Length sensing and control for ET-LF

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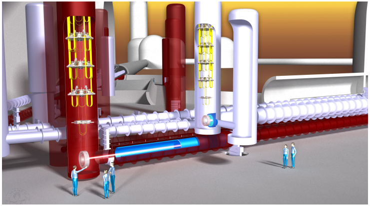
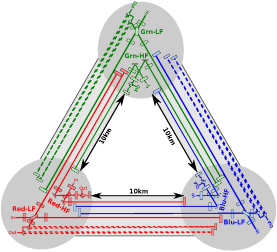


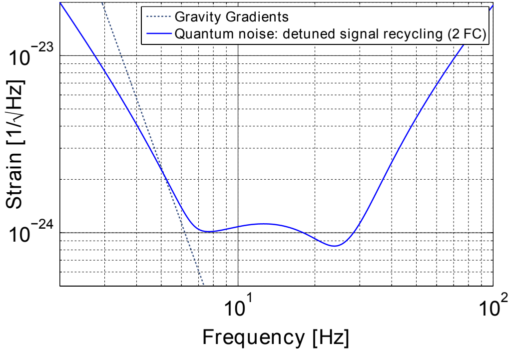
Quick reminder of ET-LF

- Underground facility, equilateral triangle with 10 km between corner stations
- Detuned signal recyling, 10 dB frequency dependent squeezing, 211 kg mirrors.
- Modified superattenuator, 17 m tall
- Cryogenic infrastructure
- 10 K, silicon, 12 cm beam radius, TEM00



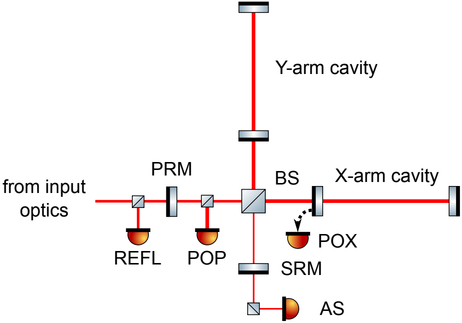
What's the problem?

- ET-LF will be most sensitive around 7 to 30 Hz
- Control noise at low frequency is potentially high
- Reduction in size of error signal locking range at low frequencies
    - We want to detune to 25 Hz which has not been done before
- We need to model the interferometer to assess its controllability
- **To model it we need to make decisions about certain loosely- or un-defined parameters from the design study**
- All modelling undertaken so far is transferrable to ET-HF



Sensing ports and length terminology

- In a dual-recycled interferometer there are five degrees of freedom to handle:
  - **CARM** $= \frac{L_Y + L_X}{2}$
  - **DARM** $= \frac{L_Y - L_X}{2}$
  - **MICH** $= l_Y - l_X$
  - **PRCL** $= l_P + \frac{l_Y + l_X}{2}$
  - **SRCL** $= l_S + \frac{l_Y + l_X}{2}$
- Sensing ports:
  - **REFL**: behind the power recycling mirror
  - **POP**: behind the beamsplitter
  - **AS**: behind the signal recycling mirror
  - **POX**: reflected light from arm cavities



What have we "optimised"?

Relevant ET-LF design parameters like mirror specifications, arm lengths etc. taken from page 347 of the design study.

Additional optimisations:

- PRM transmissivity
- Sideband frequencies
- Schnupp asymmetry
- SRC length

	ET-HF	**ET-LF**
Approximate frequency range	10–10^4 Hz	1–250 Hz
Detection scheme	DC readout	DC readout
Input power (after IMC)	500 W	3 W
Laser wavelength	1064 nm	1550 nm
Beam shape	LG_{33}	TEM_{00}
ARM CAVITIES		
Arm length	10 km	10 km
Opening angle	60°	60°
Arm power	3 MW	18 kW
Temperature	290 K	10 K
Mirror material	fused silica	silicon
Mirror diameter	62 cm	>45 cm
Mirror thickness	30 cm	about 50 cm
Mirror mass	200 kg	211 kg
Beam radius (at mirror)	7.2 cm	9.0 cm
Beam waist (symmetric cavity)	2.51 cm	2.9 cm
RoC (symmetric cavity)	5690 m	5580 m
Scatter loss per surface	37.5 ppm	37.5 ppm
Finesse	880	880
Reflective coating ITM	tantala/silica 8 $\lambda/4$ doublets	tantala/silica 9 $\lambda/4$ doublets
Reflective coating ETM	tantala/silica 17 $\lambda/4$ doublets	tantala/silica 18 $\lambda/4$ doublets
Transmission ITM	7000 ppm	7000 ppm
Transmission ETM	6 ppm	6 ppm

Choice of modulation frequencies

Requirement

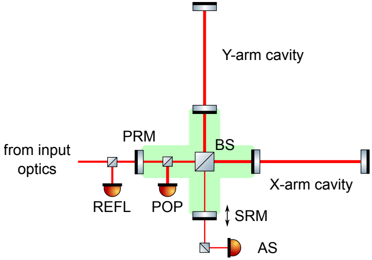
Decoupled error signals are needed to control various lengths

Problem

Presence of SRM introduces back coupling of SRCL error signal to other degrees of freedom. Carrier too coupled to use as a control signal.

Solution

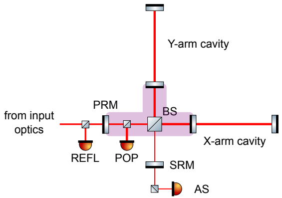
Use sidebands! Sidebands with specific resonance conditions provide us with artificial fields which can be used to obtain decoupled error signals.



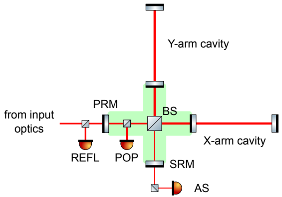
Choice of modulation frequencies

- The first sideband resonant only within the PRC
- The second sideband: resonant within both the PRC and SRC
- Both sideband frequencies anti-resonant in the arm cavities
- The modulation frequencies are resonant in the GEO-style IMC (not yet implemented in models) of lengths 20.541 m and 21.150 m

Sideband 1

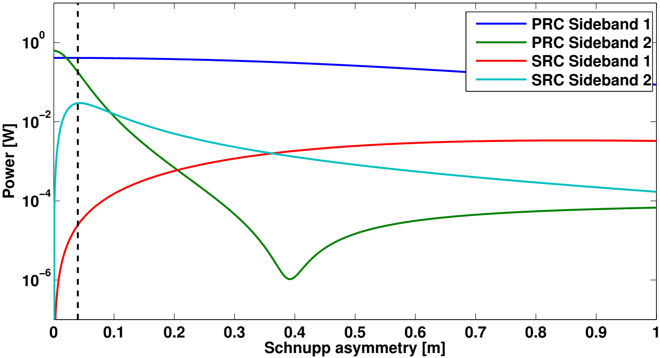


Sideband 2



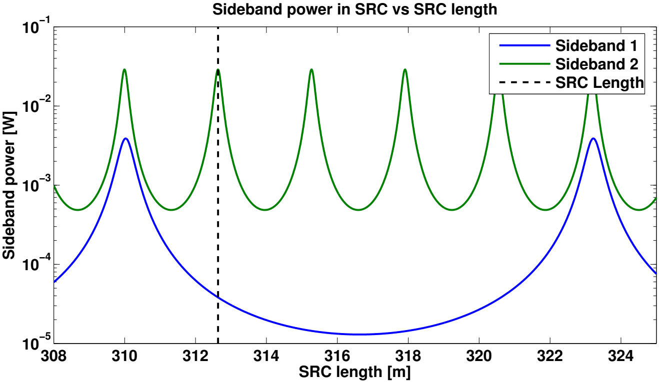
Schnupp asymmetry

- By default, the sidebands can't enter the SRC
- Introducing a Schnupp asymmetry allows the sidebands to leak into the SRC for the purposes of control. It was set to 5 cm although another choice would have been 0.4 m.
- Smaller asymmetry chosen for lower frequency noise coupling



Signal recycling cavity length

The signal recycling cavity length was changed from 310 m to 312.634 m to prevent resonance of f_1 affecting signal separation.



