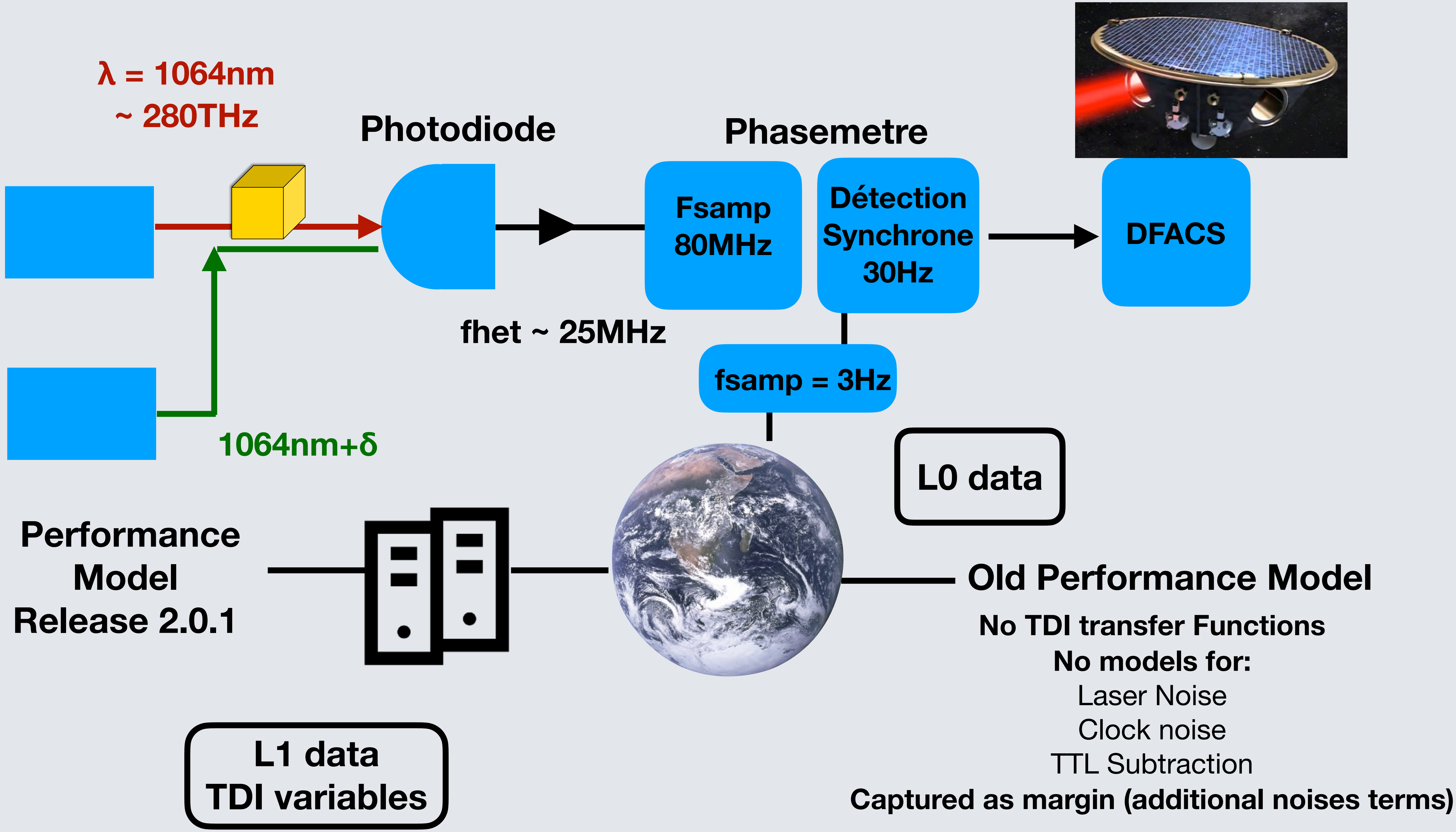
II/ Rappels sur la mesure

Mesures Généralités

- Reconstruire une mesure Test Mass/Test Mass, on combine les trois interféromètres.
- On considère les MOSA identiques dans le modele de perf



Fréquences

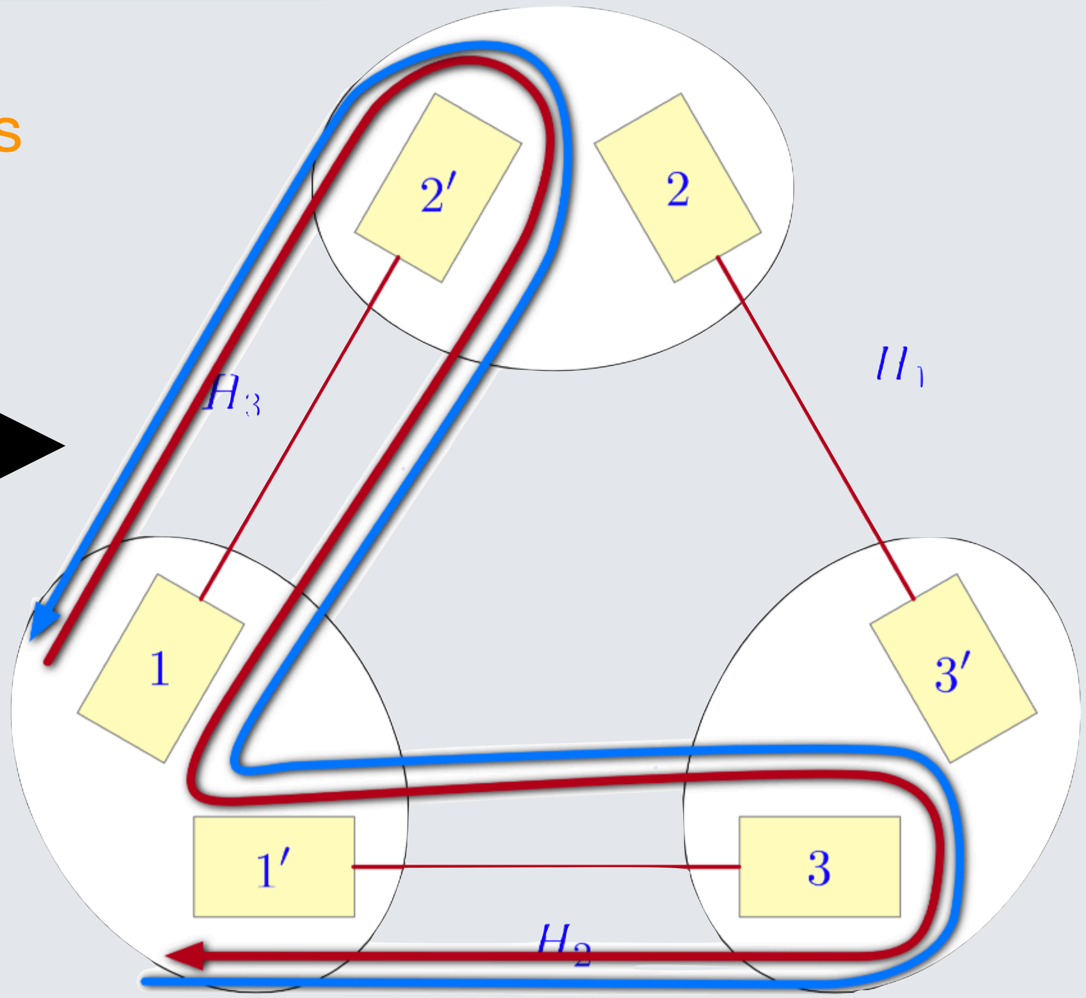


λ = 1064nm
~ 280THz
Photodiode
Phasemetre
Fsamp
80MHz
Détection
Synchrone
30Hz
DFACS
fhet ~ 25MHz
fsamp = 3Hz
1064nm+δ
L0 data
Performance
Model
Release 2.0.1
Old Performance Model
No TDI transfer Functions
No models for:
Laser Noise
Clock noise
TTL Subtraction
Captured as margin (additional noises terms)
L1 data
TDI variables

Time Delay Interferometry

Combinaison d'une mesure long bras et des mesures test masse et référence des bancs 1 et 3. Equivalent mesure test mass/test mass

$$\begin{aligned} X_{1.5} &= \eta_1' + \mathcal{D}_{2'}\eta_3 + \mathcal{D}_{2'}\mathcal{D}_2\eta_1 + \mathcal{D}_{2'}\mathcal{D}_2\mathcal{D}_3\eta_2' \\ &\quad -\eta_1 - \mathcal{D}_3\eta_2' - \mathcal{D}_3\mathcal{D}_{3'}\eta_1' - \mathcal{D}_3\mathcal{D}_{3'}\mathcal{D}_{2'}\eta_3 \end{aligned}$$



