The London-Paris link

A fibre link for optical frequency transfer between London and Paris

Objectives

- Understand the basics of optical frequency transfer over fibre
- Recognize equipment necessary to operate a link
- Interpret link parameters and performance
- Give examples of applications

Problem of variable delay noise

CLONETS CLOCK NETWORK SERVICES

Every transmission system has delay:

Stable

- phase $\Phi_{in}(t)$
- frequency $f_{in} = \dfrac{d\Phi_{\text{in}}}{dt}$

Transmission system

Variable delay

τ_D

$$\Phi_{out}(t) = \Phi_{in}(t - \tau_D)$$

$$f_{out}(t) = f_{in}(t - \tau_D) \times \left(1 - \frac{d\tau_D}{dt}\right)$$

Unstable / inaccurate

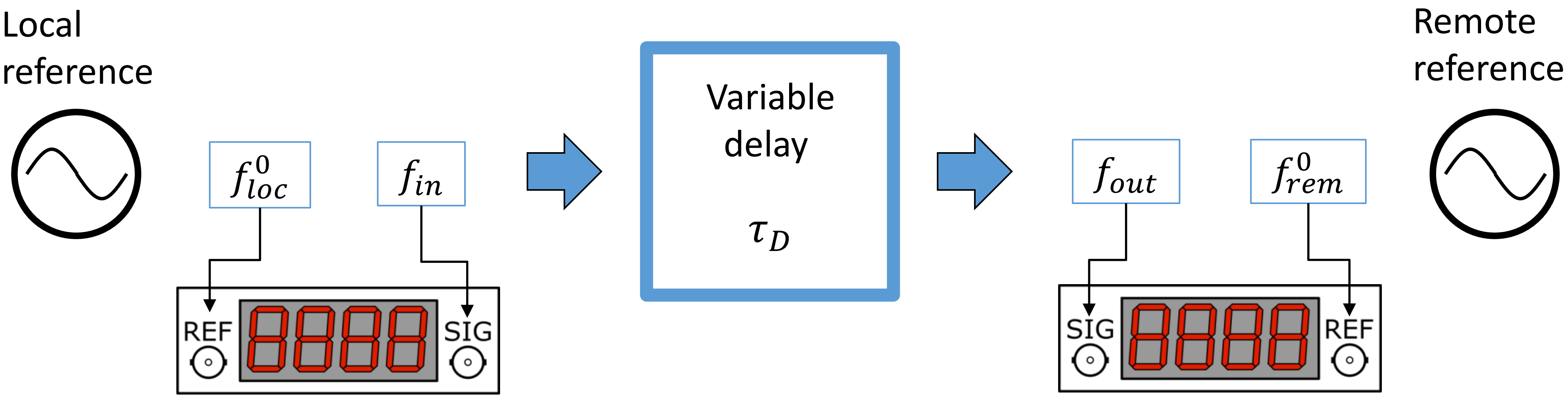
e.g. constant relative velocity

$\tau_D = (d_0 + vt)/c$ $\quad f_{out} = f_{in}\left(1 - \frac{v}{c}\right)$

Any change of transmission delay causes “**Doppler shift**”.

How to measure this noise?

Every frequency measurement needs a reference:



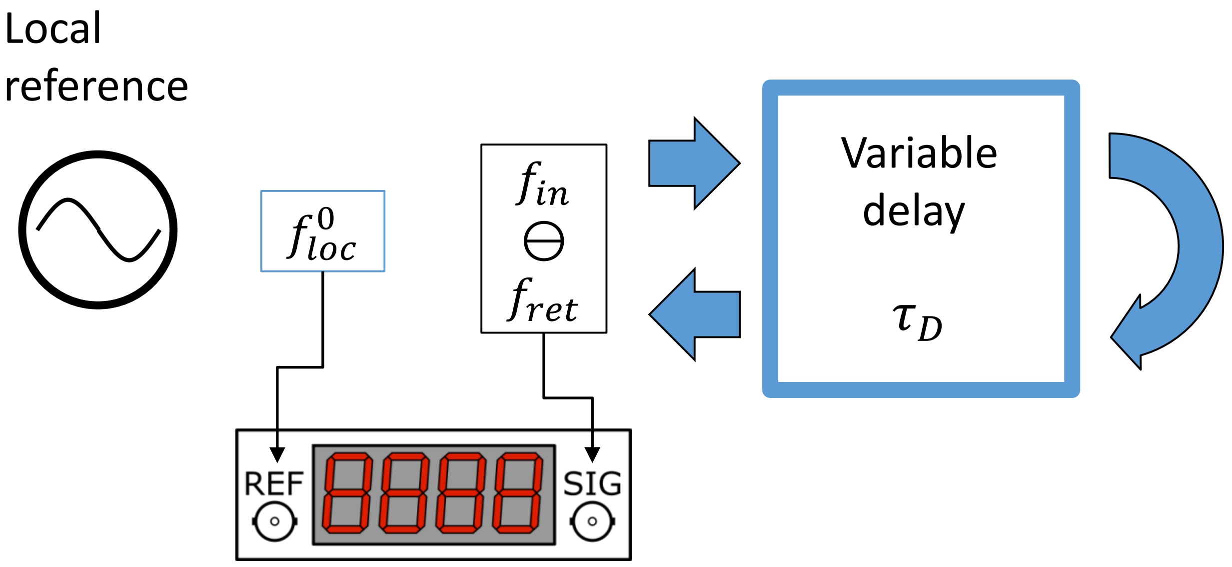
$$\frac{f_{in}}{f^0_{loc}}$$

$$\frac{f_{out}}{f^0_{rem}} = \frac{f_{in}}{f^0_{loc}} \times \frac{f^0_{loc}}{f^0_{rem}} \left(1 - \frac{d\tau_D}{dt}\right)$$

clock mismatch is indistinguishable from Doppler shift.