Introduction to the simulation models

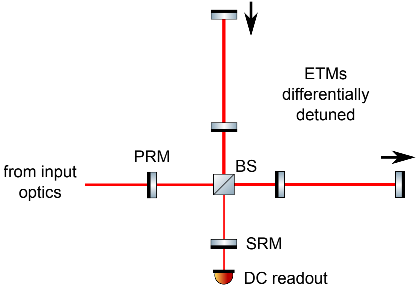
- Two models using FINESSE and Optickle simulation packages
- **FINESSE** (and **PyKat**): higher order modes, parametric instabilites
- **Optickle**: control loop noise
- Detection ports used: arm cavities, PRC, SRC, light reflected back to laser
- Carrier and sideband powers at different detection ports agree

Parameter	**Value**
P_{xArm}	17.337 kW
P_{yArm}	17.333 kW
$P_{asymmetric}$	0.129 W
P_{PR}	62.903 W

```
% as part of previous work in sibling project directories.
%
% Sean Leavey
% November 2014

%% Define stuff

% Frequency to calculate the response of the IFO for.
f = 1;

%% build ET-LF model

par = param_ETD_LF();

% get parameters for ET-LF
par = genOptickleParms(par);

% get Optickle model for ET-LF
opt = opt_ETD_LF(par);

%% add some probes

% probe reflected light
[opt, n_REFL_DC] = addProbeIn(opt, 'REFL_DC', 'REFL', 'in', 0, 0);
[opt, n_REFL_I1] = addProbeIn(opt, 'REFL_I1', 'REFL', 'in', par.Mod.f1, 0);
[opt, n_REFL_Q1] = addProbeIn(opt, 'REFL_Q1', 'REFL', 'in', par.Mod.f1, 90);
[opt, n_REFL_I2] = addProbeIn(opt, 'REFL_I2', 'REFL', 'in', par.Mod.f2, 0);
[opt, n_REFL_Q2] = addProbeIn(opt, 'REFL_Q2', 'REFL', 'in', par.Mod.f2, 90);
[opt, n_REFL_2FI1] = addProbeIn(opt, 'REFL_2FI1', 'REFL', 'in', 2 * par.Mod.f1, 0);
[opt, n_REFL_2FQ1] = addProbeIn(opt, 'REFL_2FQ1', 'REFL', 'in', 2 * par.Mod.f1, 90);
[opt, n_REFL_2FI2] = addProbeIn(opt, 'REFL_2FI2', 'REFL', 'in', 2 * par.Mod.f2, 0);
[opt, n_REFL_2FQ2] = addProbeIn(opt, 'REFL_2FQ2', 'REFL', 'in', 2 * par.Mod.f2, 90);
[opt, n_REFL_SUMI] = addProbeIn(opt, 'REFL_SUMI', 'REFL', 'in', par.Mod.f2 + par.Mod.
[opt, n_REFL_SUMQ] = addProbeIn(opt, 'REFL_SUMQ', 'REFL', 'in', par.Mod.f2 + par.Mod.
[opt, n_REFL_DIFFI] = addProbeIn(opt, 'REFL_DIFFI', 'REFL', 'in', par.Mod.f2 - par.Mo
[opt, n_REFL_DIFFQ] = addProbeIn(opt, 'REFL_DIFFQ', 'REFL', 'in', par.Mod.f2 - par.Mo
```