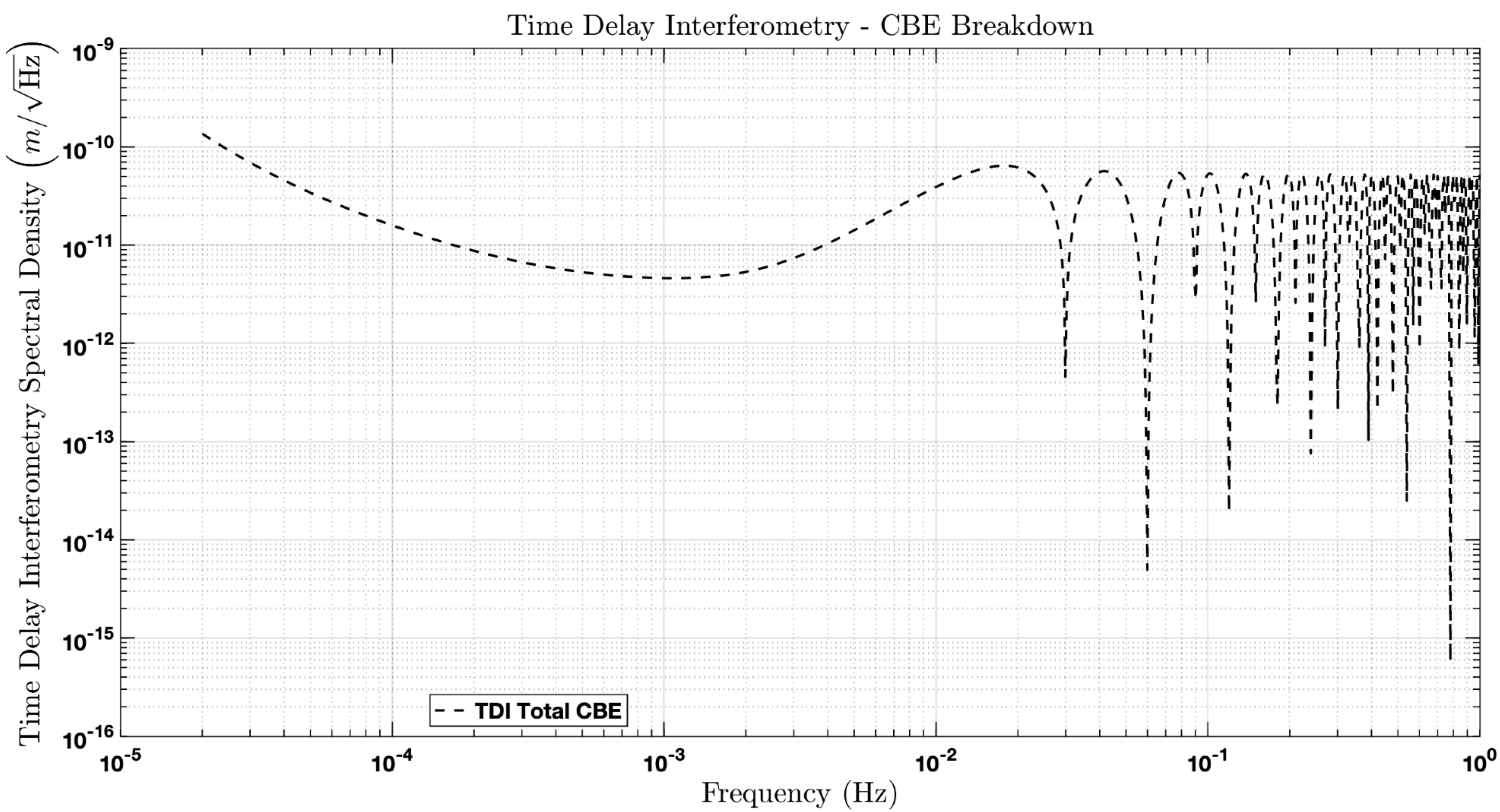
opérateurs de retard

$$PSD_{X_{1.5}} = 16\sin^2(\omega L)(S_N + (3+\cos(2\omega L))S_\delta)$$

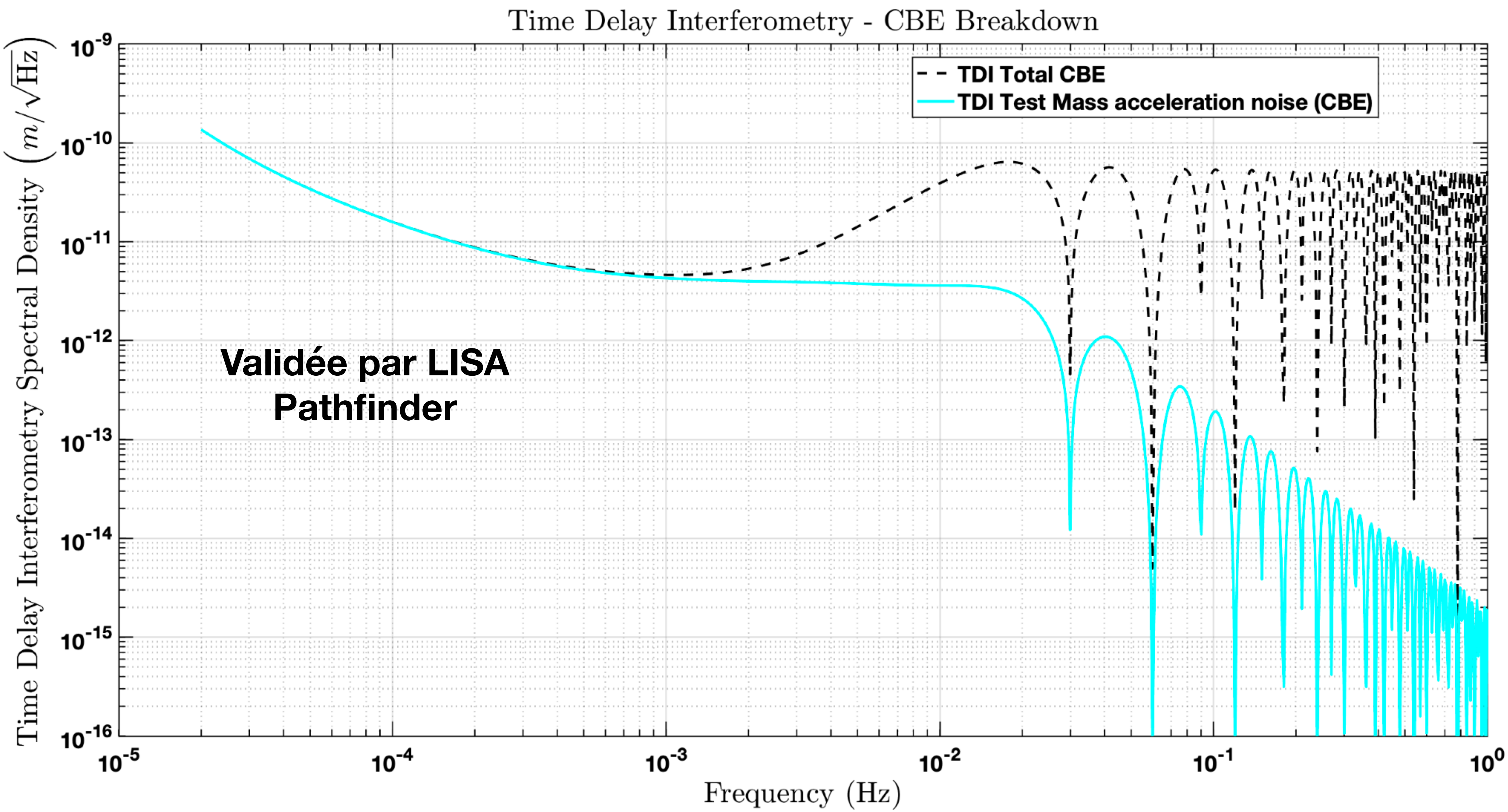
Displacement noise

Acceleration Noise

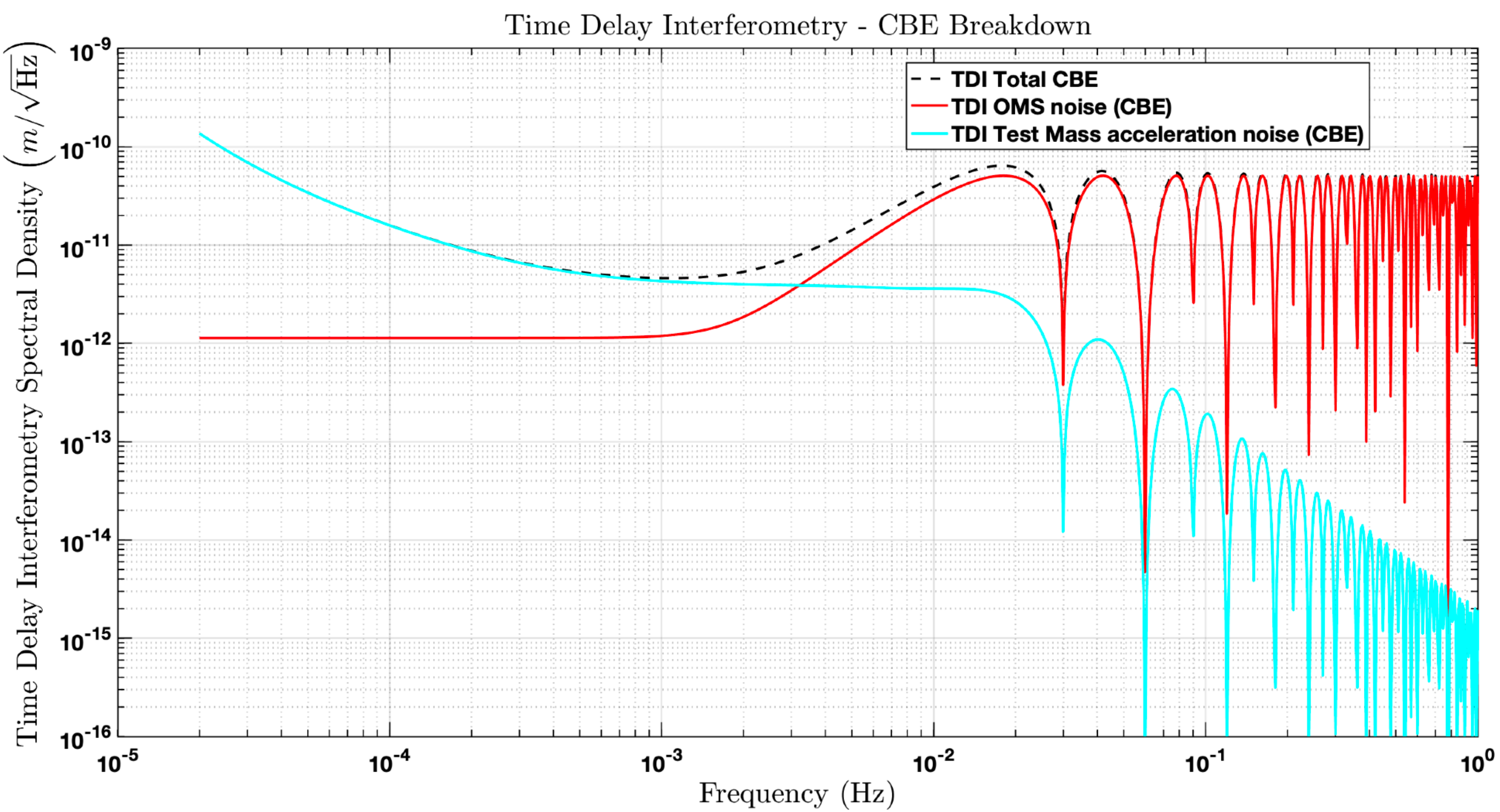
Budget De Bruit



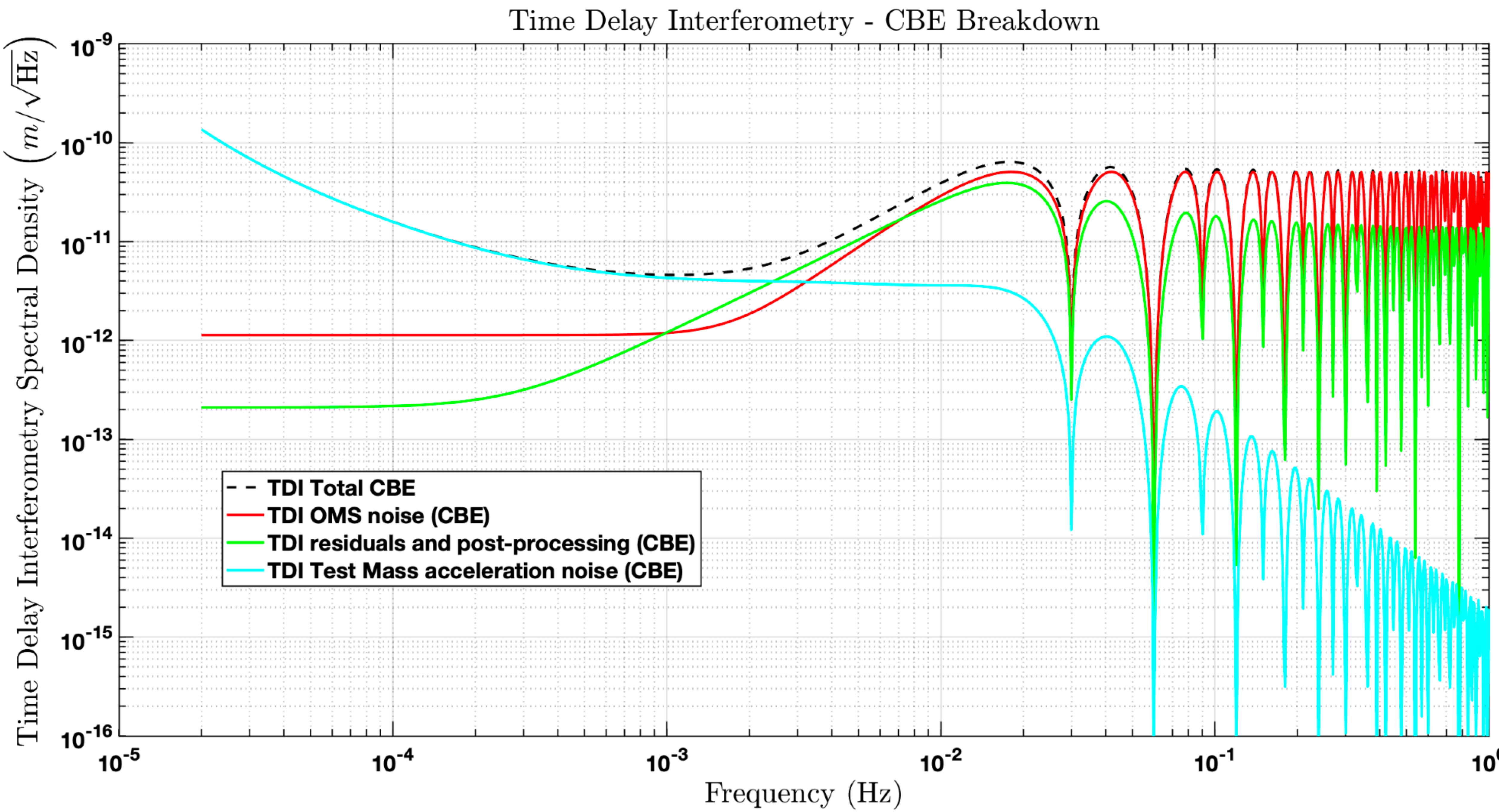
Budget De Bruit



Budget DE BRUIT



Budget De Bruit



III/ Quelques Bruits

Optical Metrology System

- Shot Noise
- Backlink stray light
- Telescope Thermo-mechanical noise

OMS : Shot Noise

- Plus importante source de bruit OMS ~ 5pm/sqrt(Hz)
- Limite « dur » par design - telescope/optique

Bruit en phase [rad/√Hz]
LISA band (20μHz - 1Hz)

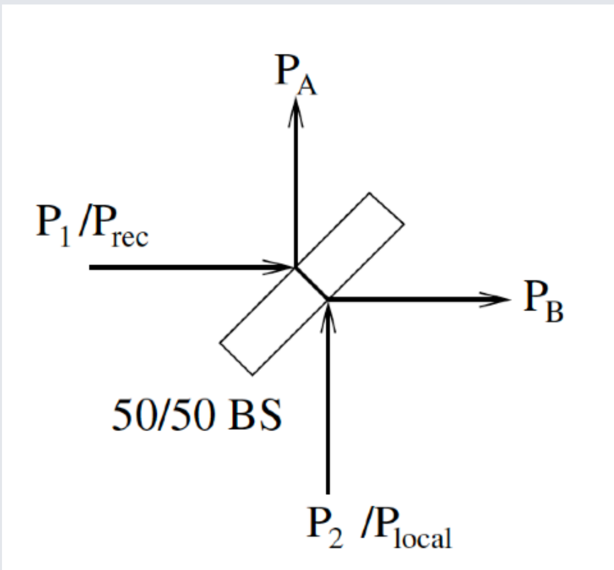
Bruit à la fréquence hétérodyne [/√Hz]

$$\widetilde{\varphi} = \frac{1}{\mathrm{C/N_0}} = \frac{\widetilde{x}}{x_{\mathrm{signal,rms}}},$$

Amplitude de la porteuse à la fréquence hétérodyne fhet (25MHz)

Dérivation des bruits OMS: électronique, RIN, shot noise, phasemètre.

OMS : Shot Noise



Signal Scientifique

$$P_{A/B} = \frac{1}{2}\left(\overbrace{P_1 + P_2}^{\text{average}} \pm \underbrace{\overbrace{2\sqrt{\eta_{\text{het}} P_1 P_2}}^{\text{amplitude}}\,\overbrace{\sin\left(2\pi f_{\text{het}} t + \varphi\right)}^{\text{time dependence}}}_{\text{AC term (heterodyne beat note)}}\right)$$

P1 = 3mW
P2 = 520pW

Heterodyne efficiency

$$P_{sig,rms} = \frac{P_{sig}}{\sqrt{2}} = \sqrt{2}\sqrt{\eta_{het} P_1 P_2}$$

$$I_{sig,rms} = R_{pd} P_{sig,rms}$$

R_{pd} **Responsivity of InGaAs**

OMS : Shot Noise

$$\tilde{I}_{shot} = \sqrt{2 q_e R_{pd} (P_1 + P_2)}$$

$$I_{sig,rms} = R_{pd} \sqrt{2} \sqrt{\eta_{het} P_1 P_2}$$

$$\tilde{\phi}_{\text{tot,shot}} = \frac{\sqrt{q_e (P_1 + P_2)}}{\sqrt{R_{pd} \eta_{het} P_1 P_2}}.$$

Conversion factor: phase to displacement

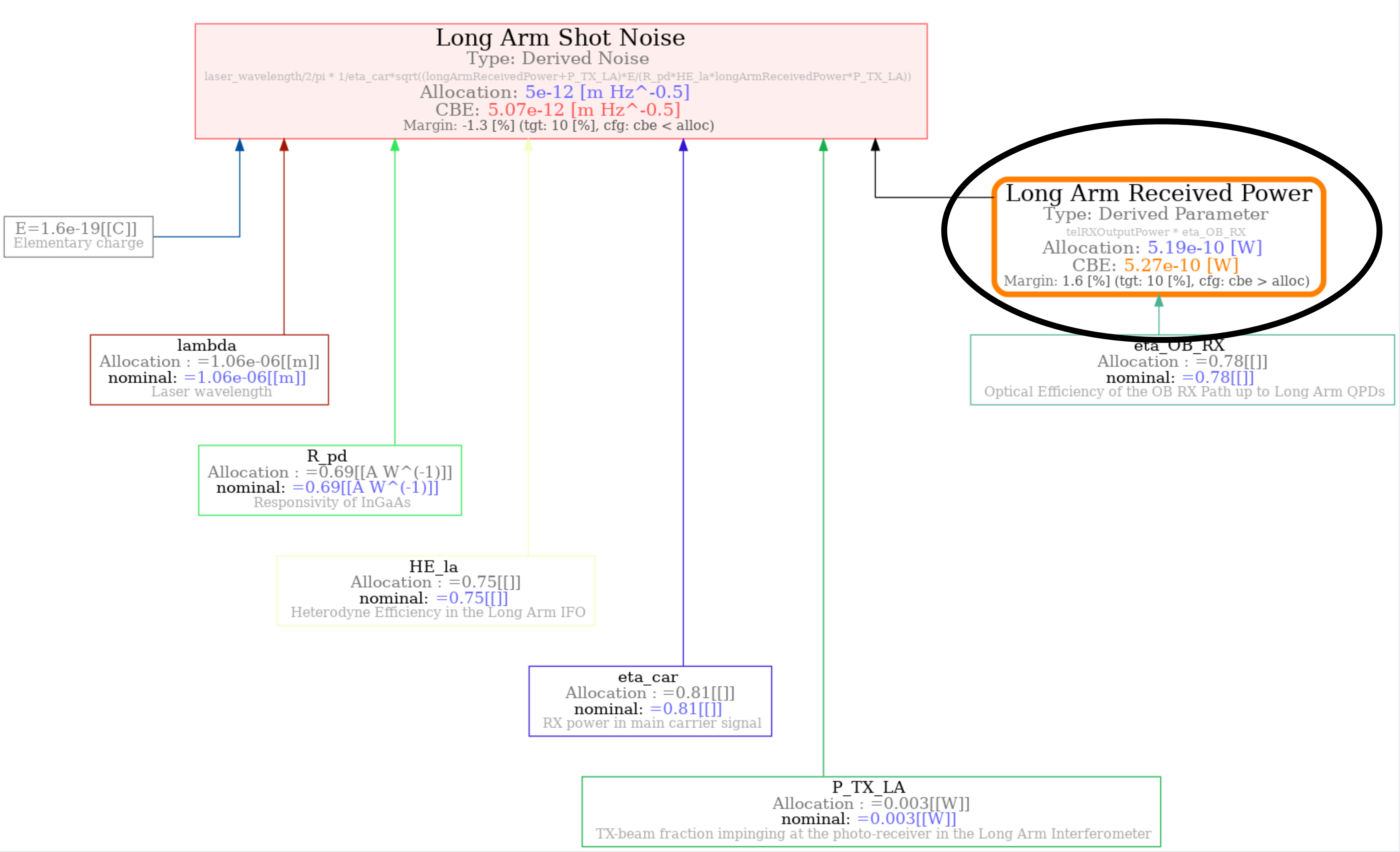
500pW **3mW**

$$\tilde{s}_{\text{LA, shot}} = \frac{\lambda \sqrt{q_e (P_{\text{Rec}} + P_{\text{TX,LA}})}}{2\pi \epsilon_{\text{Carr}} \sqrt{R_{\text{PD}} \eta_{\text{het,LA}} P_{\text{Rec}} P_{\text{TX,LA}}}}$$

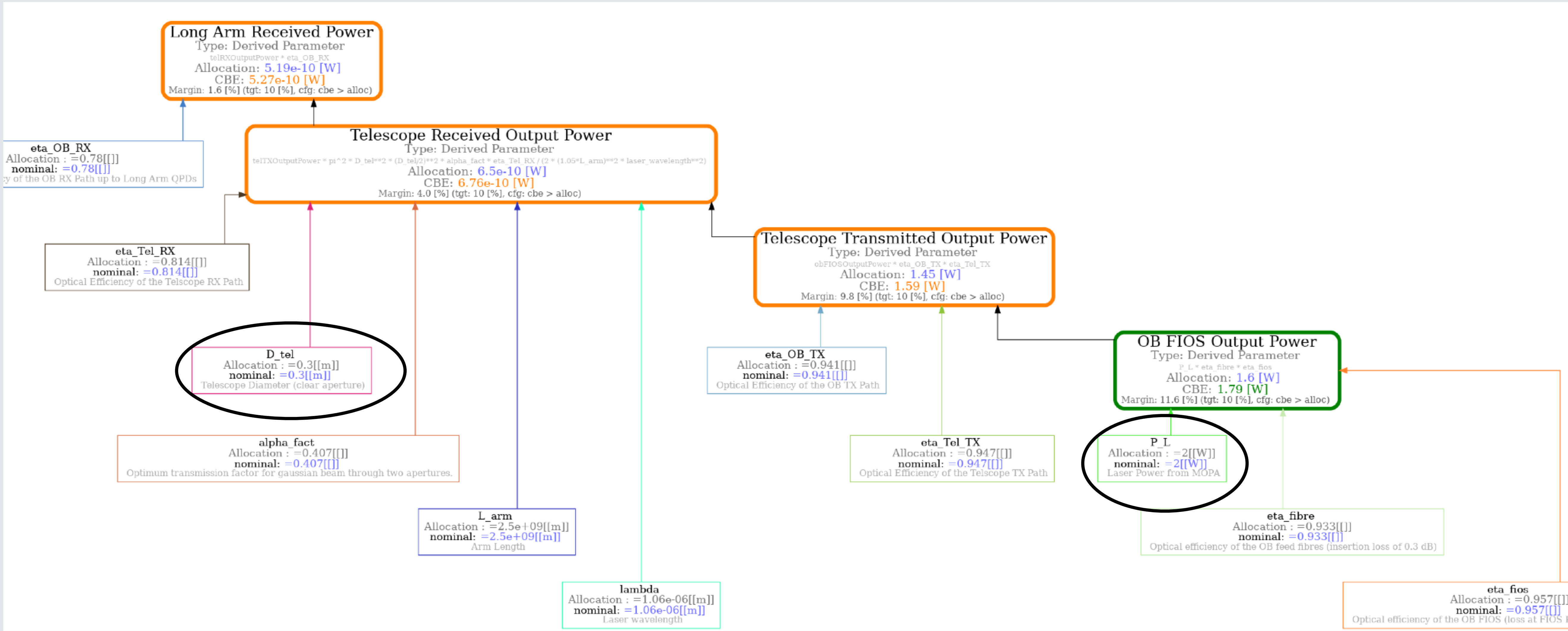
Shot noise in the performance model: 5pm/√Hz

Carrier Efficiency: 0.8

OMS : Shot Noise

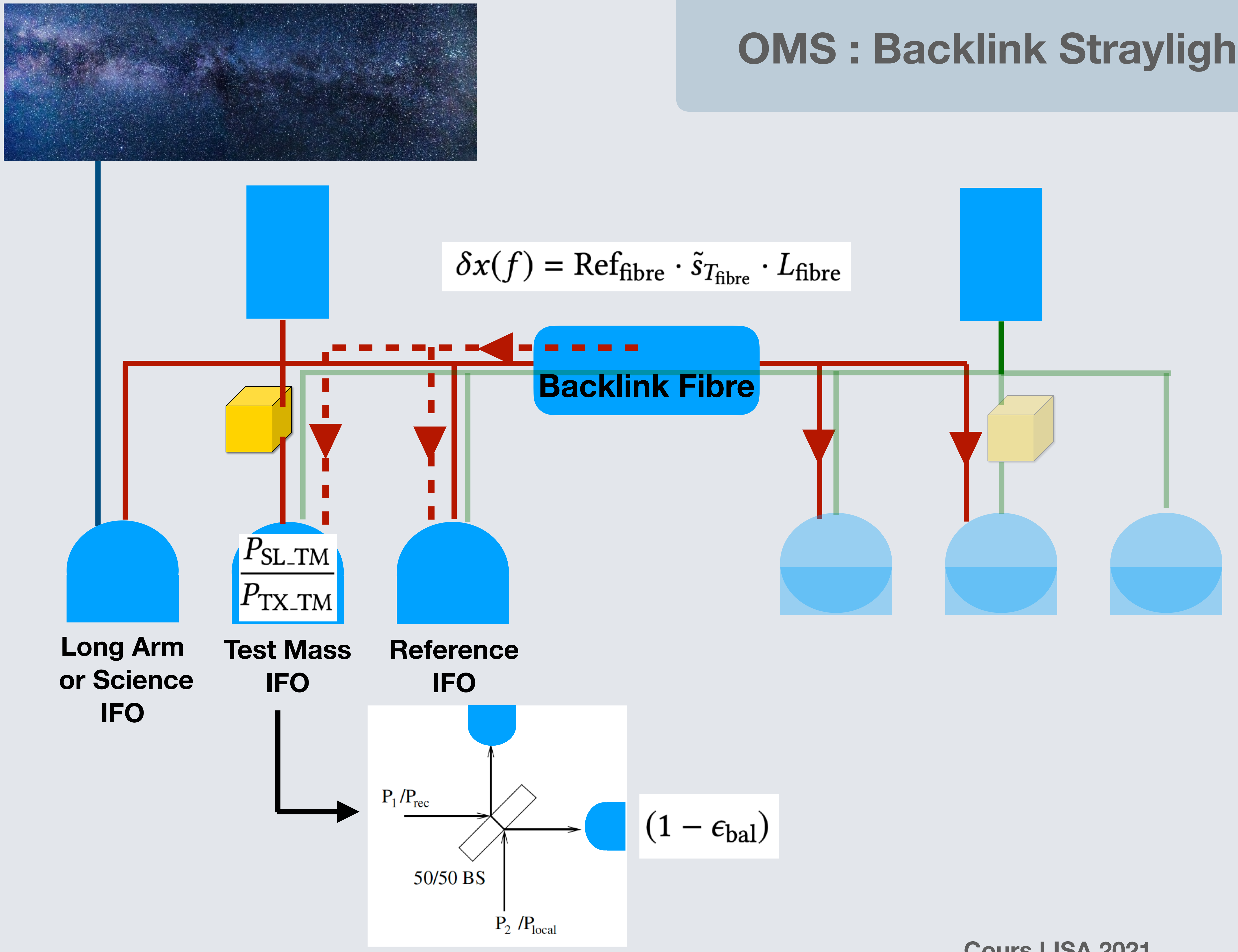


OMS : Shot Noise



[15] Ewan Fitzsimons. OMS Optical Power Budget. Technical Report LISA-UKOB-INST-RP-001 ,V1.2, UKATC and UGL, 05 2019.