Principle of delay noise compensation

Solution: double pass transmission



$$f_{out} = f_{in} \times \left(1 - \frac{d\tau_D}{dt}\right)$$

Correct

$$\frac{f_{ret} - f_{in}}{f^0_{loc}} = \frac{f_{in}}{f^0_{loc}}\left(1 - 2\frac{d\tau_D}{dt}\right)$$

Measure

Requires reciprocity!

Measuring the round-trip enables correcting the output

General principle for time and frequency transfer

e.g. **not** 10 MHz

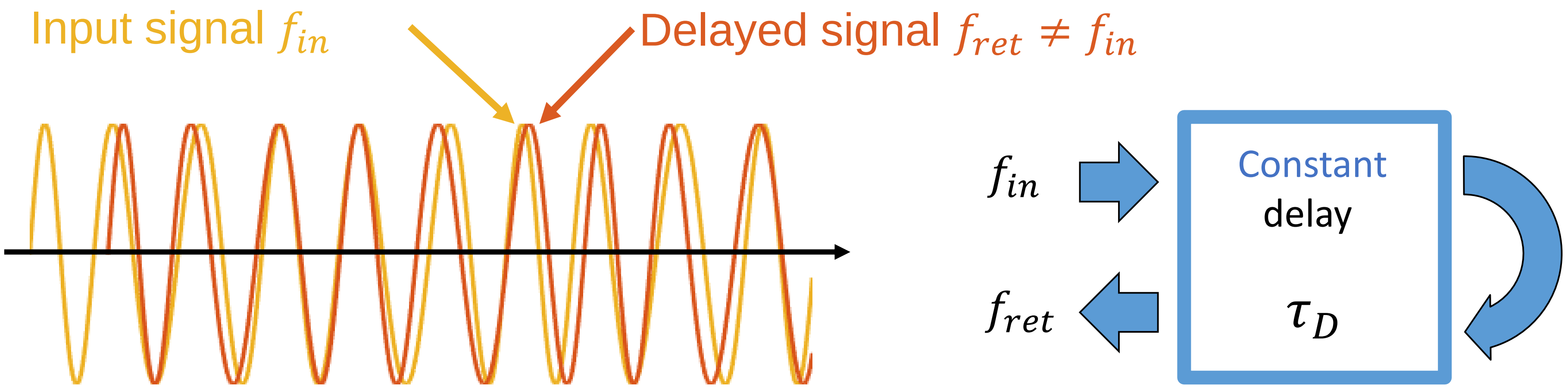
e.g. **not** GNSS

All non-trivial point-to-point time or frequency transfer methods use the double-pass principle.

Cable	or	Radio
Fibre	or	Copper
Carrier	or	Modulated
Packet	or	Physical layer
Time	or	Frequency

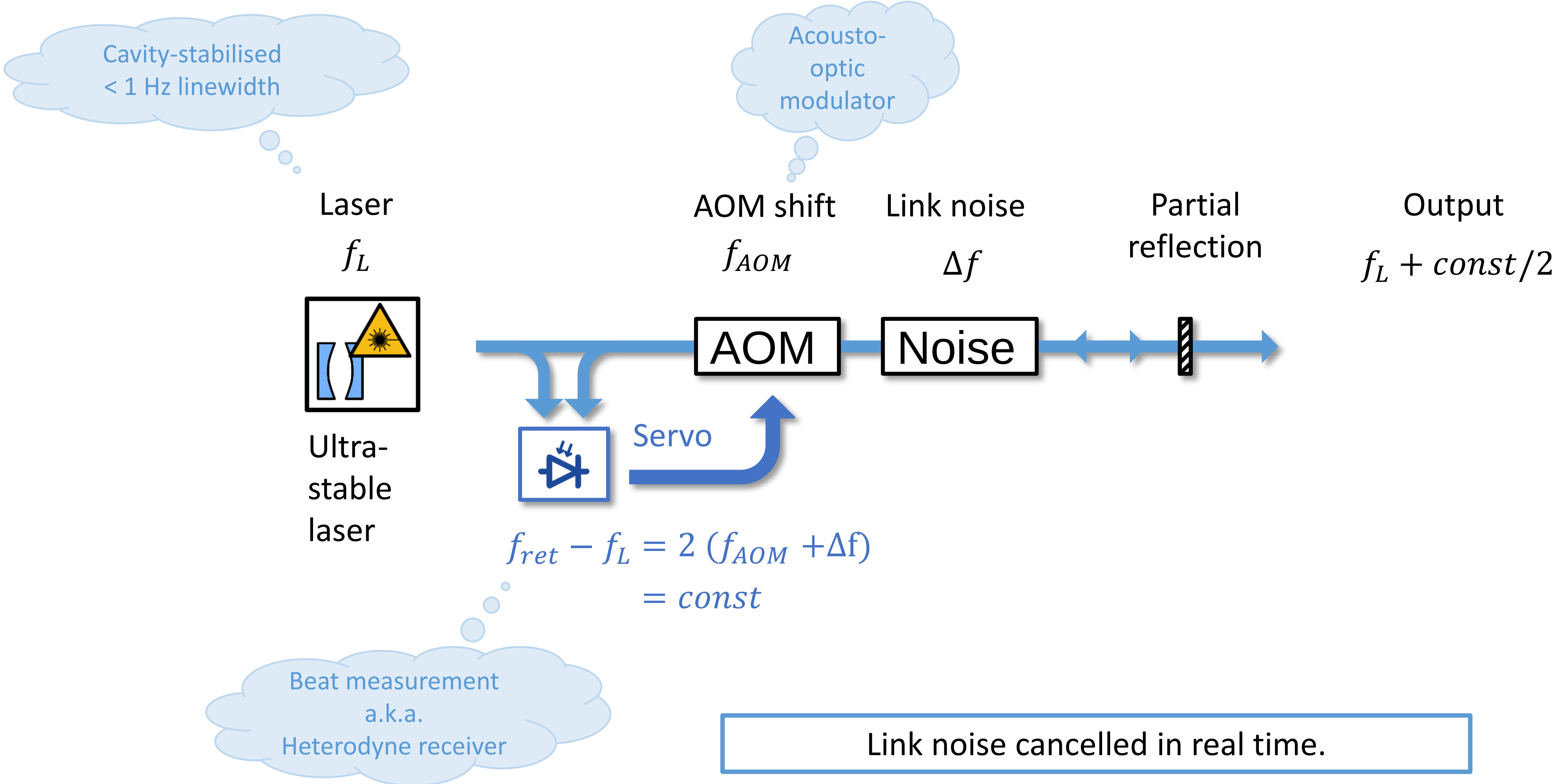
The need for a stable local frequency

Fluctuating input frequency and constant delay:



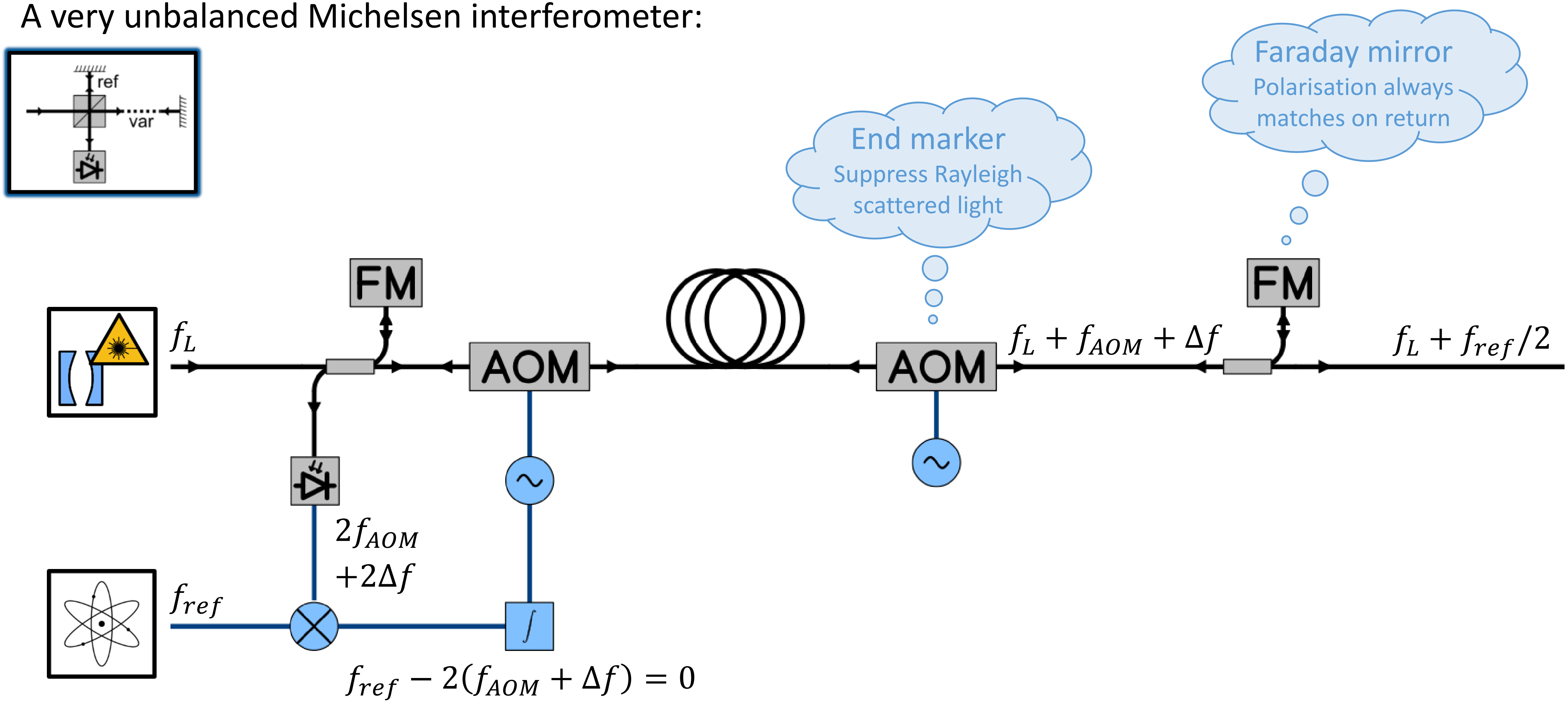
Self-heterodyne noise indistinguishable from delay noise.

Optical frequency transfer over fibre

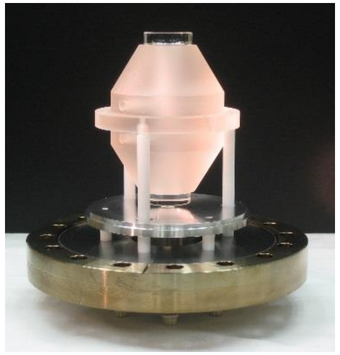


A bit more technical

A very unbalanced Michelsen interferometer:



Ultrastable cavity-stabilised laser



[Jeff Sherman](#)
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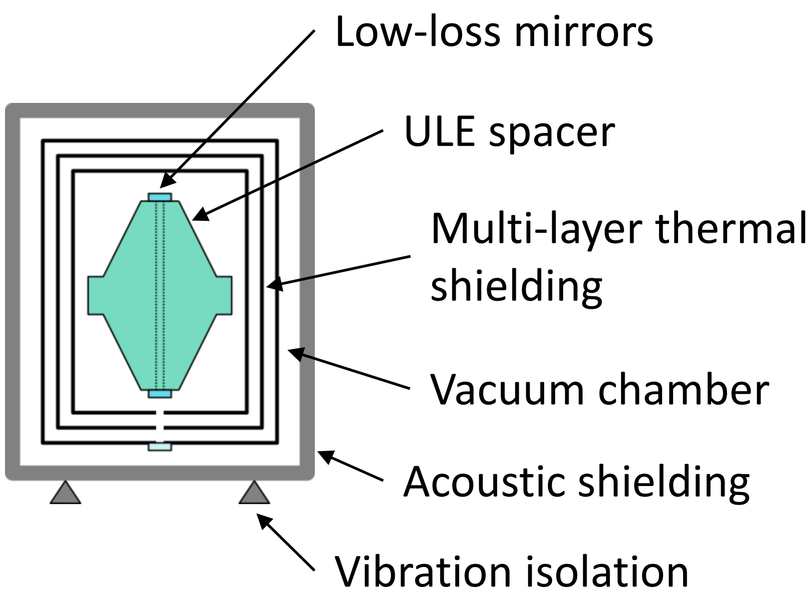
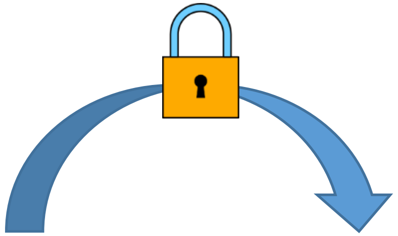
NPL

Very high Q resonator + Pound-Drever-Hall + Tunable laser

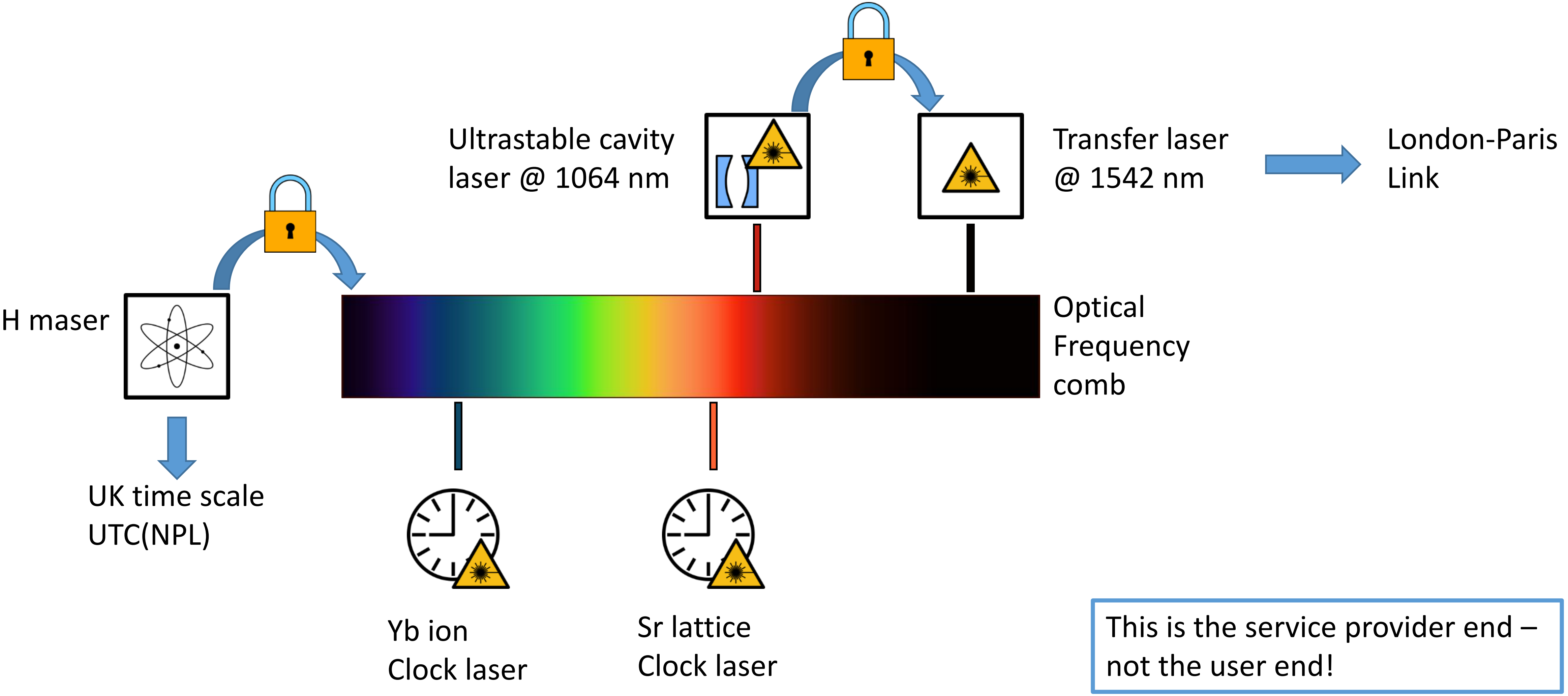




Commercial products available

Sub-Hz linewidth laser

London-Paris link – Local setup



This is the service provider end – not the user end!