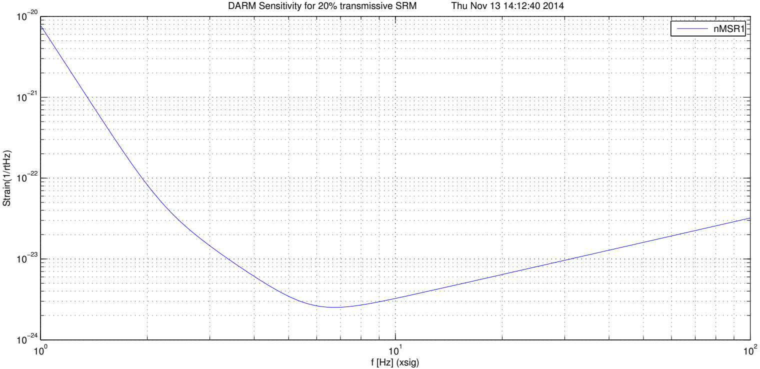
DARM offset: why do we need it?

- DC readout: homodyne local oscillator created by putting a small **offset** into the **MICH** or **DARM** degree of freedom
- The **carrier** that leaks out behaves as a **LO**
- DC readout moves the interferometer slightly **off** of the dark fringe
- **Realistic DC readout** included in both the models such that no more than 100 mW is incident on the photodiodes
- The DC power in the AS port due to DARM offset is **quadratic** in DARM offset
- Detune the **ETMs** and not the BS or the ITMs



Sensitivity: how close are we to design?

- Comparision between DARM quantum noise limited sensitivity obtained from Optickle and PyKat to the design study
- Matches the design study apart from the 10 dB squeezing effect



The control matrix

- What is a control/sensing matrix?
  - The sensing matrix describes the relation between the DOFs and signal extraction ports
  - Ideal case: matrix diagonal implying all sensing signals are decoupled. However this is not the case and we get non zero off diagonal elements.

POP_I1	DOF
-8.66E+07	CARM
-8.10E+03	DARM
5.35E+02	MICH
1.38E+05	PRCL
1.31E+03	SRCL

MICH	PORTS
-1.30E+02	reflI1
-6.33E+01	reflq1
1.07E+03	refli2
2.71E+03	reflq2
2.61E+02	refl2fi
7.51E+02	refl2fq
-5.18E+02	refl2f2i
6.03E+02	refl2f2q
-1.58E-02	refl_f2-f1I
-2.65E-03	refl_f2-f1Q
-1.01E-02	refl_f2+f1I
-2.42E-03	refl_f2+f1Q
-9.13E+04	asi1
4.84E+04	asq1
-2.85E+06	asi2
-1.05E+05	asq2
-6.32E+01	as2fi
-4.25E+01	as2fq
-2.44E+01	as2f2i
2.46E+00	as2f2q
-4.93E-02	as_f2-f1I
-1.20E-01	as_f2-f1Q
6.23E-02	as_f2+f1I
6.09E-02	as_f2+f1Q
5.35E+02	popi1
-6.78E+03	popq1
5.55E+04	popi2
1.10E+05	popq2
1.42E+01	pop2fi
8.96E+00	pop2fq
8.18E+00	pop2f2i
-1.47E+01	pop2f2q
9.45E-03	pop_f2-f1I
2.40E-03	pop_f2-f1Q
1.39E-02	pop_f2+f1I
-2.02E-02	pop_f2+f1Q
1.85E+07	poxi1
-2.92E+08	poxq1
-3.54E+08	poxi2
-1.25E+08	poxq2
6.11E+03	pox2fi
-5.82E+04	pox2fq
3.15E+03	pox2f2i
5.67E+04	pox2f2q
-1.21E+01	pox_f2-f1I
8.07E+00	pox_f2-f1Q
-7.38E+01	pox_f2+f1I
7.38E+01	pox_f2+f1Q

The control matrix

Modelling the IFO with these new conditions, we can see where best to control each DOF:

- **CARM** can be controlled with $\mathbf{f_1}$ at **REFL**
- **PRCL** can be controlled with $\mathbf{f_1}$ in **POP** (CARM and PRCL coupled)
- **DARM** can be controlled with **DC** at **AS**
- **MICH** can be controlled with $\mathbf{f_2}$ in **POP** (DARM, MICH, SRCL coupled)
- **SRCL** can be controlled with the $\mathbf{f_2}$ that leaks into the SRC and then back out into the PRC (at **POP**)

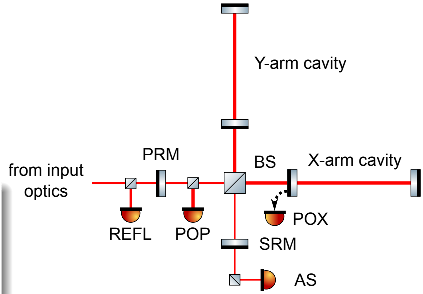
# CARM	DARM	MICH	PRCL	SRCL	PORTS
3.37E+08	3.38E+04	1.65E+02	-5.87E+05	-6.45E-01	reflI1
1.08E+08	1.08E+04	5.15E+01	-1.89E+05	-2.42E-01	reflq1
1.55E+08	1.55E+04	5.20E+03	-2.93E+05	-5.60E+03	refli2
-4.69E+07	-4.67E+03	7.52E+03	9.17E+04	3.03E+03	reflq2
-1.16E-04	2.57E-06	5.13E-05	2.62E-03	-3.46E-07	refl2fi
1.65E-04	-2.68E-06	-5.84E-05	-3.77E-03	3.54E-07	refl2fq
-1.36E-05	-1.78E-05	-7.51E-03	6.56E-03	1.38E-03	refl2f2i
-1.06E-05	1.23E-05	5.78E-03	6.75E-03	2.21E-03	refl2f2q
-2.39E-01	-7.77E+08	-1.37E+06	5.50E+00	4.05E-02	asi1
1.75E-01	8.16E+06	1.44E+04	-4.09E+00	1.54E-01	asq1
-9.86E+00	4.87E+10	8.56E+07	3.40E+03	-7.33E+02	asi2
-8.14E+00	-4.30E+10	-7.55E+07	2.85E+03	-5.91E+02	asq2
-7.16E-06	-3.19E-05	-7.39E-04	1.72E-04	6.06E-06	as2fi
1.07E-05	4.76E-07	1.05E-05	-2.43E-04	-3.80E-06	as2fq
1.77E-02	8.36E-04	5.96E-01	-5.40E+00	1.03E+00	as2f2i
1.51E-03	-3.14E-03	-6.67E-01	-5.42E-01	1.25E-01	as2f2q
-6.01E+07	-5.99E+03	3.68E+02	9.59E+04	-3.46E+00	popi1
-7.58E+07	-7.79E+03	-4.55E+03	-1.41E+05	2.85E+01	popq1
1.35E+08	1.37E+04	1.13E+05	-3.98E+04	6.19E+04	popi2
-8.34E+07	-7.81E+03	2.23E+05	1.79E+04	-2.31E+04	popq2
-3.55E-05	5.00E-07	1.19E-05	8.25E-04	-8.07E-08	pop2fi
-4.22E-05	8.11E-07	1.77E-05	9.72E-04	-1.10E-07	pop2fq
1.57E-05	1.17E-05	4.94E-03	-8.11E-03	-1.98E-03	pop2f2i
5.46E-06	-1.82E-05	-8.09E-03	-3.79E-03	-1.53E-03	pop2f2q

Outlook

- Implement detuned SRC in models
- Optimisation of demodulation phases used for RF readout
- Optimisation of the control matrix for detuned signal recycling case
- Complete noise budget for sensing and control of ET-LF

What we still need

- Suspension TFs
- Seismic and facility noise
- Laser intensity/phase noise
- Oscillator phase/intensity noise and control noise



The End!