OMS : Backlink Straylight



OMS : Backlink Straylight

- LISA-APC-INST-TN-005_i1.2_StrayLightToPhase
- LISA-AEI-PRDS-RP-001_v1_PRDS_Fibre_Irradiation_Test_Report
- LISA-AEI-PRDS-TN1-2109
- Optical Power Budget, LISA-UKOB-INST-RP-001

$$\delta x(f) = \mathrm{Ref}_{\mathrm{fibre}} \cdot \tilde{s}_{T_{\mathrm{fibre}}} \cdot L_{\mathrm{fibre}} \,.$$

OPD noise/kelvin/ fibre length. Mesure AEI

Stabilité en température de la fibre 1.4mk/sqrt(Hz)

$$\tilde{s}_{\mathrm{TMI,Stray,PRDS}} = \sqrt{\epsilon_{\mathrm{pol,Rayl}}\epsilon_{\mathrm{mod,Rayl}} \frac{P_{\mathrm{SL\_TM}}}{P_{\mathrm{TX\_TM}}}}\,\delta x(f)\,(1-\epsilon_{\mathrm{bal}})\,,$$

Educated Guess

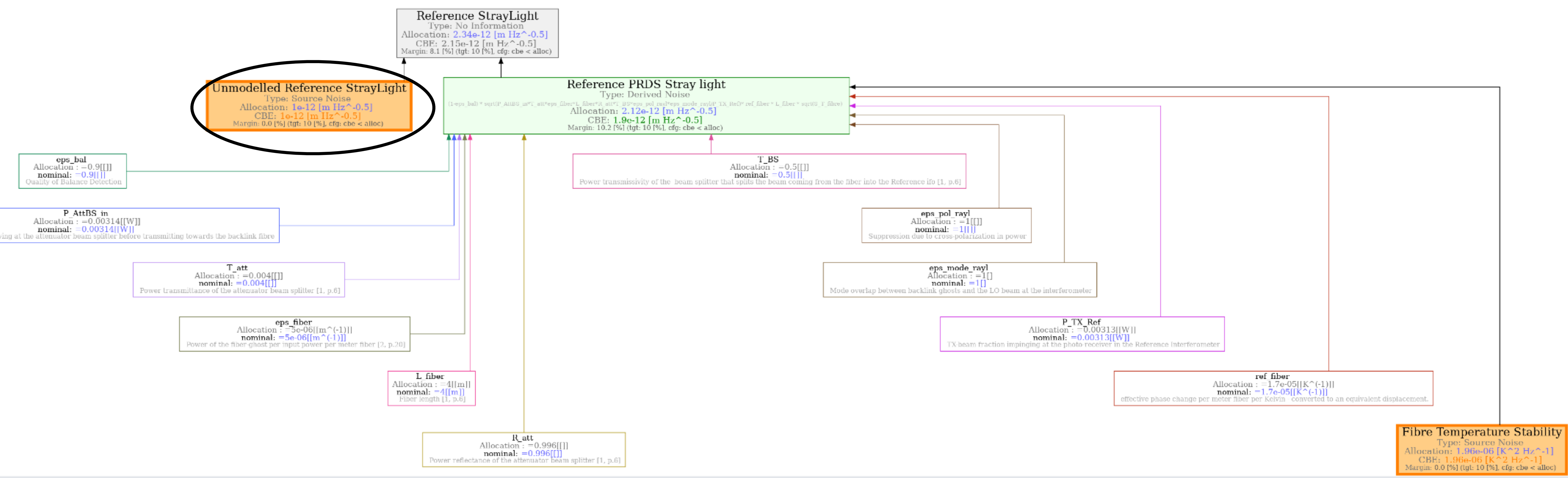
Optical bench design

Optical Components uncertainties = 0.9

- **Same contribution in reference IFO**
- **Dominant source of noise for Test Mass IFO: 3.4 pm/sqrt(Hz) and reference IFO: 2 pm/sqrt(Hz)**

OMS : Backlink Straylight

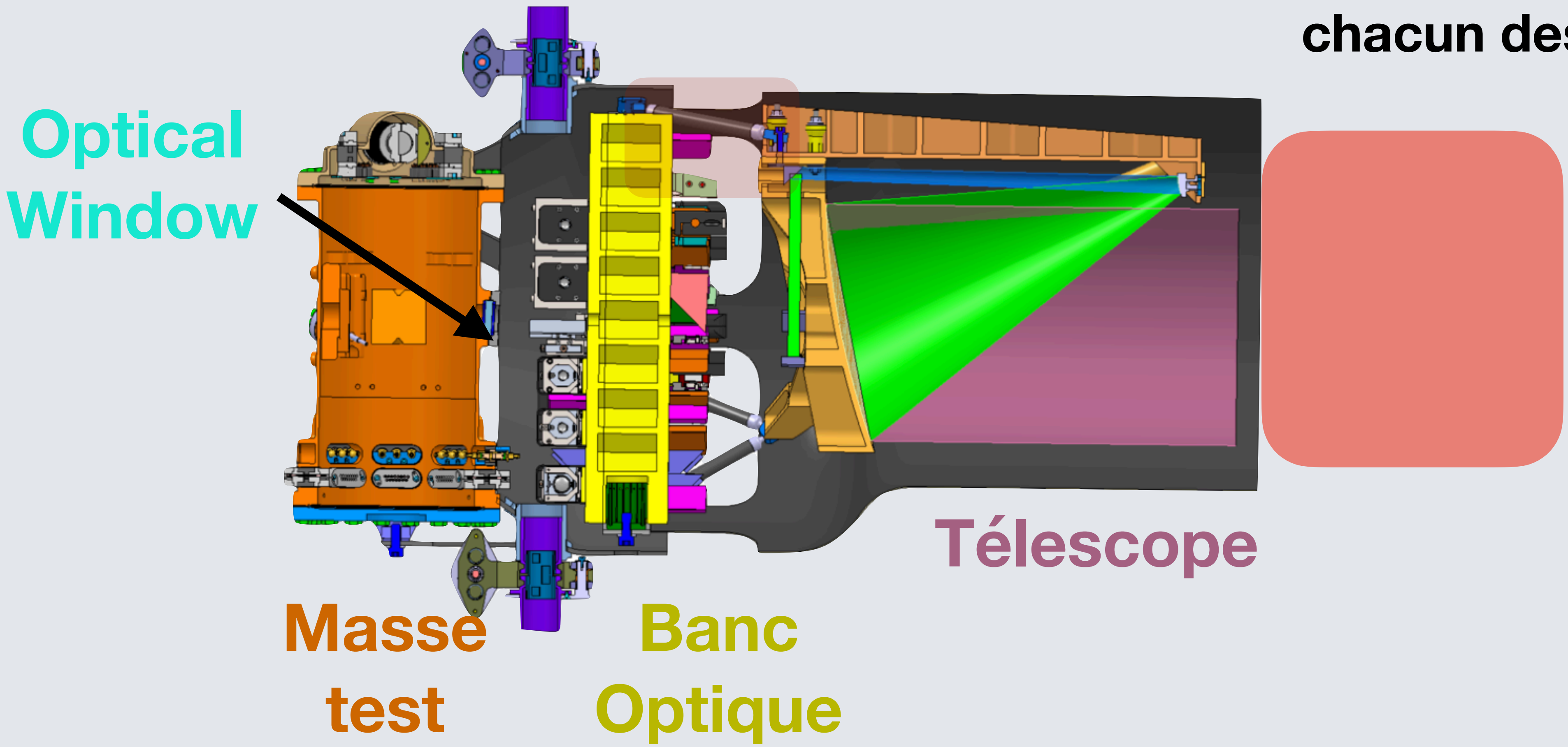
Source de straylight non modelisées: 1pm/sqrt(Hz)



- LISA-APC-INST-TN-005_i1.2_StrayLightToPhase
- LISA-AEI-PRDS-RP-001_v1_PRDS_Fibre_Irradiation_Test_Report
- LISA-AEI-PRDS-TN1-2109
- Optical Power Budget, LISA-UKOB-INST-RP-001

OMS : Thermal Noises

On définit une température pour chacun des sous-système



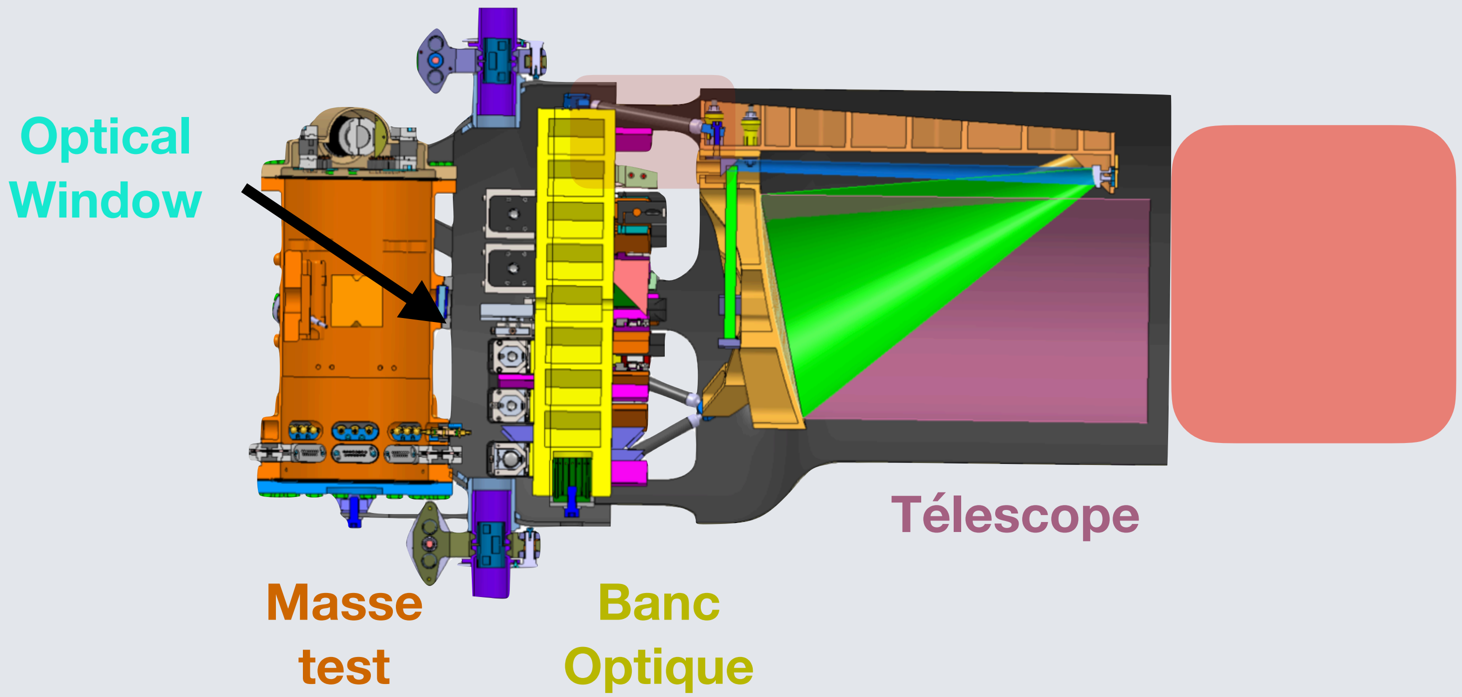
Taille caractéristique du banc optique

$$\tilde{s}_{\mathrm{Therm,OB}} = \alpha_{\mathrm{cte,Zer}} \cdot \tilde{s}_{T_{\mathrm{OB}}} \cdot D_{\mathrm{OB}}$$

Coefficient d'expansion thermique du zerodur

Stabilité thermique du banc optique ~ 10uK/sqrt(Hz) [Primes]

OMS : Thermal Noises



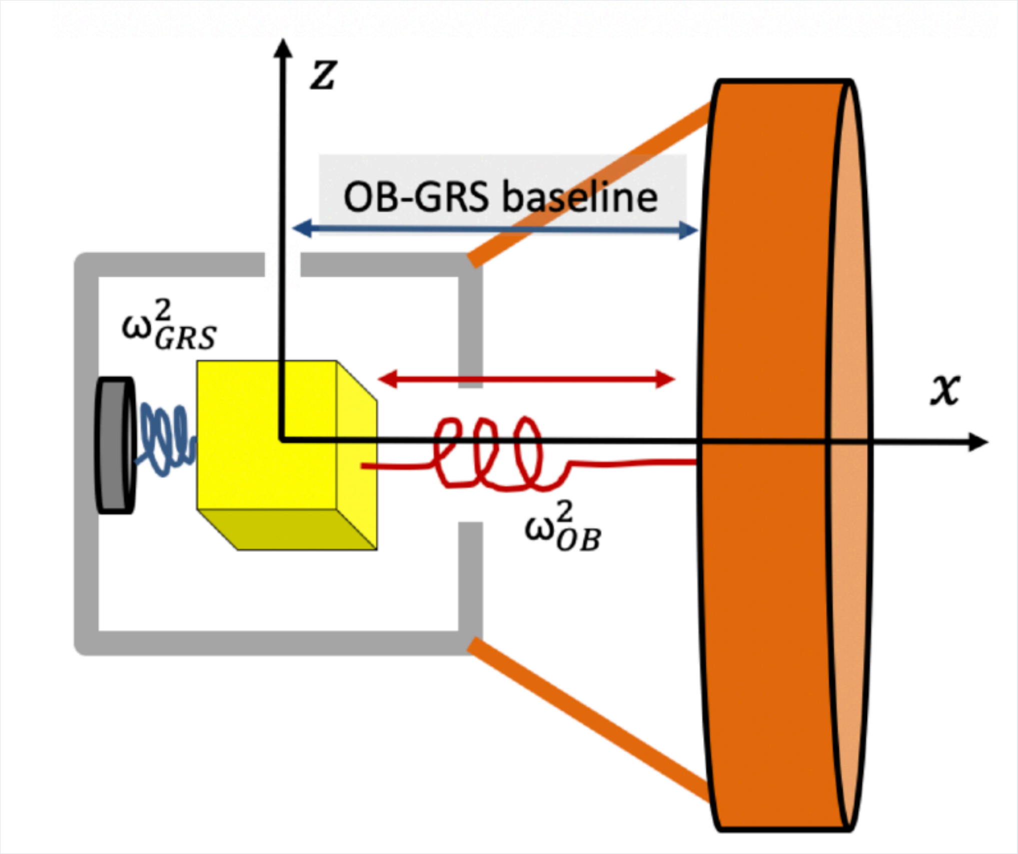
- PAAM Piston
- OB Baseplate Thermoelastic
- Long Arm Waveplates
- Test Mass Waveplates
- Mirror Thermoelastic
- Component Thermoelastic
- Long Arm Telescope contribution
- GRS Optical Window Thermoelastic
- Test Mass Thermoelastic

- Impact of correlation not known
- Each contribution is summed up linearly
- What matters for the OMS is the mHz temperature stability
- 10uK/sqrt(Hz) is the limitation of the sensor in LPF.
- We might have some margin (cf: telescope dimension study)
- Inputs from the prime are expected during the phase A extension.

Reference Gravitationnelle

- Stiffness coupling noise
- Thermal Force noise
- Actuation crosstalk

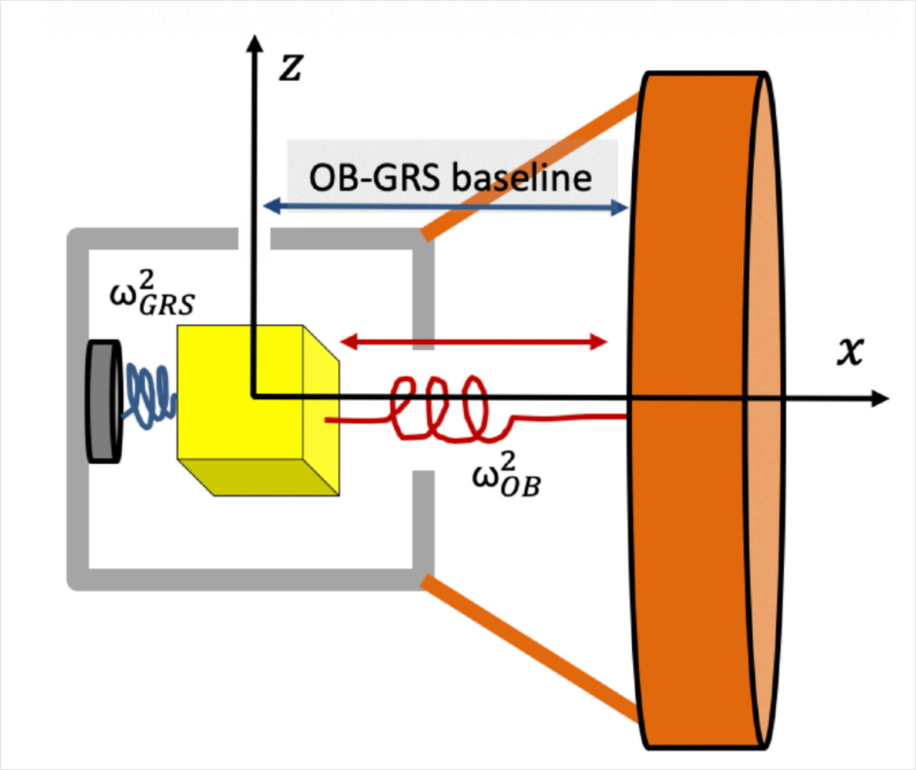
GRS : Stiffness Coupling

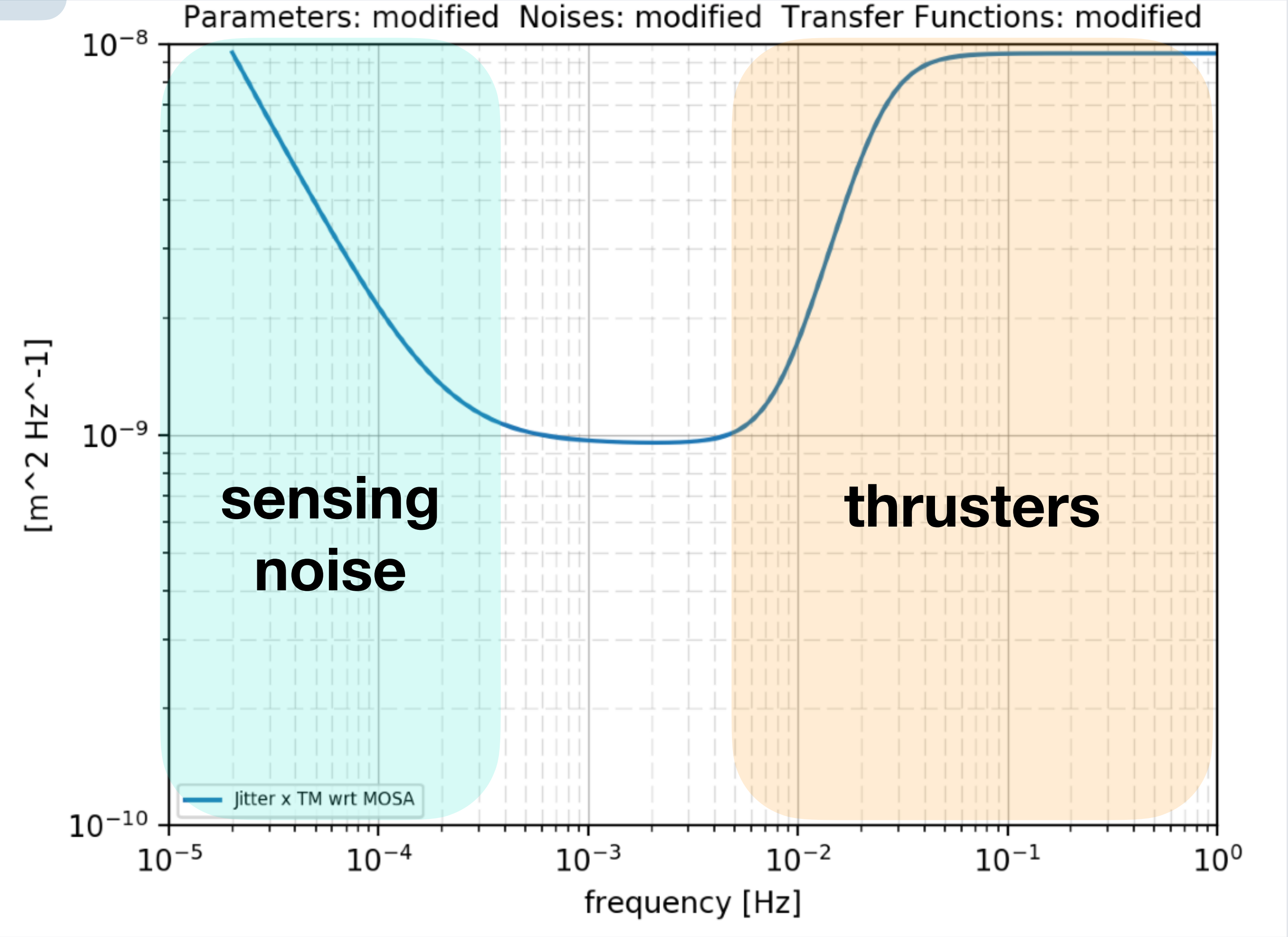


- **La masse test est dans un champ gravitationnel et électrique non uniforme**
- **Tout déplacement relatif à la masse test entraine un couplage avec ces champs.**