Optical frequency transfer - Remote setup

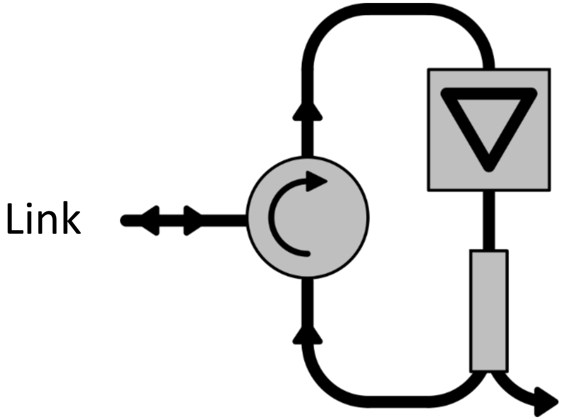
Simplest case:
Partial Faraday mirror

Standard fibre-optic component

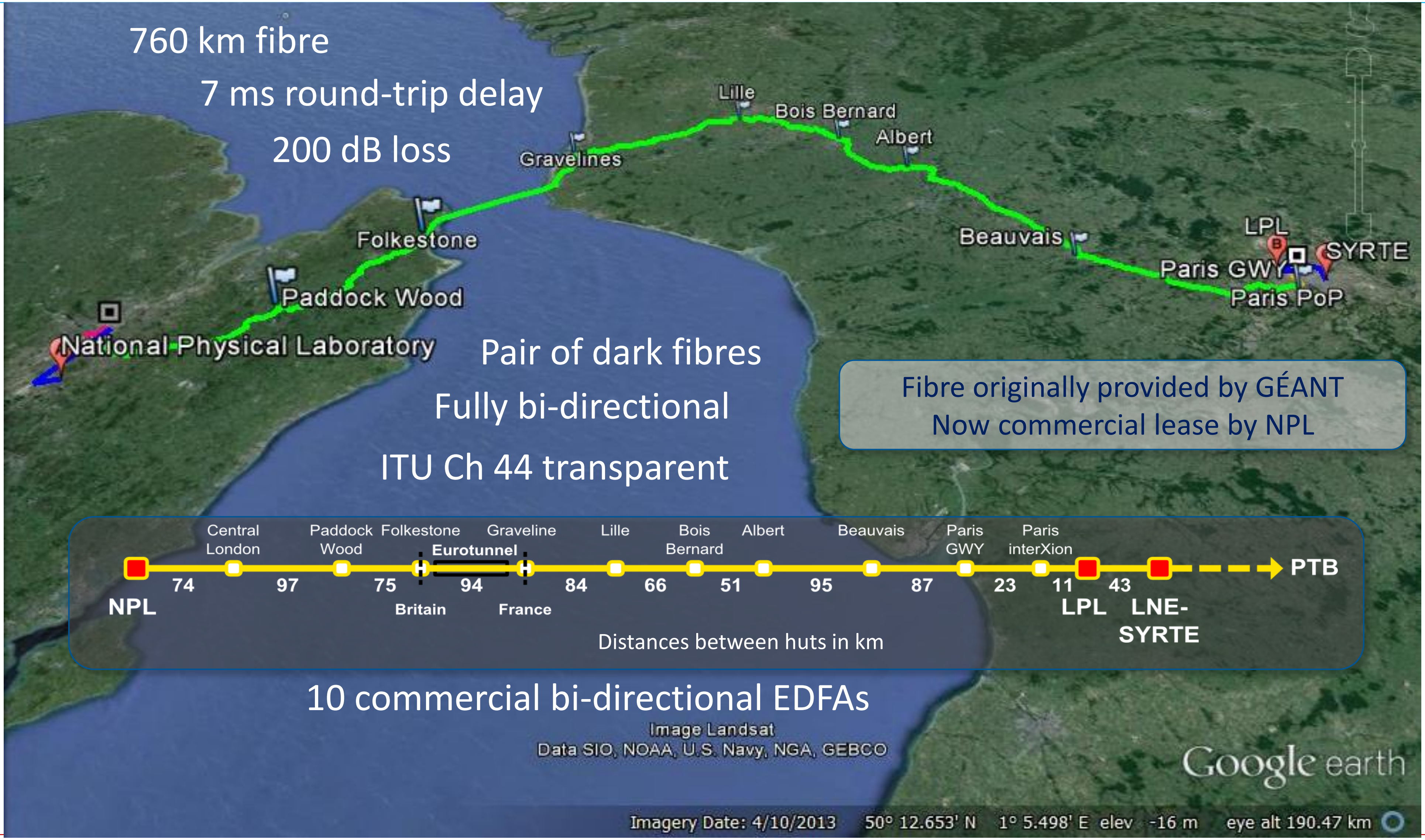
Longer links:
Signal regeneration

London-Paris link:
Repeater laser station

Anne Amy-Klein

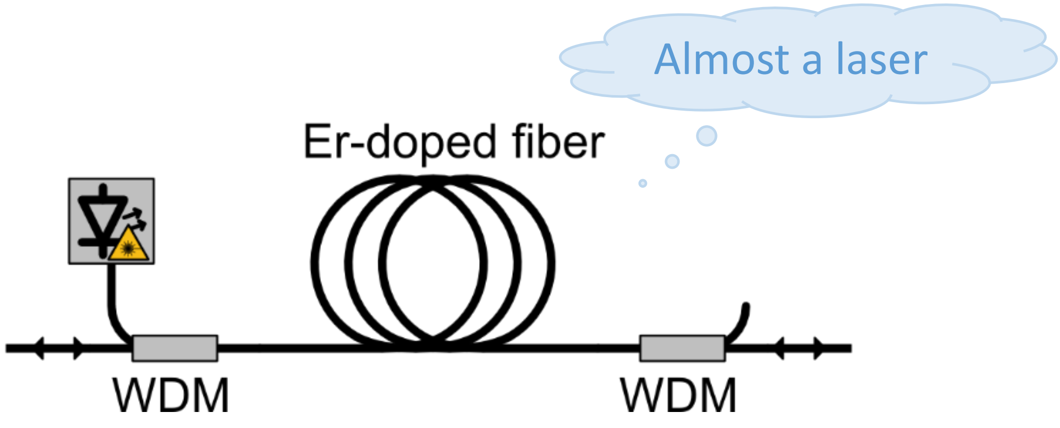


London-Paris link – Fibre route



Amplification techniques

Bidirectional EDFA (Erbium-doped fibre amplifier)



- Gain limited by tendency to oscillate, typically < 15 dB
- Proven technology, benefits from telecom know-how
- Standard telecom EDFAs are **unidirectional**, **not suitable**

Repeater laser station (RLS)

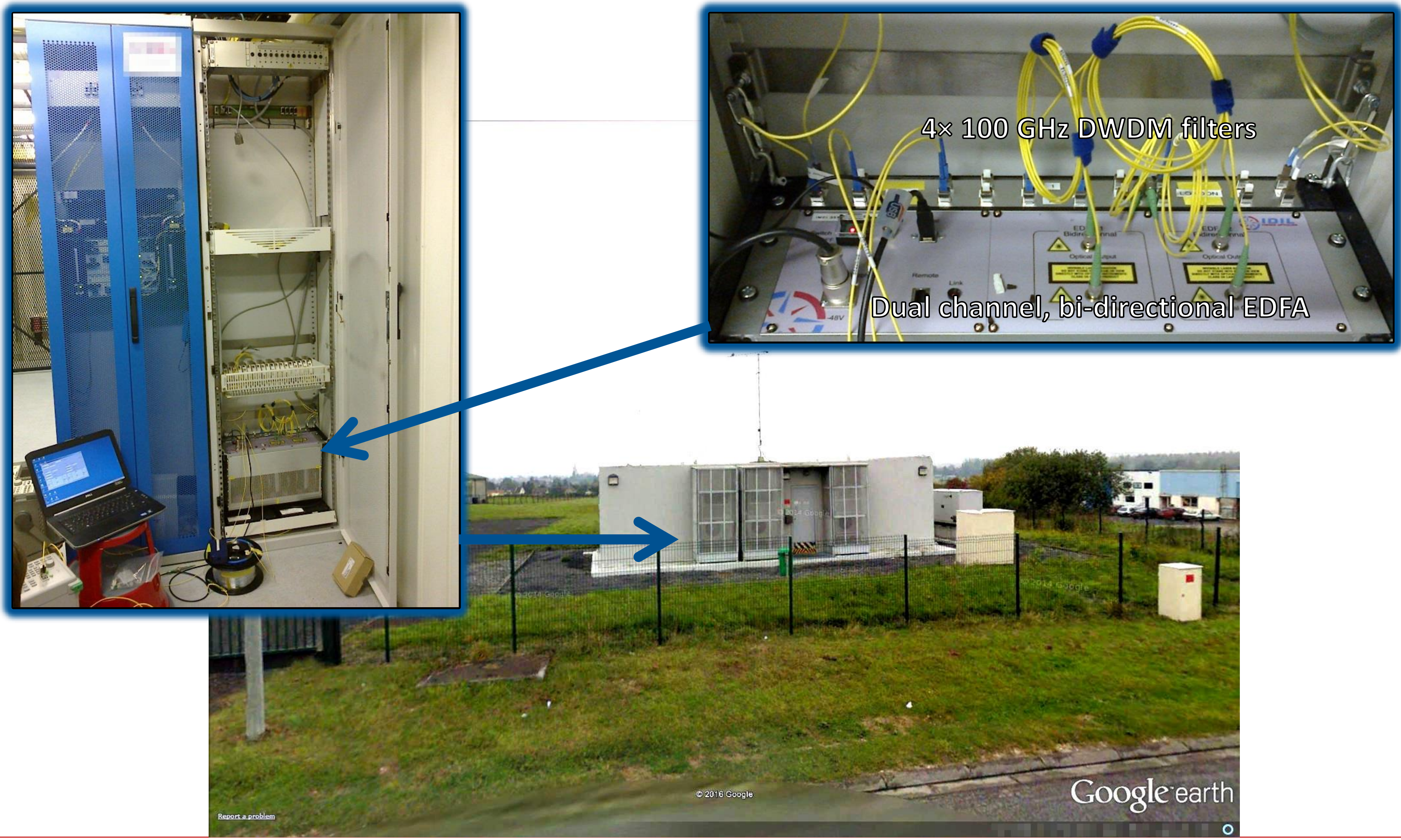
- Essentially a phase locked laser with multiple outputs
- Used to regenerate the signal at the link endpoint