- **Valable sur tous les autres axes.**
- **Dominant à basse fréquence.**

GRS : Stiffness Coupling





$$\delta g_x = -\omega^2_{xx,TOT} \times (\delta x_{TM} - \delta x_{OB}) - (\omega^2_{xx,TOT} - \omega^2_{xx,OB}) \times (\delta x_{OB} - \delta x_{GRS}) ,$$

Bruit accélération de la masse test (δg_x)

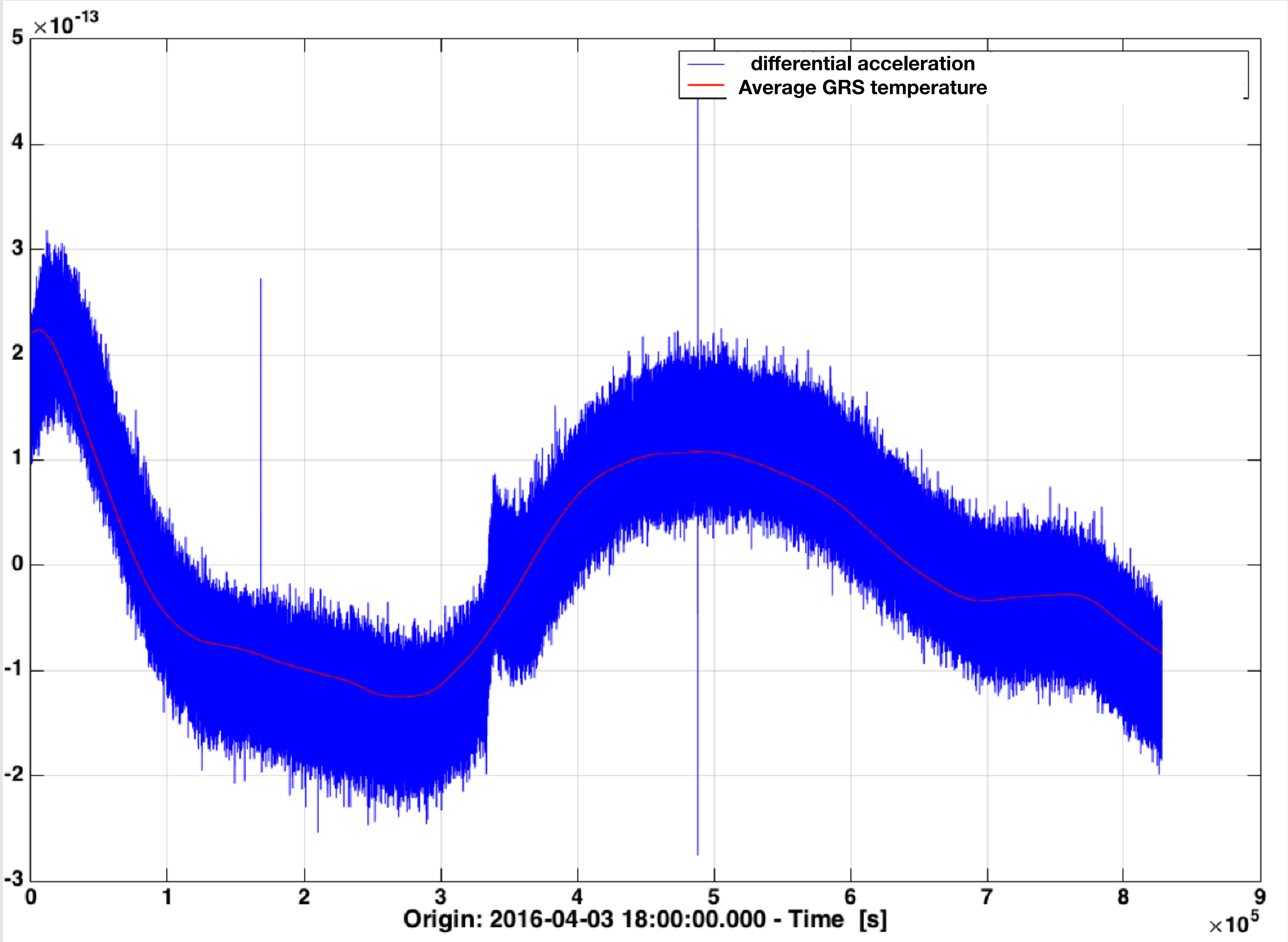
Stiffness coefficient ($-\omega^2_{xx,TOT}$) **[Gravitational balancing]**

Stabilité de la plateforme en X Axe Drag Free ($\delta x_{TM} - \delta x_{OB}$) **[DFACS design & sensing noise]**

Déformation thermo-méchanique entre OB et le GRS ($\delta x_{OB} - \delta x_{GRS}$) **[MSS design and temperature stability]**

EH/GRS average temperature force noise

During LPF : correlation between the GRS average temperature and the differential acceleration between two test masses.



EH/GRS average temperature force noise

Model for the LISA

Acceleration noise on a TM

$$S_g^{T_{GRS}} \approx \left|\frac{\partial gx}{\partial T_{GRS}}\right| S_{T_{GRS}}.$$

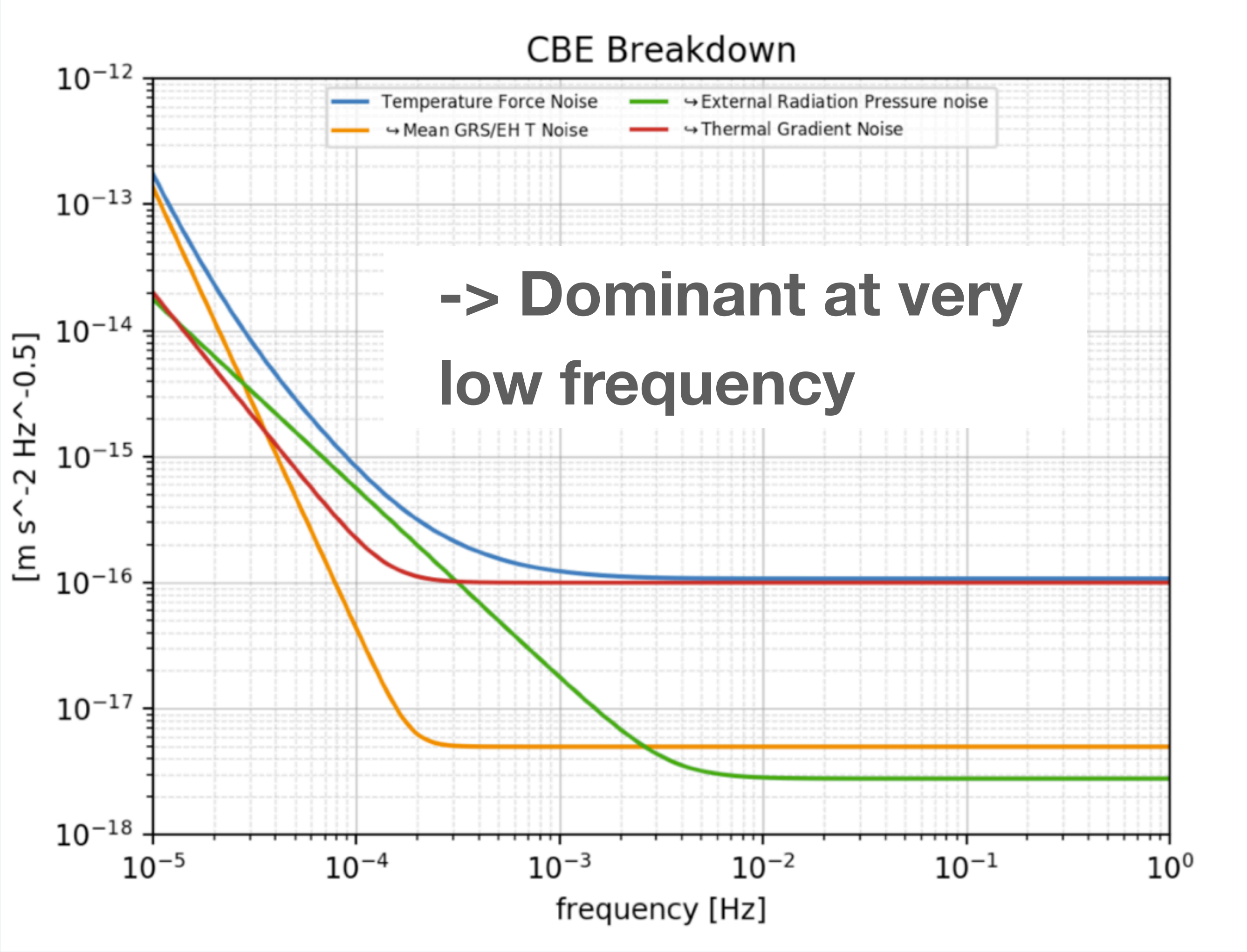
Average GRS temperature

Measured during LPF

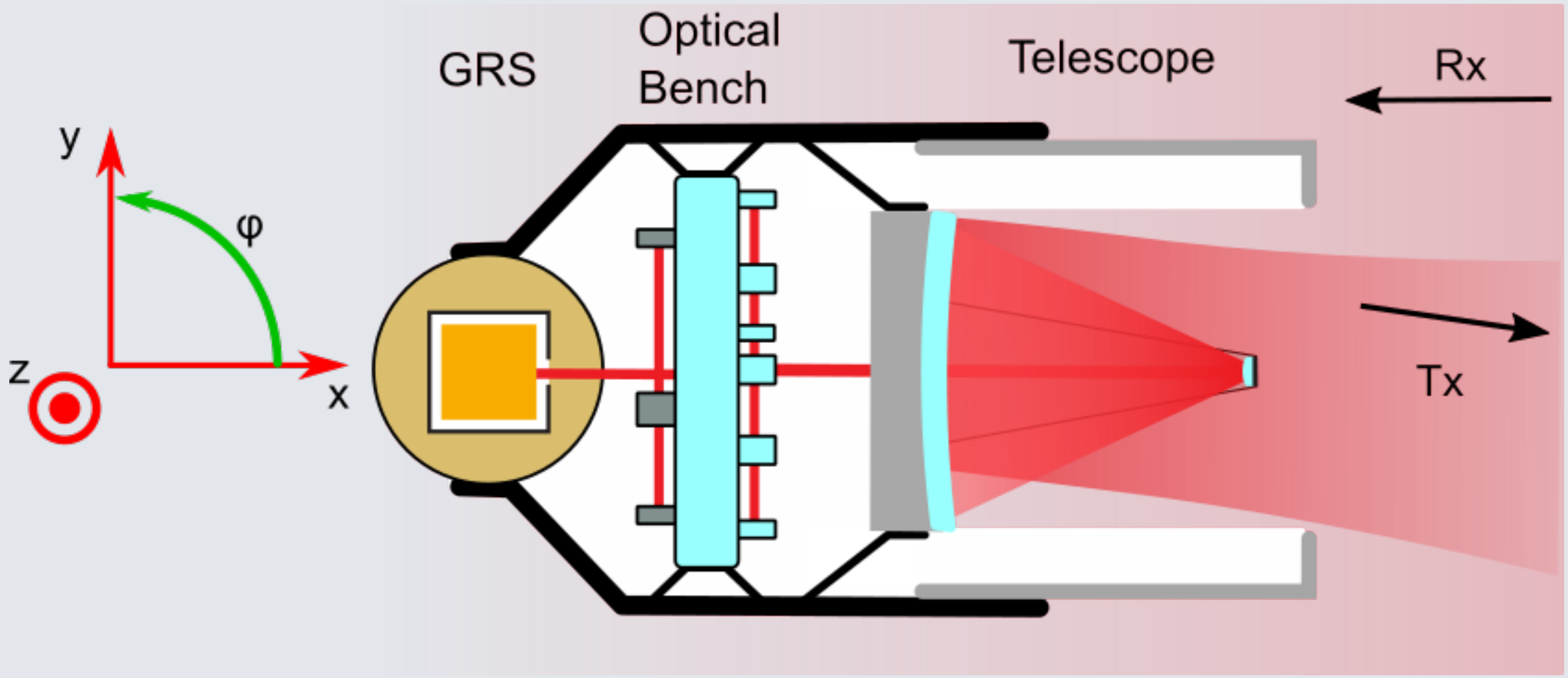
Physical explanation

associated most likely with assymetric outgassing sources, in and immediately around the EH in view of the TM through the laser holes,

Contribution to the LISA budget noise



GRS : Actuation Crosstalk



X axis is drag free - Spacecraft follow Test Mass -> Thrusters

Phi axis is suspension - Test Mass Follow Spacecraft -> Electrostatic actuators

LISA Instrument Group. Payload Description Document. Technical Report ESA-L3-EST-INSTDD-001, version 2.2, ESA, 05 2018.

GRS : Actuation Crosstalk

Acceleration de la masse test sur X

Coefficient crosstalk

$$S_g = \beta^2_{ACT_{\phi x}} S_{\Upsilon_{\phi c}} ,$$

Bruit torque en Phi appliquée par les actuateurs électrostatiques

Bras de levier

$$\beta_{ACT_{\phi x}} \approx R^*_{\phi} \delta$$

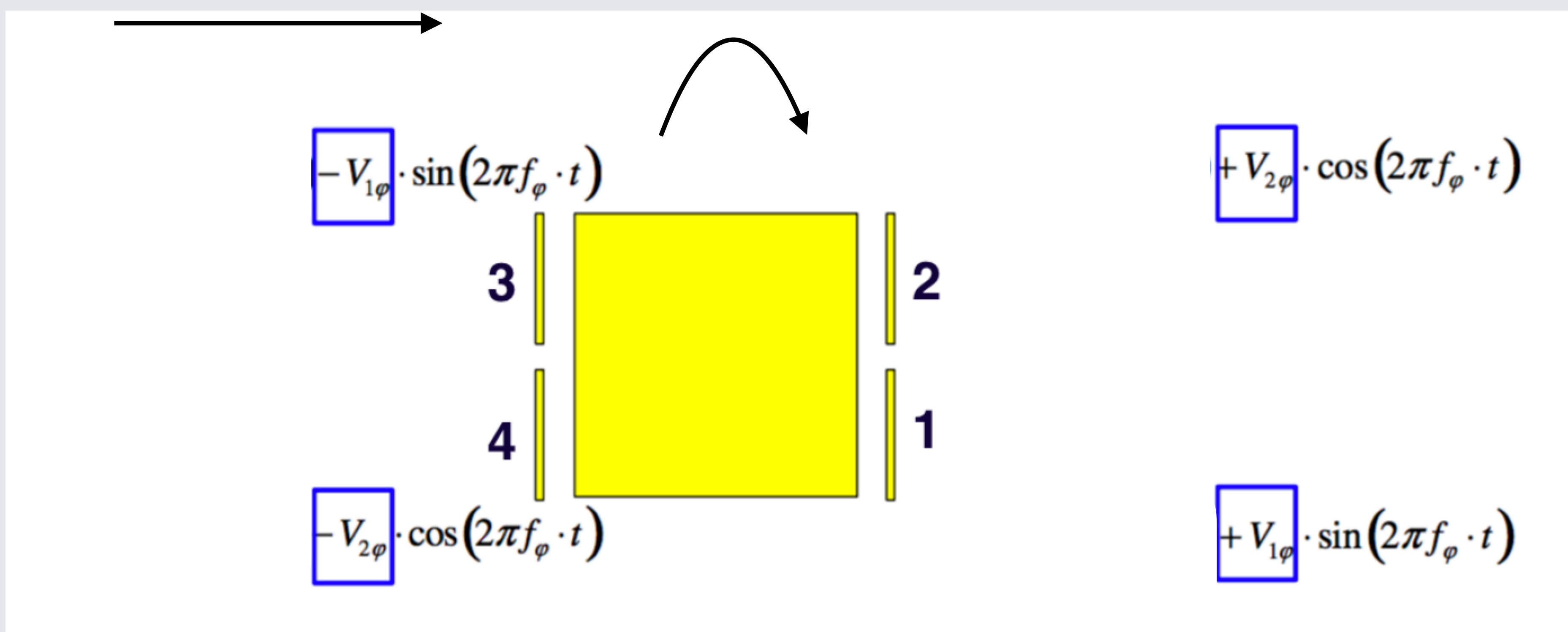
Voltage gain imbalance : 0.5%

$$S_{\Upsilon_{\phi c}} \approx \left| T_{TM\phi}(\omega) \right|^2 \left[\omega^4 S^{\phi}_{\mathrm{SC/IS}} + S_{\Upsilon_{\phi_{INT}}} \right]$$