↳ Anne Amy-Klein

Other options

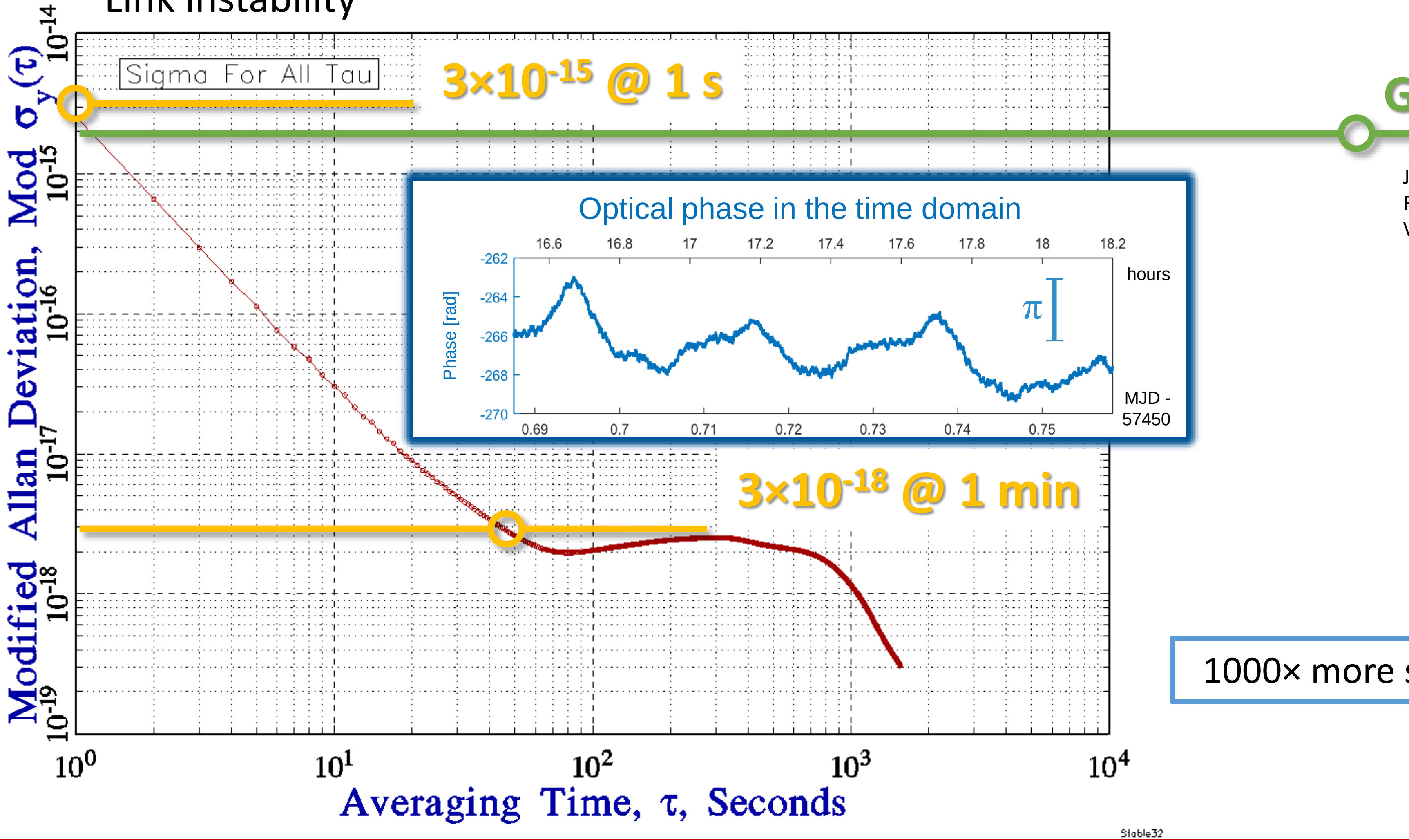
…

Inside an amplifier hut



Performance

Link instability

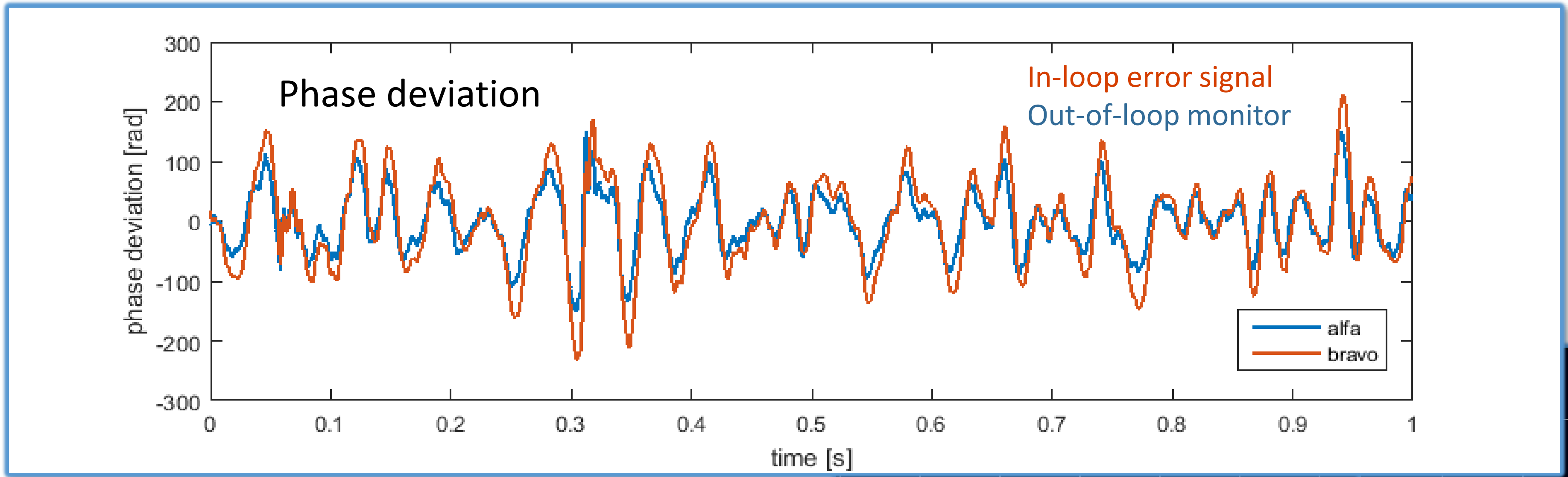


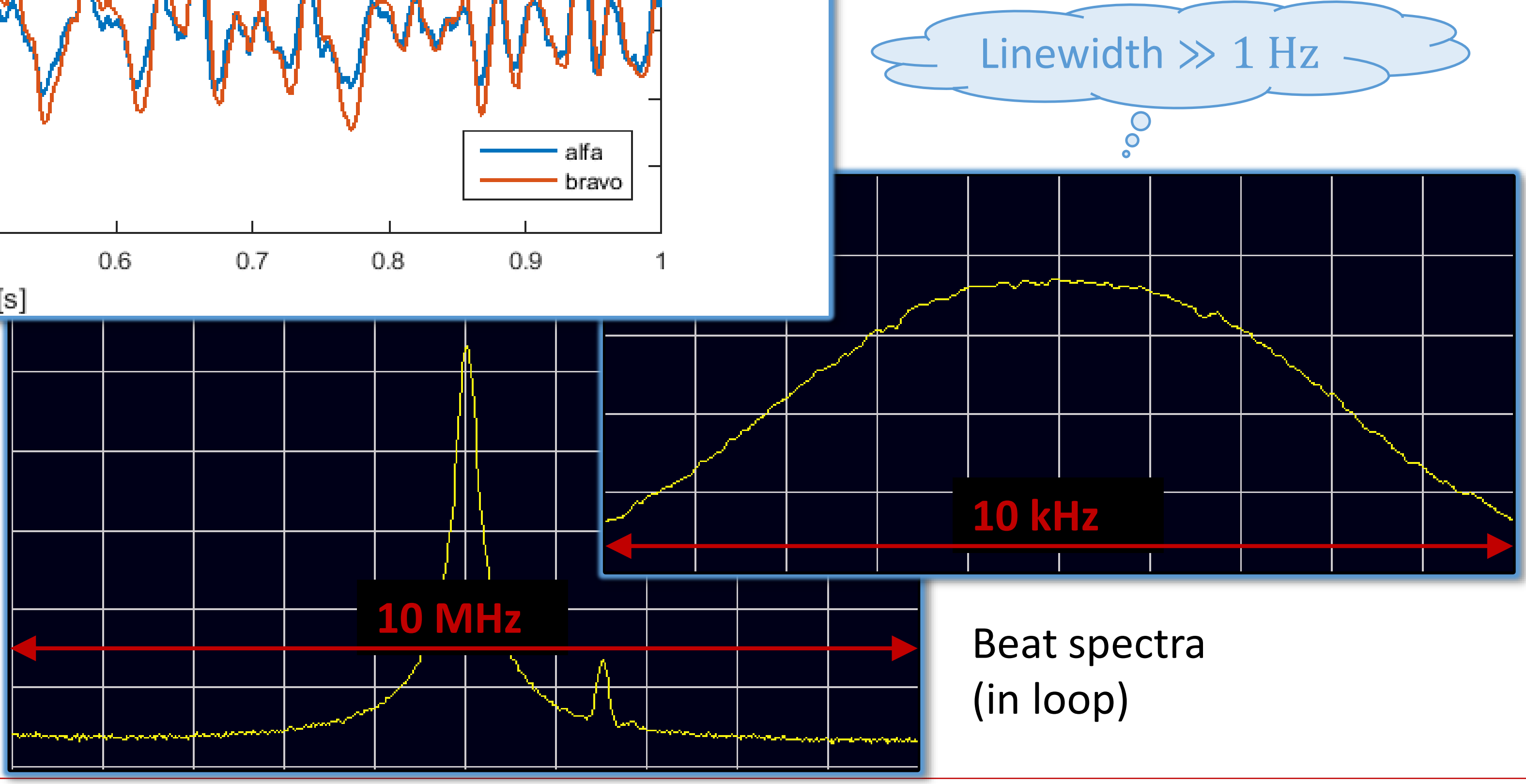
J. Leute et al., IEEE TRANSACTIONS ON ULTRASONICS, FERROELECTRICS, AND FREQUENCY CONTROL, p. 981, VOL. 63, NO. 7, JULY 2016