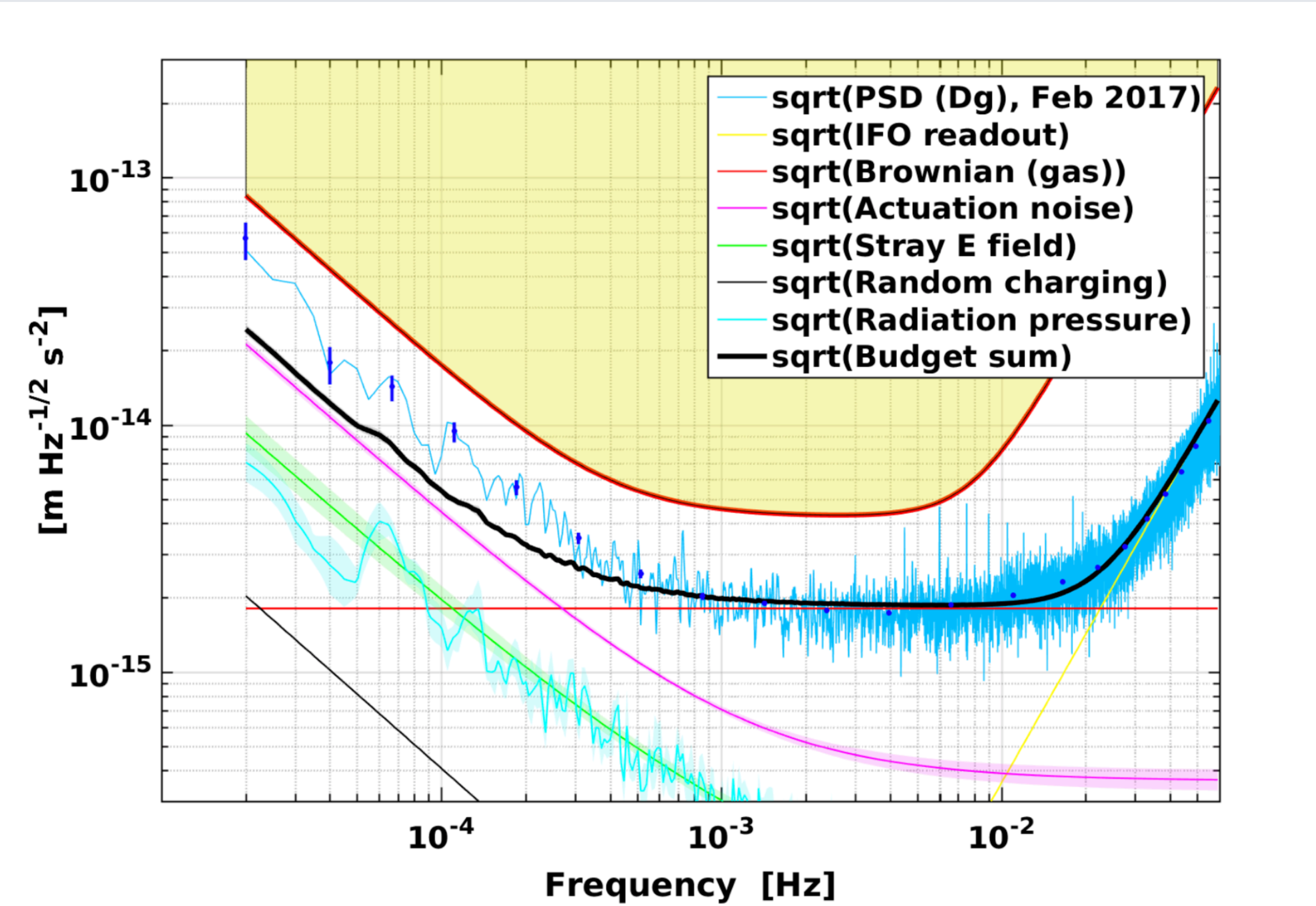
Force ~ V²

Xaxis

Phi



Mystery noise and LPF

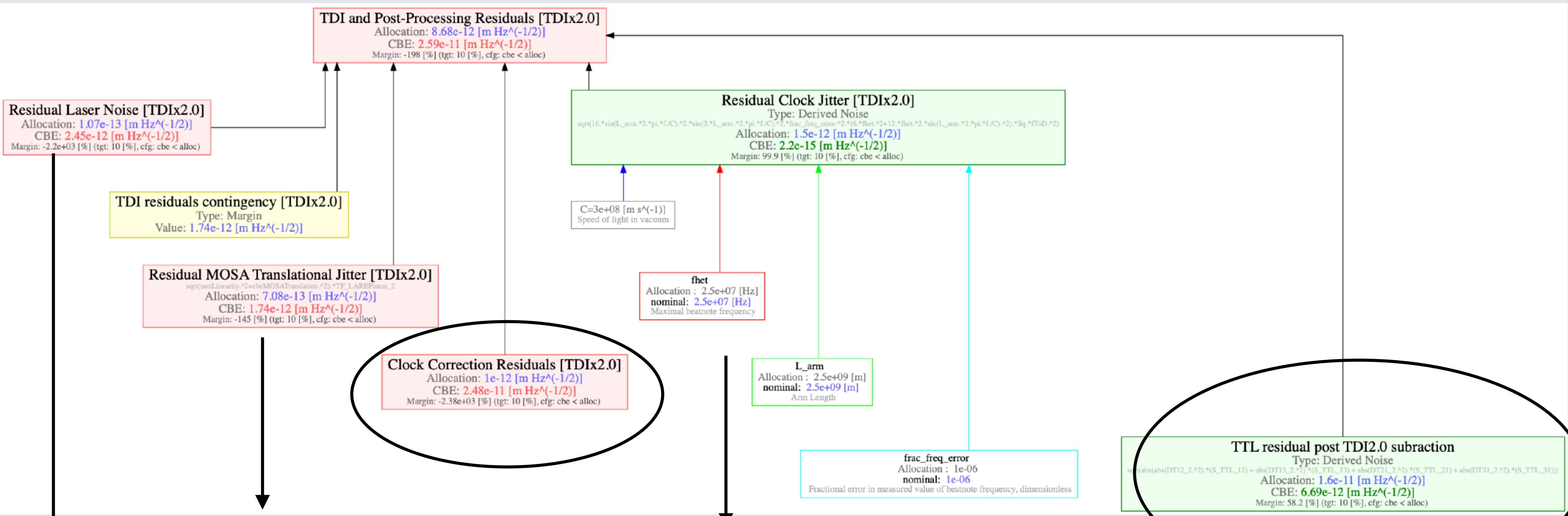


TDI residuals & Post Processing

- Modulation noise
- Tilt-To-Length coupling

TDI and Post processing residuals

- Concernent tous les bruits réduits ou ajoutés au sol
- Les bruits réduits dépassent largement les specs



~ 3 ordres de grandeur

~ Requirements

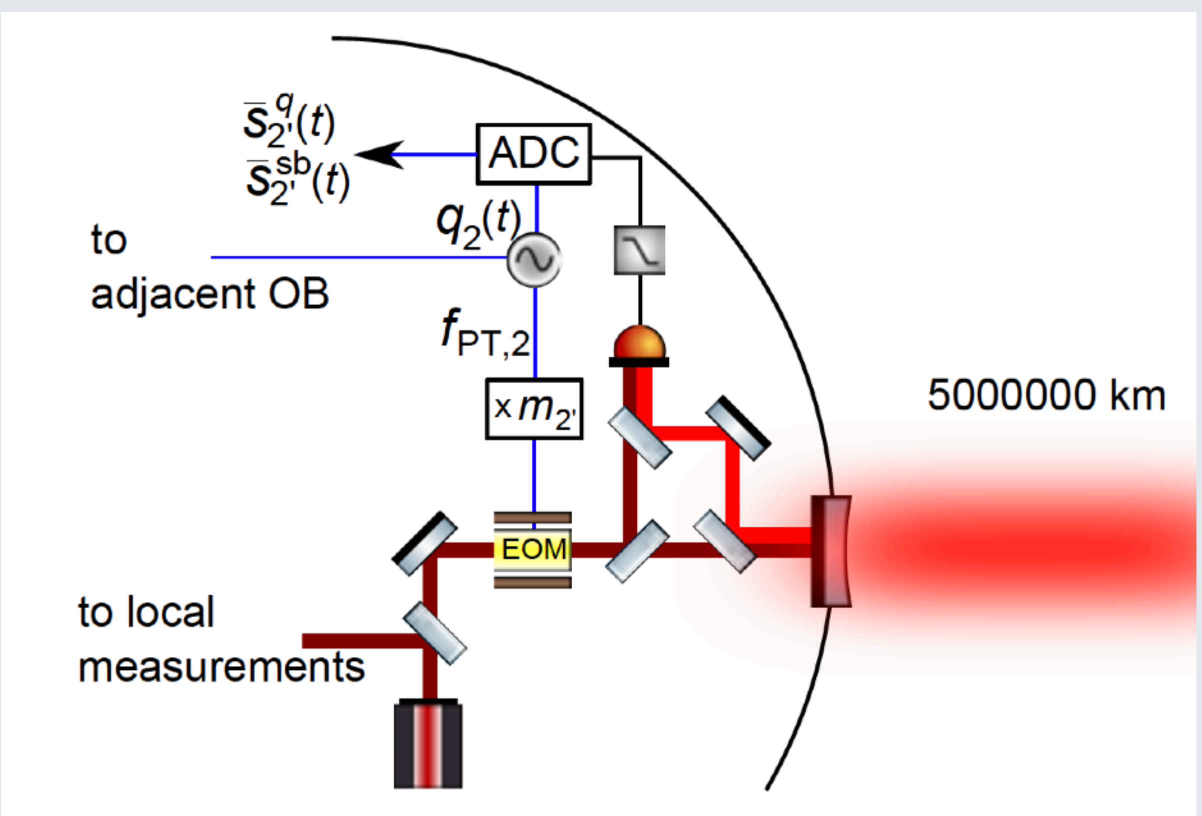
~ 8 ordres de grandeur

~ 1 ordre de grandeur

Cours LISA 2021

TDI : Clock Modulation

- Rappel : le signal et digitalisé à 80MHz par une horloge entachée d’une erreur δt
- On va « imprimer » l’erreur d’horologe sur des sidebands à 2GHz et le transférer au S/C distant
- Le signal d’horloge est dominant sur les sidebands -> mesure indépendante.



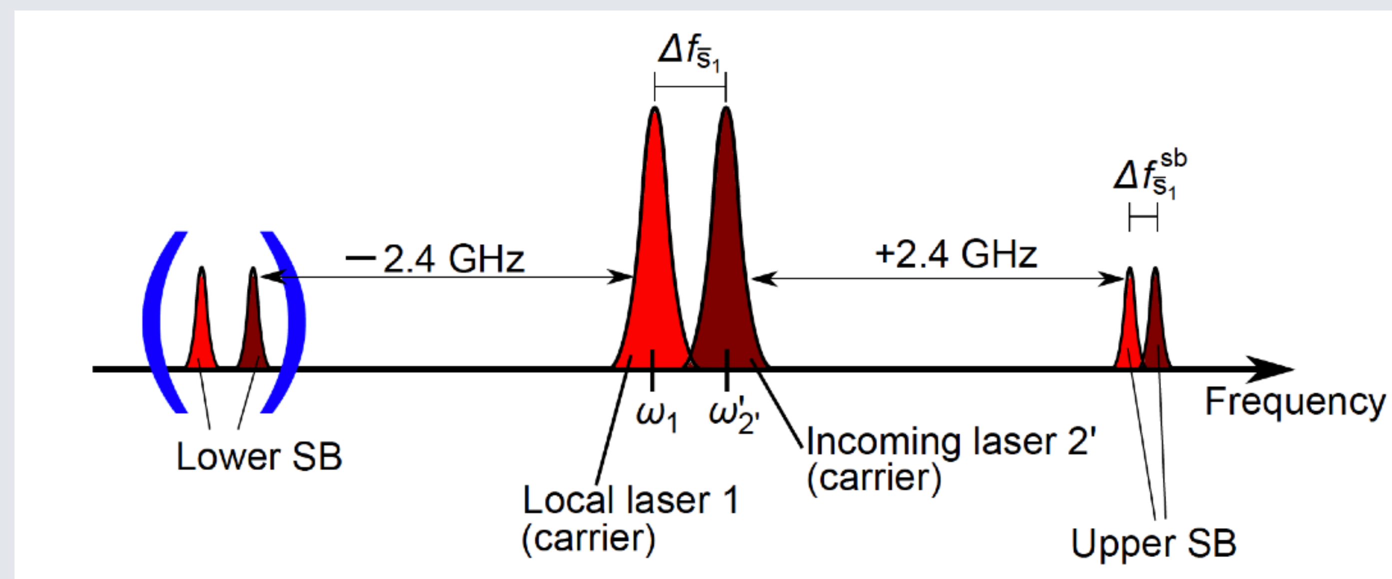
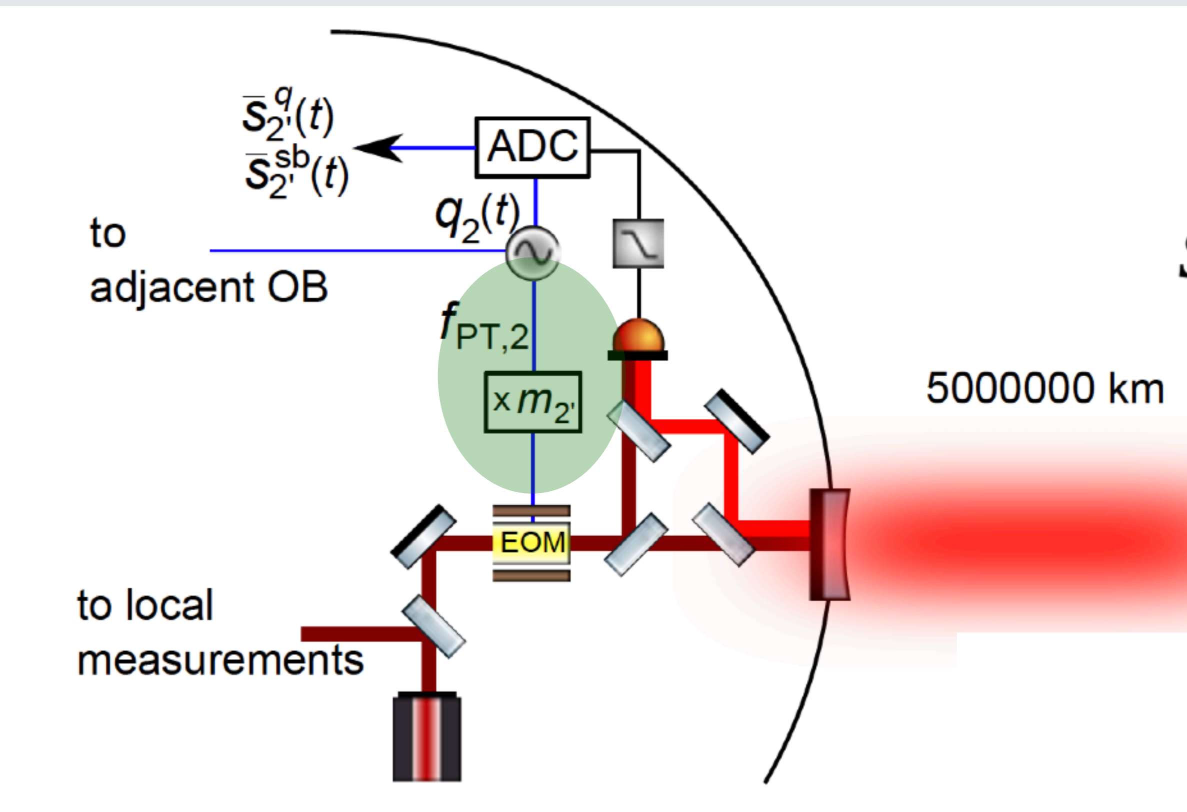


image: Time-Delay Interferometry Simulations for the Laser Interferometer Space Antenna.
Phd thesis. M.otto

TDI : Clock Modulation

- Chaque IFO va produire un canal de mesure supplémentaire : bande latérale.
- Ce dernier va être soustrait à la mesure principale.

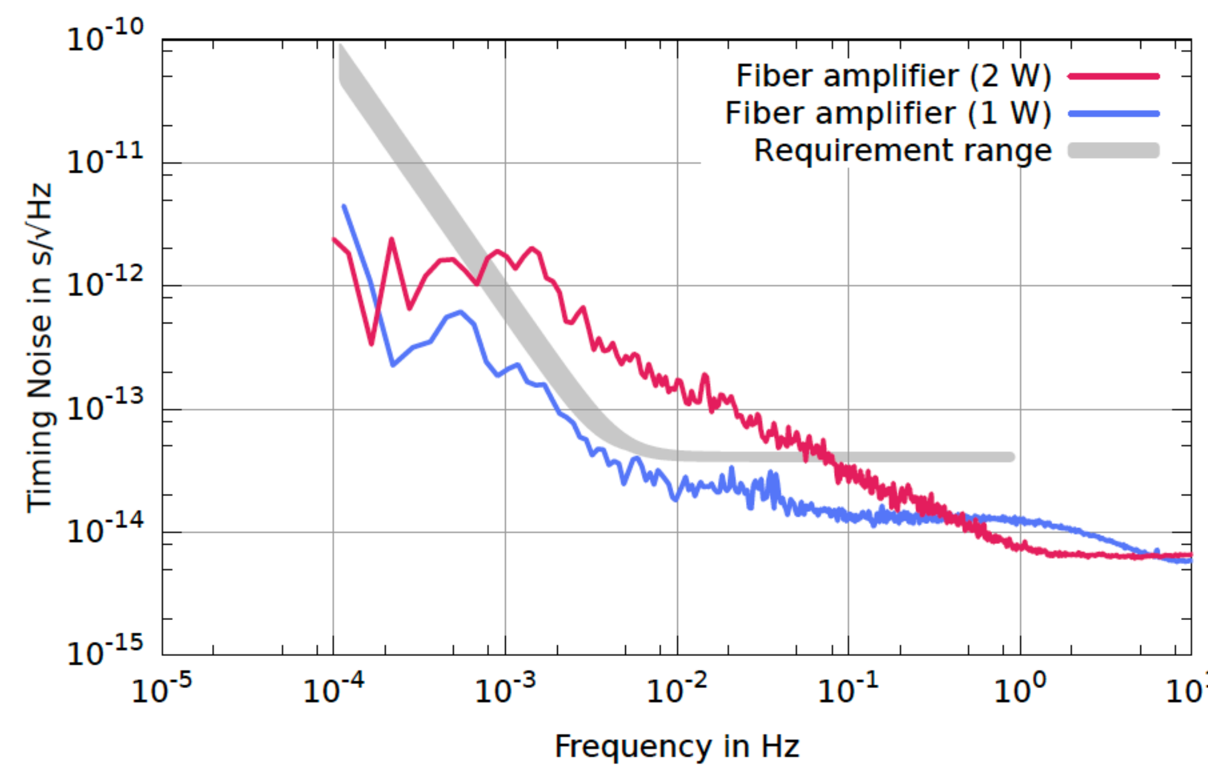


Beatnote Frequency

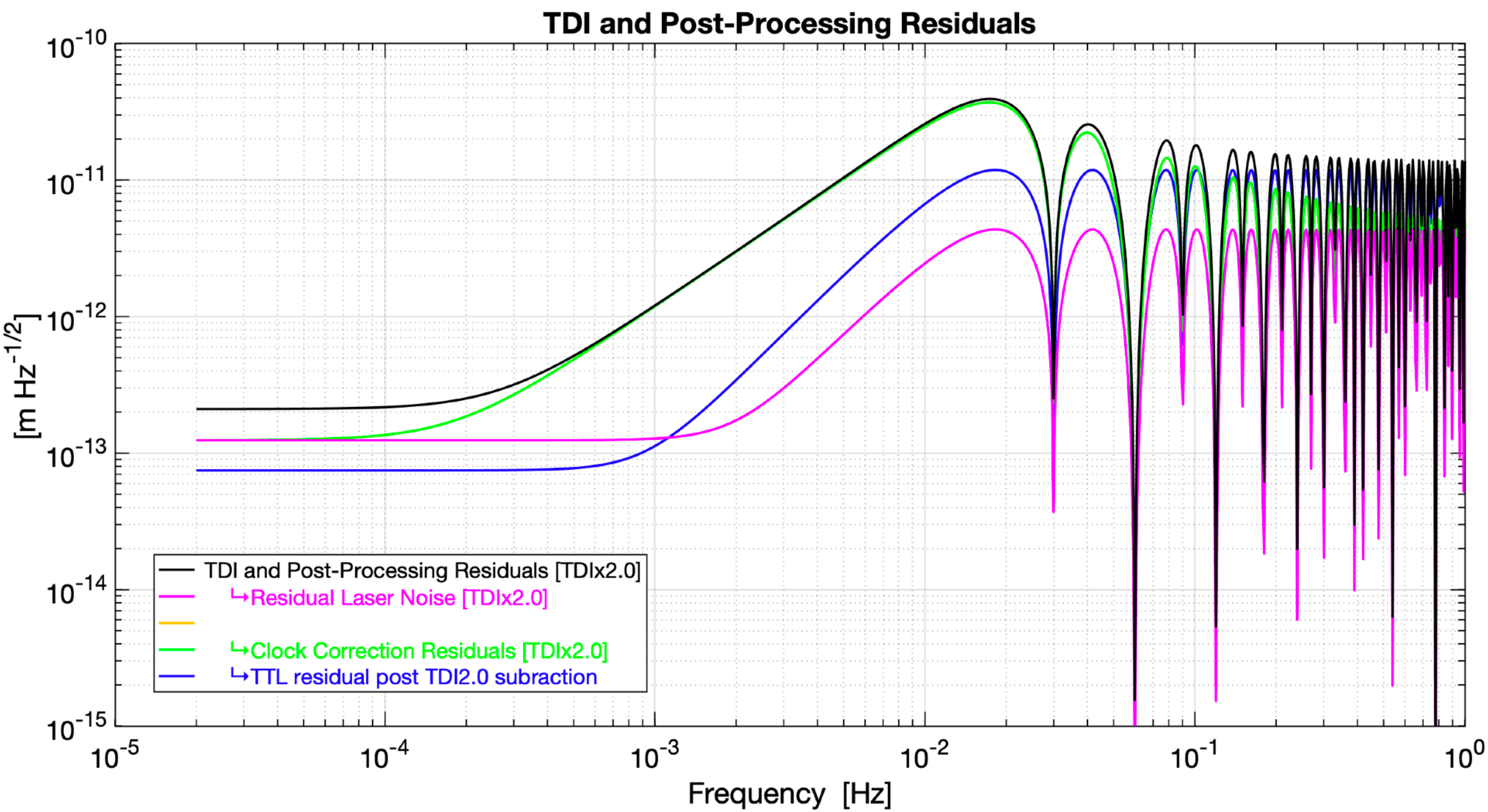
$$S_q^{\text{modulation-error}} \approx \left[6\nu_{\text{BN}}^2 + 12\nu_{\text{BN}}^2 \sin(\omega L)^2\right] \tilde{s}_M^2 C_{\text{XX}}$$

- Mesure : These S. Barke (AEI)

Figure 5.13: Timing jitter of an Ytterbium-doped fiber amplifier measured at 2 GHz modulation frequency for 1 and 2 W output power. The requirements are met for a power of 1 W but clearly violated for an output power of 2 W [66].



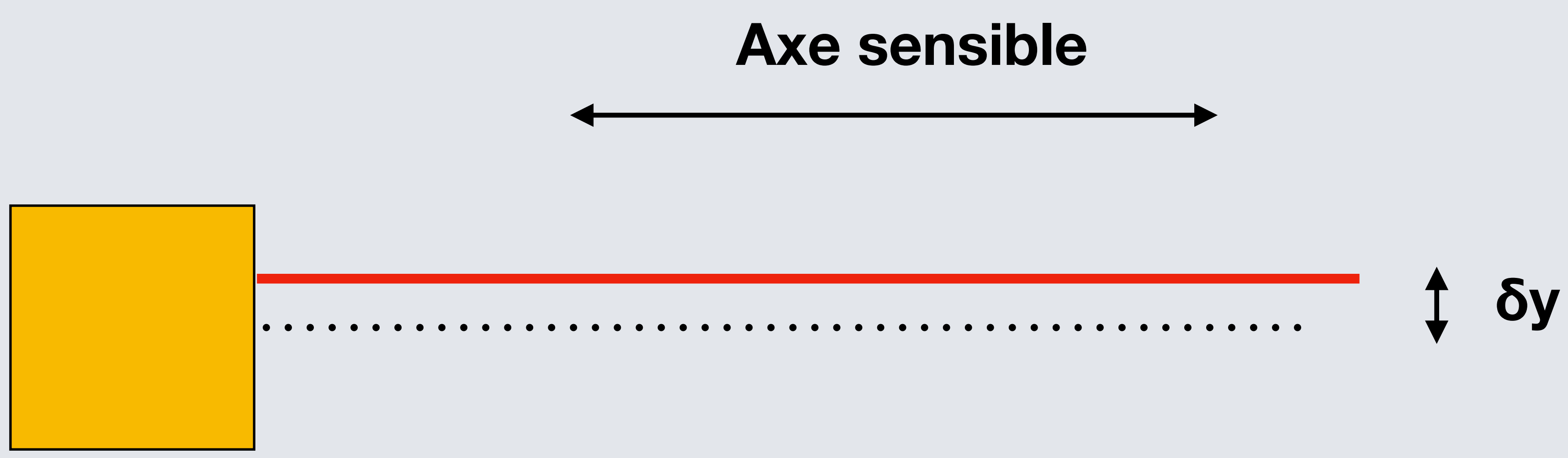
TDI : Clock Modulation



TDI residuals: TTL

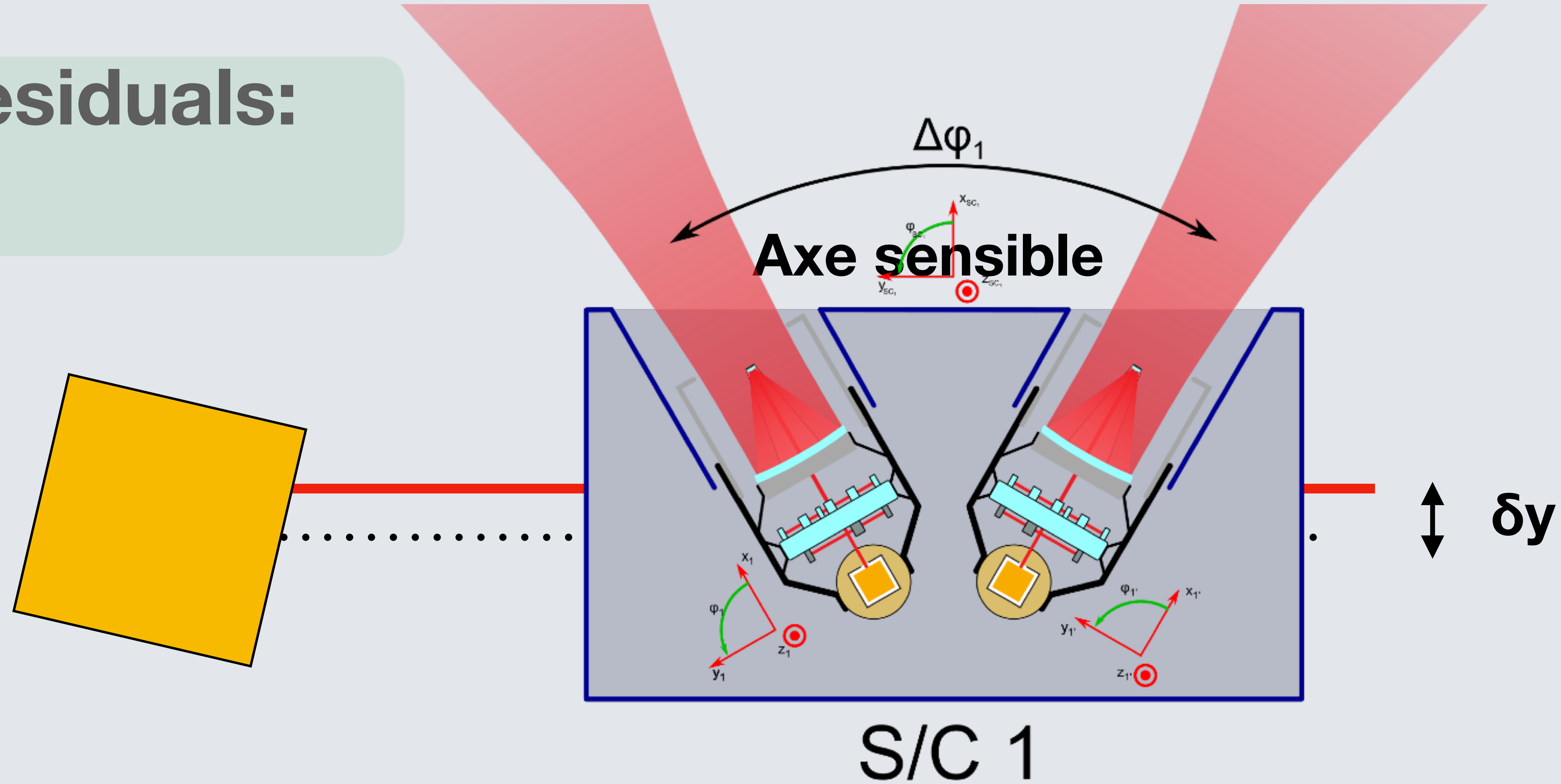
TTL is any effect which couples a rotation of the system to a measured pathlength

- Coupling driven entirely by misalignment and imperfections in the OMS



- **Split interférométrie - chaque interféromètre contribuera au TTL**
- **Beam Alignment mechanism - Calibration au sol**
- **Calibration en Vol.**

TDI residuals: TTL



Dans le modèle de performance on ne modélise pas les TTL mais leur couplage avec la mesure.

Principe de mesure par interféromètre et par dégré de liberté:

[Noise] = [TTL coupling factor] x [Angular Jitter]

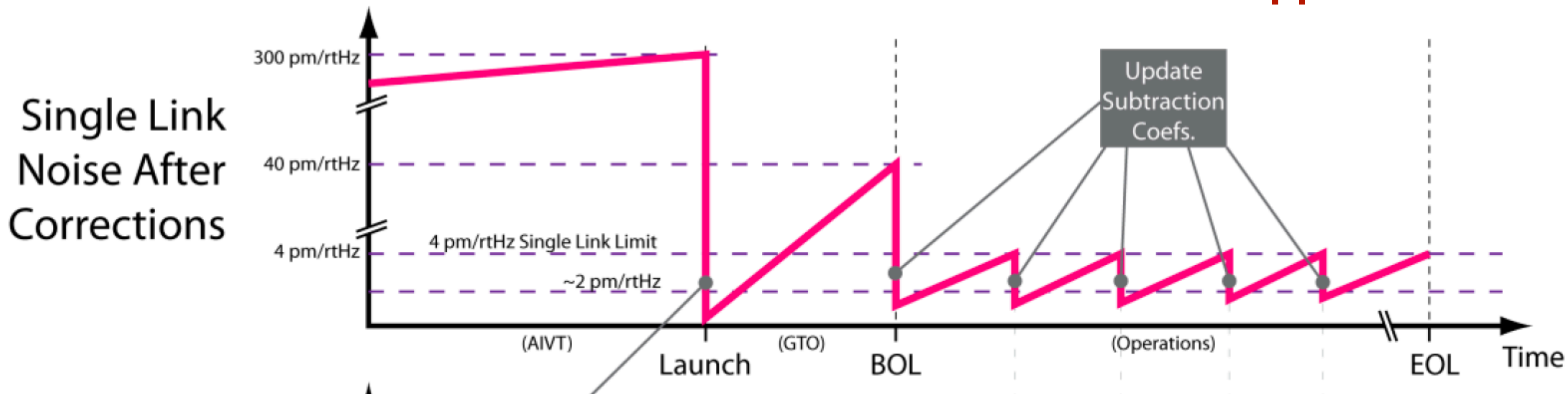
Coefficients TTL effectifs — **Bruits des DWS** — **Magnification du Telescope et de l'OB**

$$S_{x,\mathrm{TTLRes}} \quad + S_{\mathrm{jitter/IS}} \cdot \left(\delta C^2_{\mathrm{TTL/IS}} + C^2_{\mathrm{TTLdrift/IS}}\right),$$

Jitters angulaires correlations — **Résidus calibration** — **Drift des alignements**

TTL calibration scenario

All numbers are approximate.



Beaucoup de contraintes importantes interdépendante :

- Bruit des DWS
- Alignement sol
- Calibration sol
- Calibration vol
- Stabilité de la plateforme

TTL Effective coefficient decomposition

Table 2: *Total budget for TTL in the RX Path.*

Contributor	TTL per DOF (External) [mm/rad]	Correlates with Telescope	Limiting Requirement
Relative alignment between OB and Telescope nominal	4.02	Y	δy,δz = ±30 µm alignment tolerance at OB/Telescope interface
Telescope pupil knowledge error	4.02	Y	δy,δz = ±30 µm uncertainty at the internal (small) pupil
Telescope internal-external axis tolerance	1	Y	δy,δz = ±1 mm tolerance on the axis-axis separation of the telescope
Pupil shear	0.2	Y	δy,δz = ±0.2 mm max offset of the external pupil for any FOV position
Longitudinal-Lateral cross coupling	0.5		Δx = ±3 mm longitudinal alignment tolerance between the OB and Telescope nominal pupils, δη,δφ = 10 µrad boresighting of the telescope
Telescope geometric	0.55		Inherent property of the telescope
Imaging system residual	1.7		Inherent property of the imaging
LO lateral alignment	0.59		δy,δz = ±30 µm alignment tolerance at recombiner
LO waist matching	0.1		δx = ±1.5 m tolerance of positioning the waist to the entrance pupil of the imaging system
QPD lateral	1.96		δy,δz = ±10 µm alignment tolerance
QPD longitudinal	0.08		δx = ±2 mm alignment tolerance
Wavefront Error	0.8		λ/20 RMS total WFE
Other Terms	0.5		To be evaluated
Margin	1		
RX Aperture Stop	*0*		*This is our compensator, so we exclude its alignment from the total budget.*
Total (RSS), $\|C_{RX}\|$	**6.55**		

Reference: LISA-UKOB-INST-TN-004 LISA Optical Alignment Analysis

TDI Transfer Functions

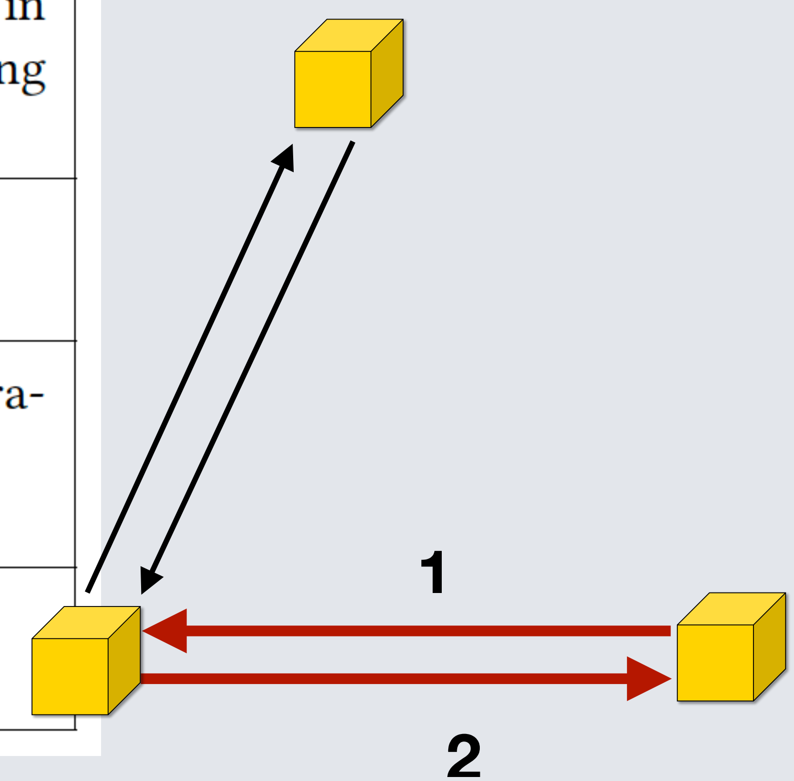
TDI Transfer Functions

$$C_{XX}(\omega) = 16\sin^2\left(\omega\frac{L}{c}\right)\sin^2\left(2\omega\frac{L}{c}\right)$$

Categories of TDI transfer function	XX 2.0	XY 2.0	Example noises in current Performance Model
Uncorrelated long-arm (science) and reference IFO	$4\,C_{XX}(\omega)$	$C_{XY}(\omega)$	Long-arm noise, Reference noise, Thermal-mechanical noise, OMS unallocated contingency, Unmodelled noises in TDI and post-processing residuals
Uncorrelated test-mass IFO	$C_{XX}(\omega)\left(3+\cos(2\omega\frac{L}{c})\right)$	$C_{XY}(\omega)$	Test-mass IFO noises
Uncorrelated test-mass acceleration	$4\,C_{XX}(\omega)\left(3+\cos\left(2\omega\frac{L}{c}\right)\right)$	$4\,C_{XY}(\omega)$	Single test-mass acceleration noise
Fully-correlated telescope	$4\,C_{XX}(\omega)(3+\cos\left(2\omega\frac{L}{c}\right))$	...	Not yet implemented

~ 4 à basse fréquence

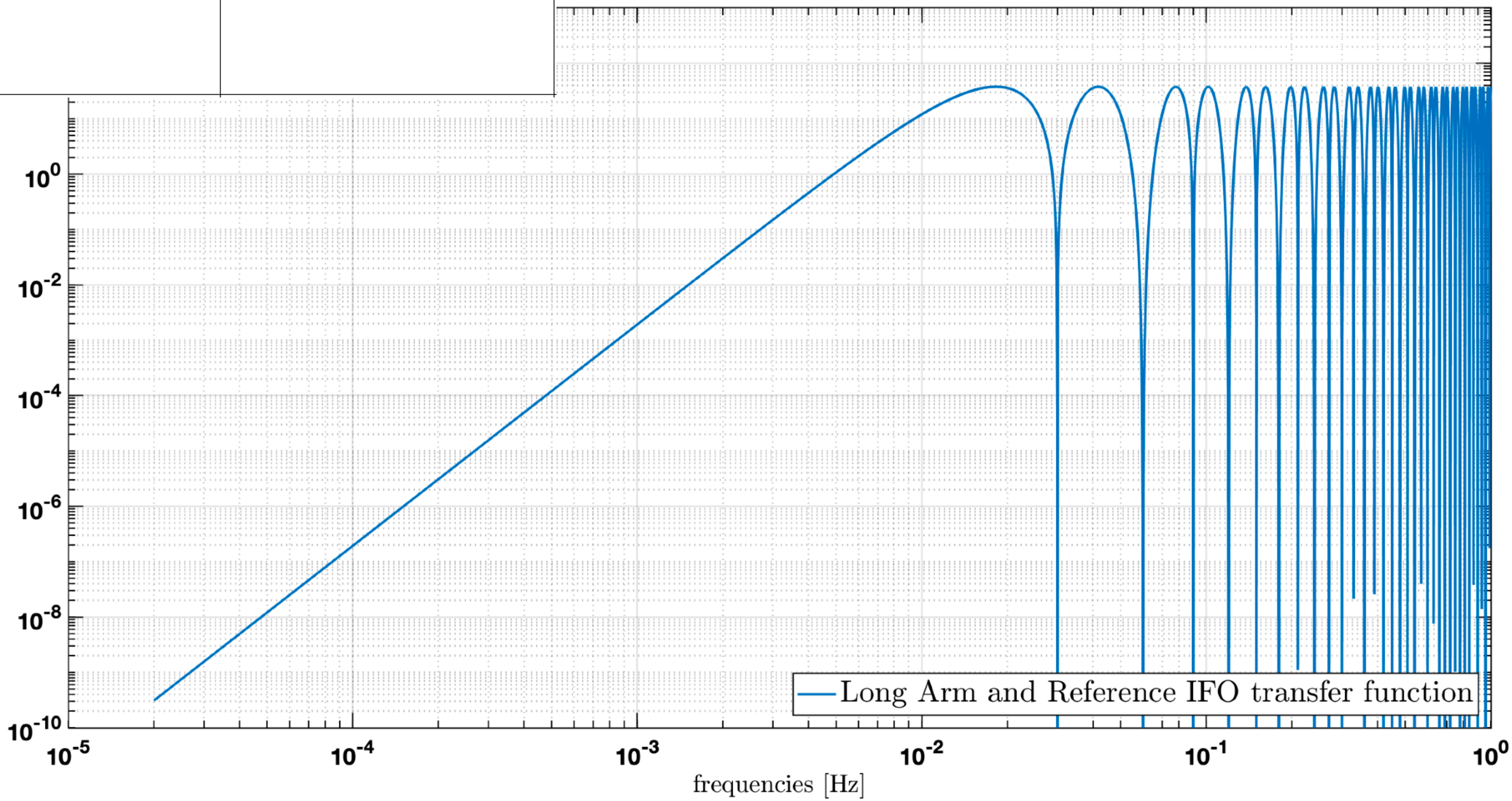
Le mouvement de la masse test est mesuré deux fois.



TDI Transfer Functions

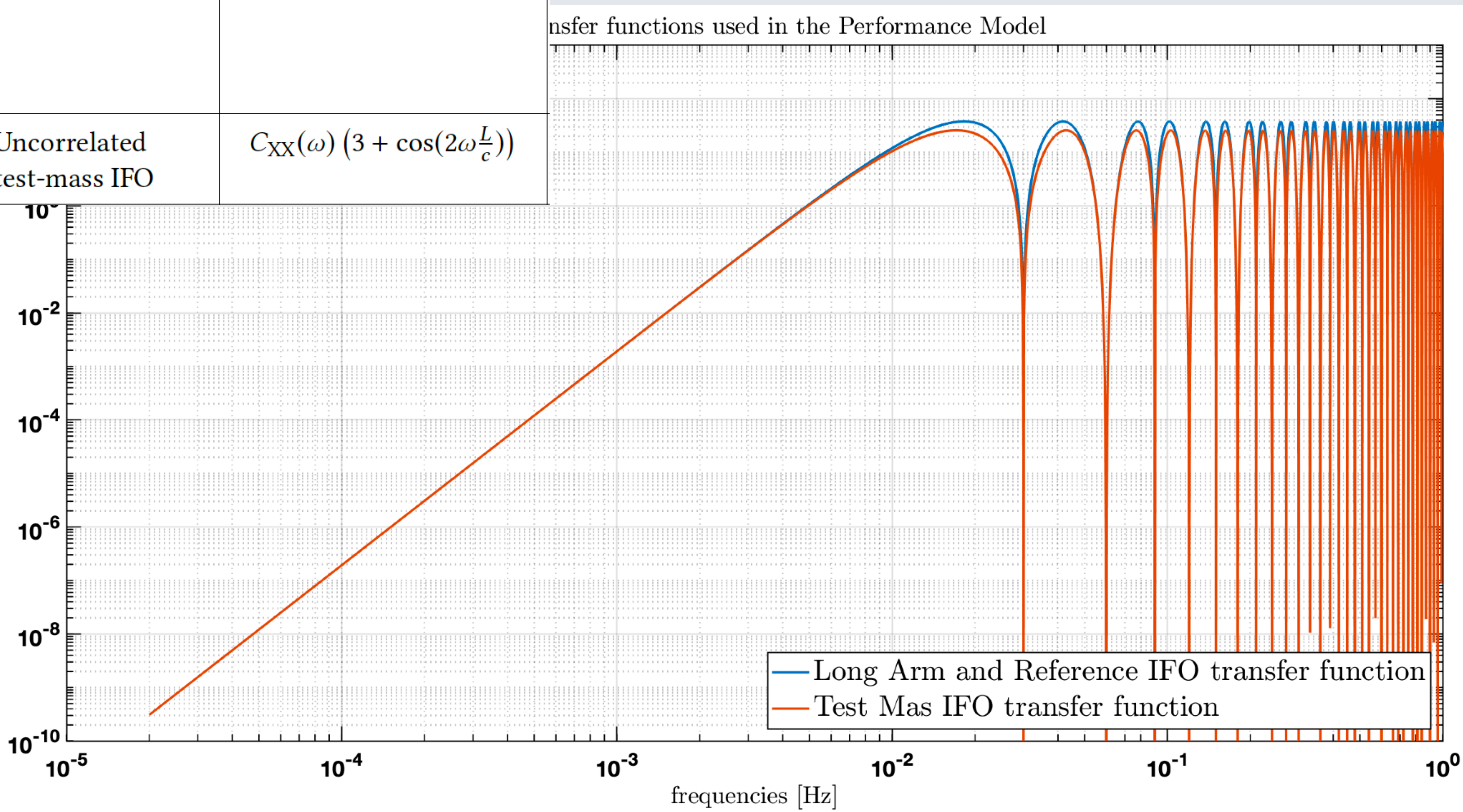
Categories of TDI transfer function	XX 2.0
Uncorrelated long-arm (science) and reference IFO	$4\, C_{XX}(\omega)$

ansfer functions used in the Performance Model

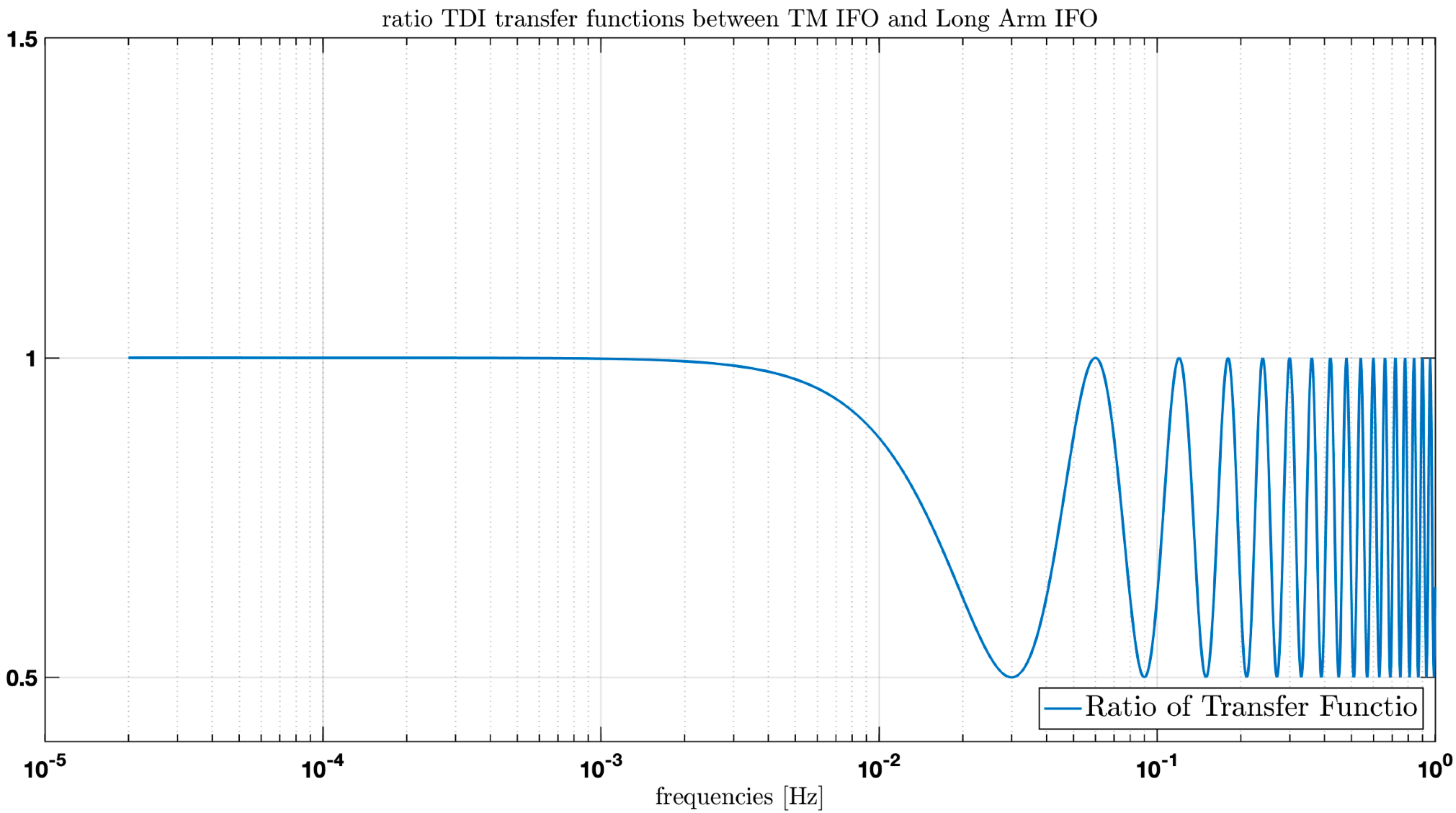


TDI Transfer Functions

Categories of TDI transfer function	XX 2.0
Uncorrelated long-arm (science) and reference IFO	$4\, C_{\mathrm{XX}}(\omega)$
Uncorrelated test-mass IFO	$C_{\mathrm{XX}}(\omega)\left(3 + \cos(2\omega \frac{L}{c})\right)$



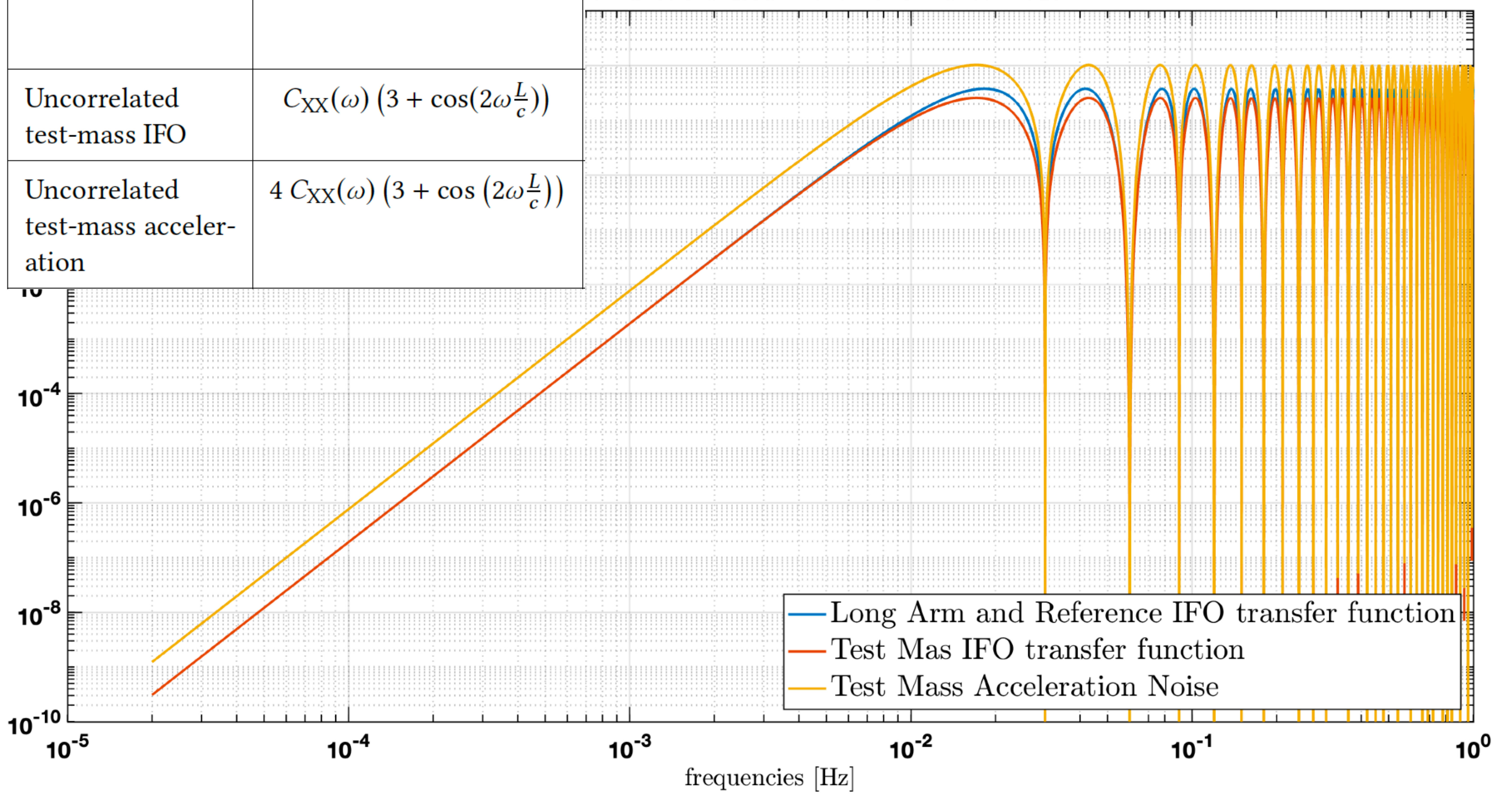
TDI Transfer Functions



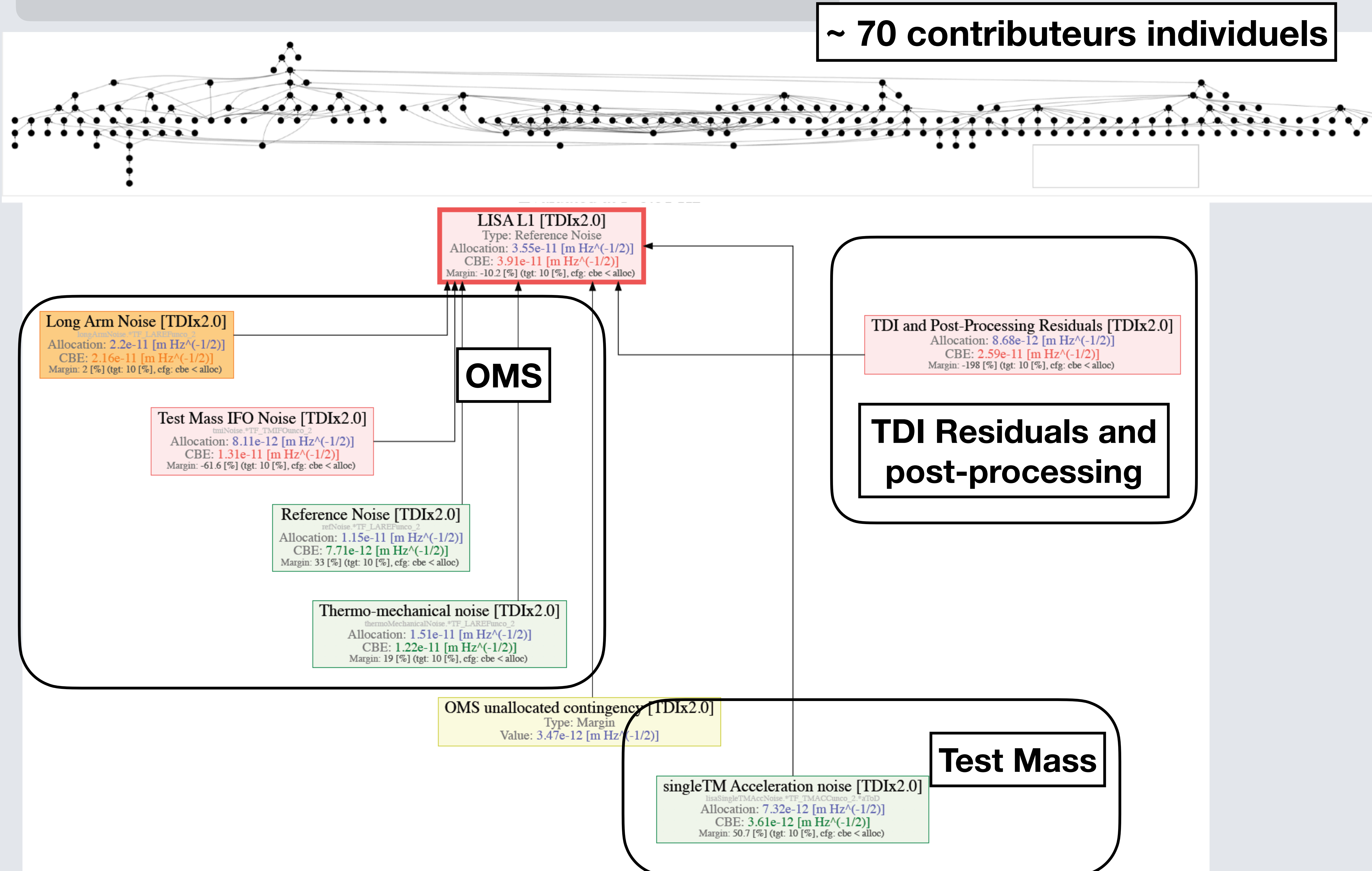
TDI Transfer Functions

Categories of TDI transfer function	XX 2.0
Uncorrelated long-arm (science) and reference IFO	$4\, C_{XX}(\omega)$
Uncorrelated test-mass IFO	$C_{XX}(\omega)\left(3 + \cos(2\omega\frac{L}{c})\right)$
Uncorrelated test-mass acceleration	$4\, C_{XX}(\omega)\left(3 + \cos\left(2\omega\frac{L}{c}\right)\right)$

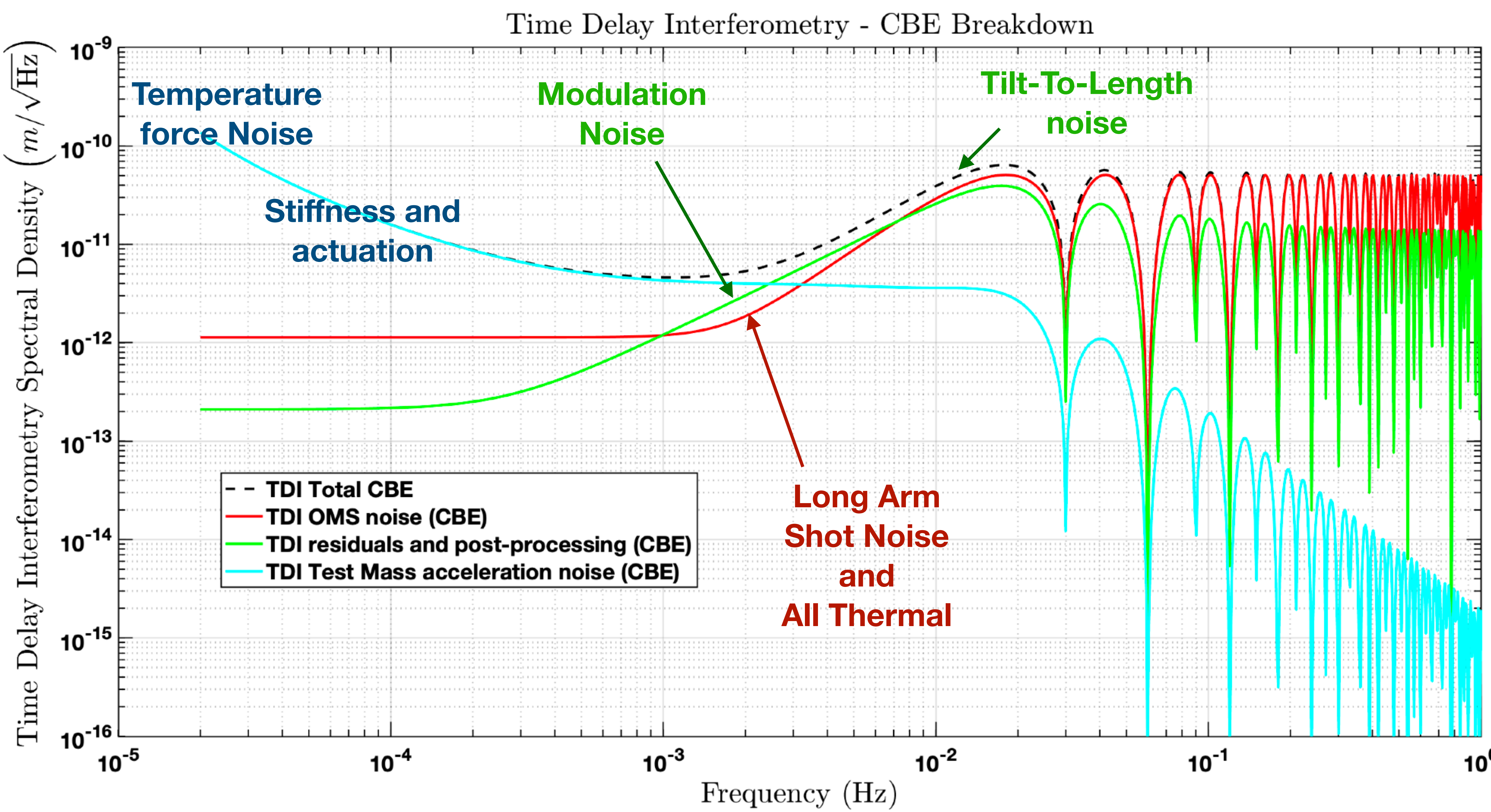
fer functions used in the Performance Model



Combiner les sources de bruits

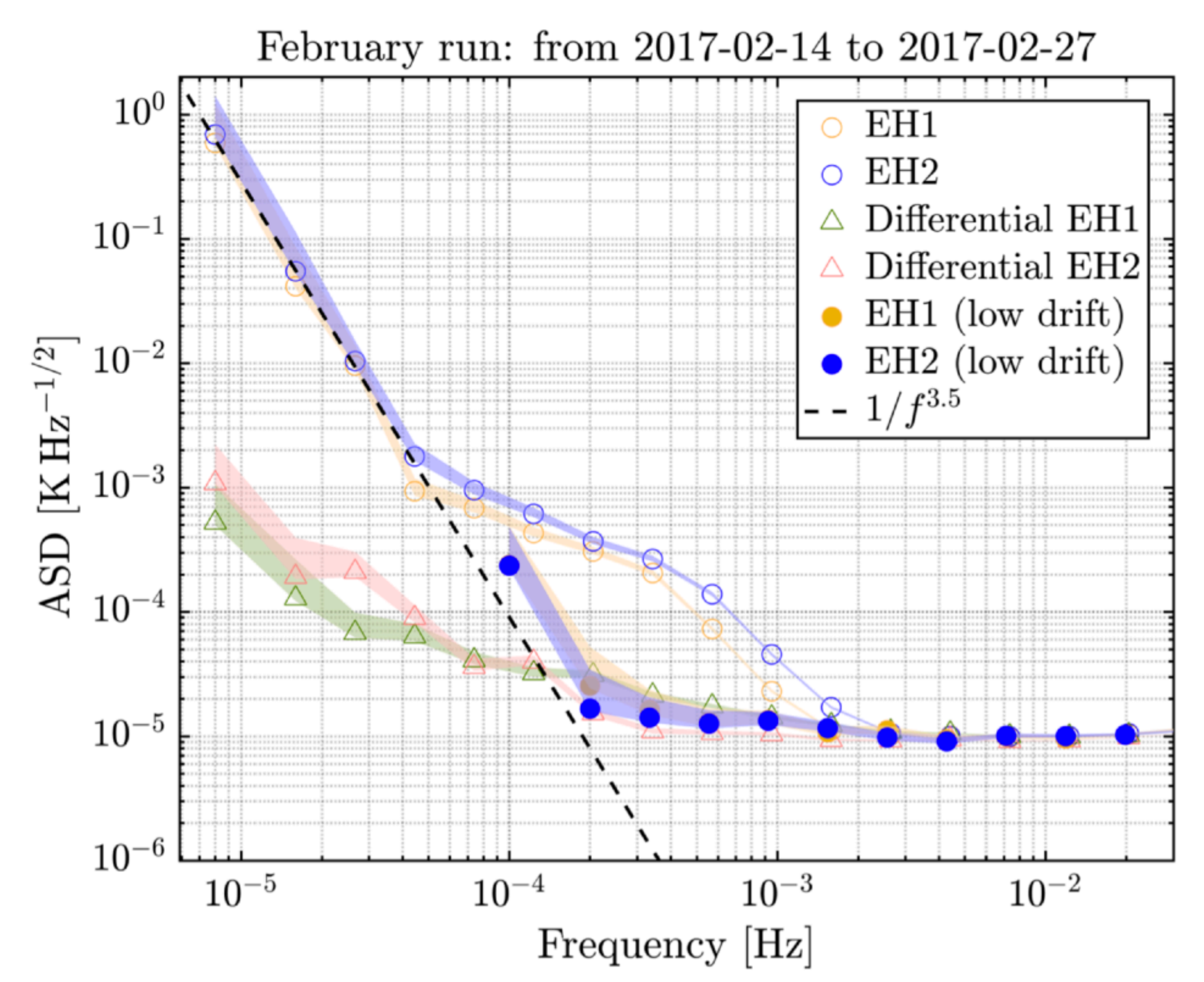


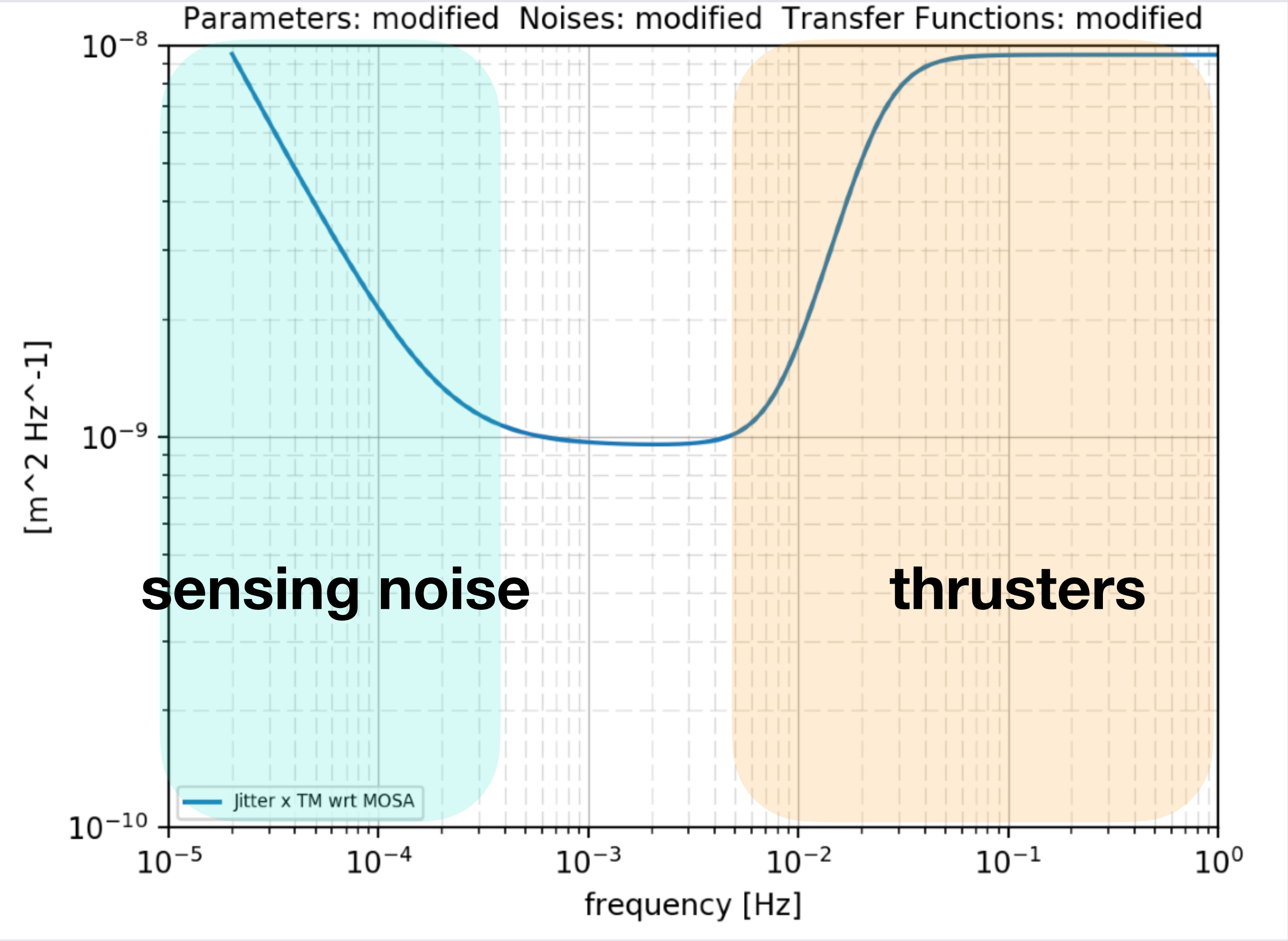
Budget De Bruit



IV/ Limitations

Thermal and Platform stability : correlations

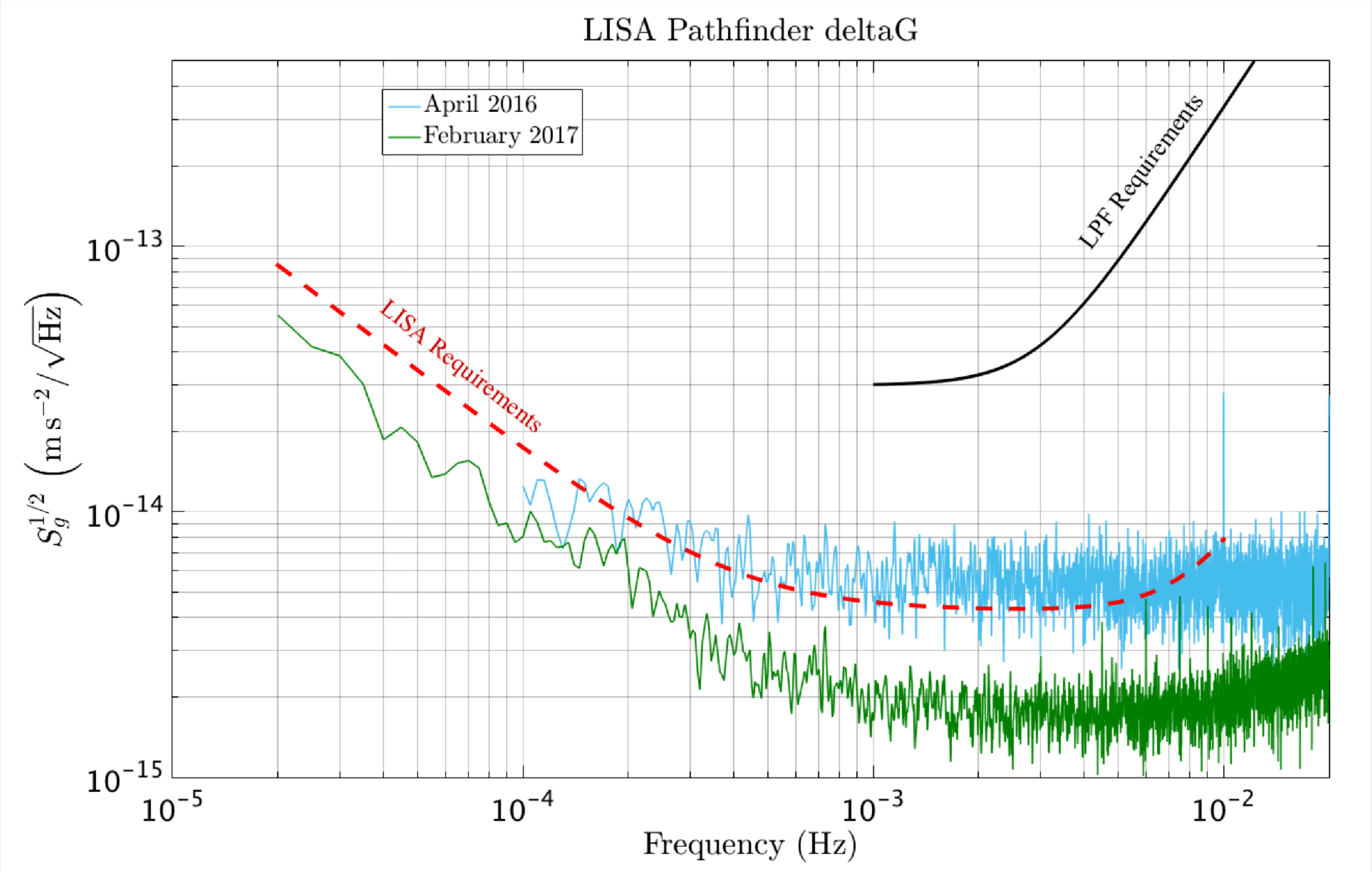




- **Héritage Pathfinder limité au GRS**
- **Design LISA différent**

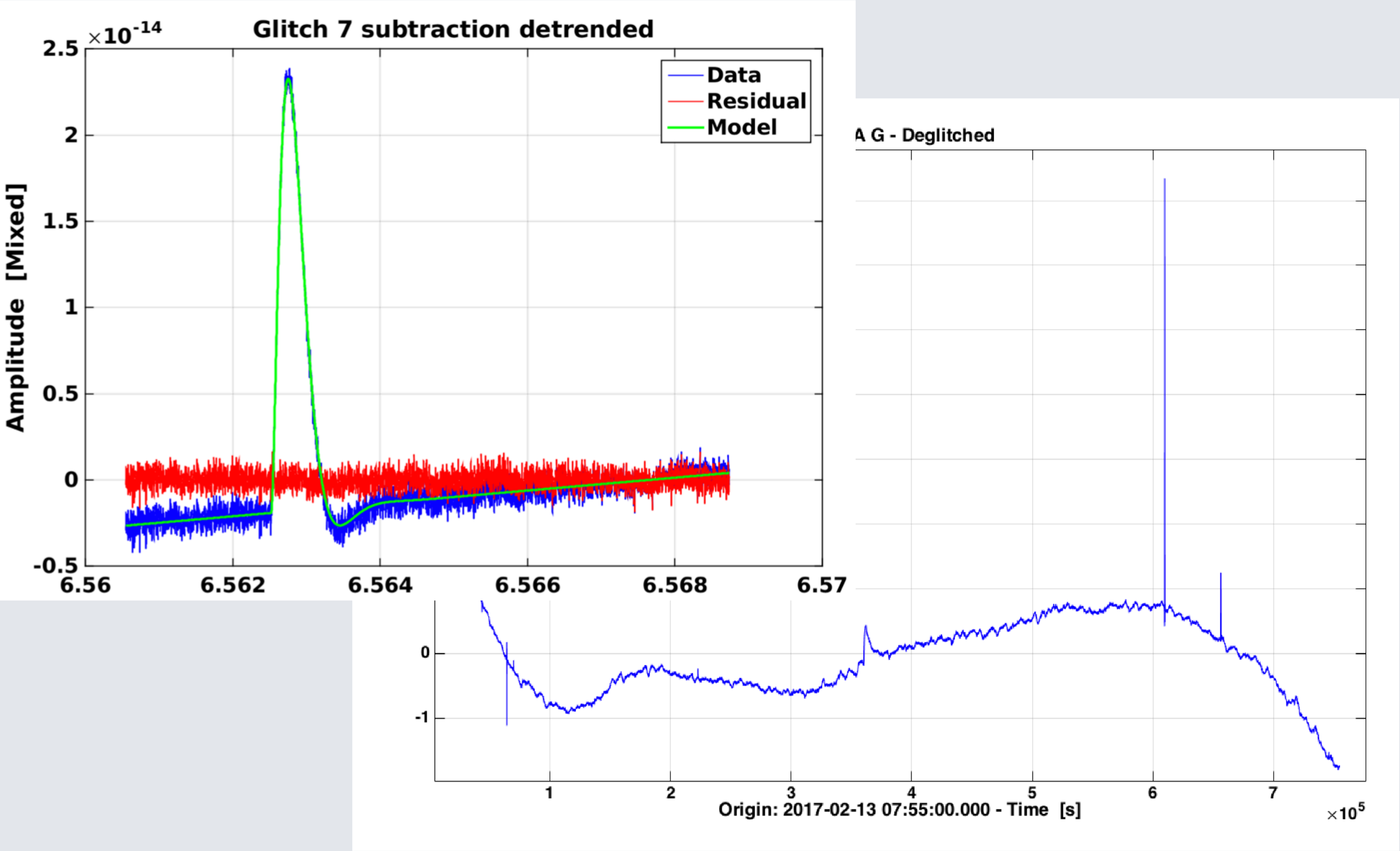
- **Héritage Pathfinder sur l'axe sensible**
- **Jitters angulaires différents.**

Non stationarity



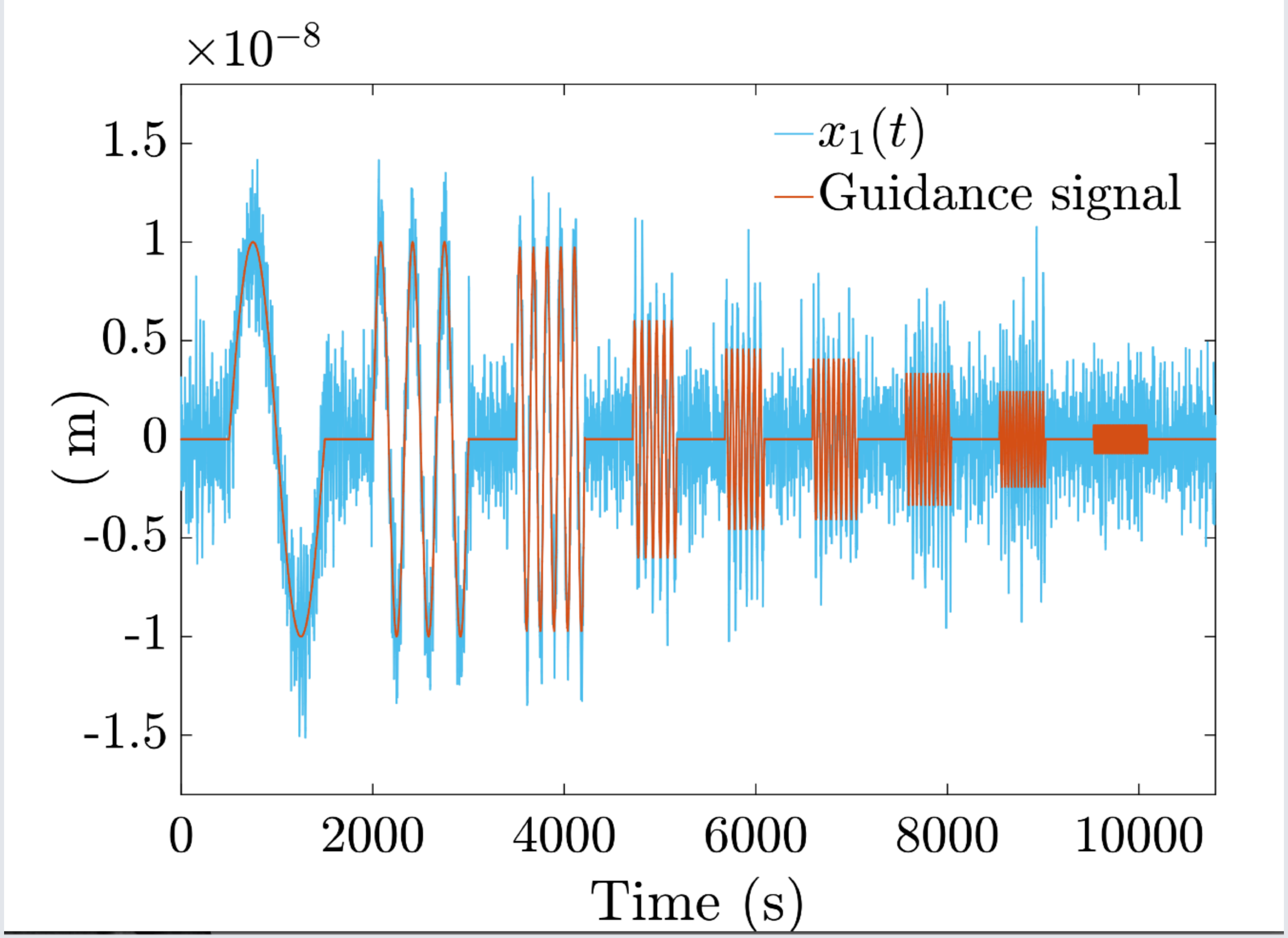
M. Armano et al. Beyond the Required LISA Free-Fall Performance: New LISA Path.nder Results down to 20 µHz. Phys. Rev. Le.., 120:061101, 2018.

Glitches



Glitch 7 subtraction detrended
×10^-14
2.5
2
1.5
1
0.5
0
-0.5
Amplitude [Mixed]
Data
Residual
Model
6.56
6.562
6.564
6.566
6.568
6.57
A G - Deglitched
0
-1
1
2
3
4
5
6
7
Origin: 2017-02-13 07:55:00.000 - Time [s]
×10^5

Calibration



- Clock Noise / TTL / Stiffness ?
- Du fait de la présence du bruit laser - TDI indispensable (simulation)

Missing noises

- Modélisation du Phasemètre
- Modélisation des DWS.
- Résidu du mouvement du SC sur l'axe sensible.
- Interpolation - Laser
- Armlength Stochastic
- Sidebands coupling because of clock calibration.
- Modelling of the Anti Aliasing filter in the performance model.
- Long Arm Line Of Sight alignment.

Merci

Acces au data pack de la release 2.0.1 (Technical Note+ release Note + Changelog):

https://atrium.in2p3.fr/87d2870c-5aef-4f4d-8a60-9a3afc4fe62f

Site web pour produire plots et récupérés les données de WebNSDF :

https://perf-lisa.in2p3.fr/

contact : martino@apc.in2p3.fr