1000× more stable and accurate than GNSS

Limits to performance

Loop bandwidth limited by round-trip delay



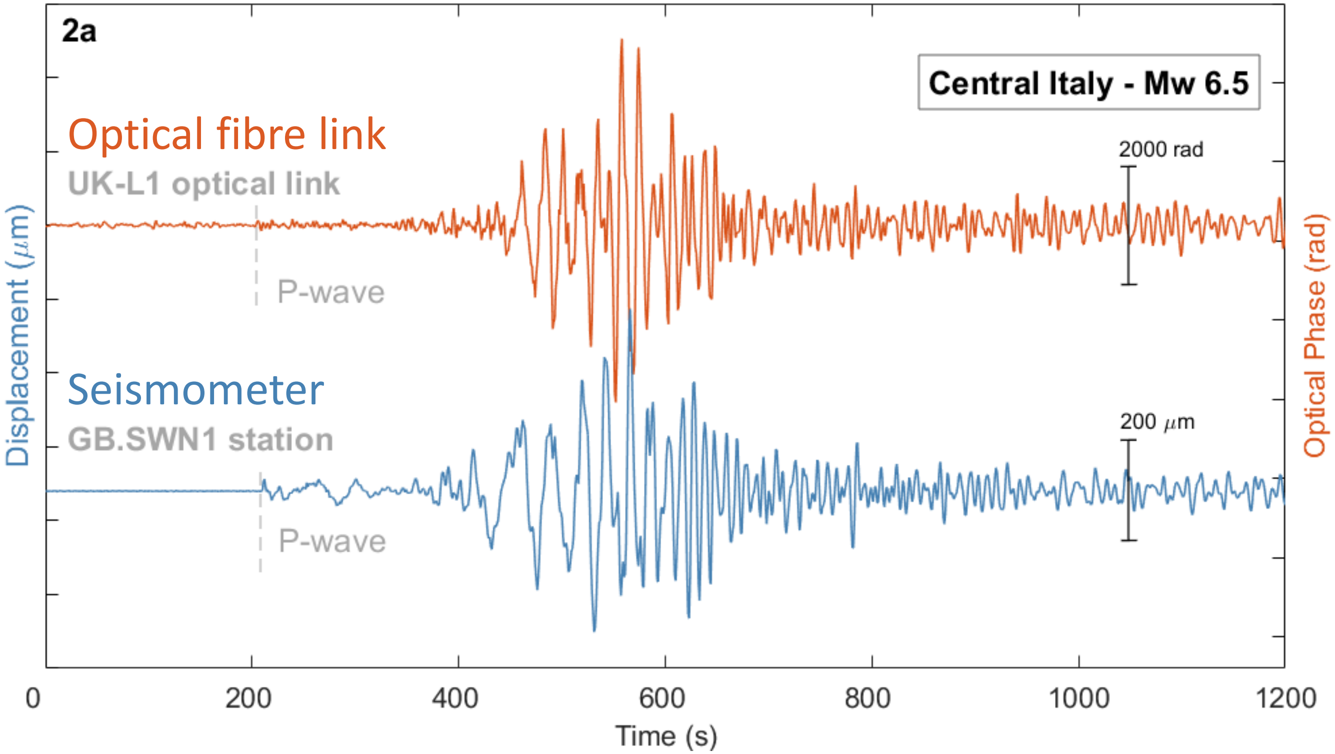


Round-trip delay $\tau = 7.3\ \text{ms}$
Feedback BW $f_{BW} \approx {}^{1}/_{4\tau} = 34\ \text{Hz}$

Beat spectra
(in loop)

Applications

- ➢Optical clock comparison ⇨ Anne Amy-Klein
- ➢Test of fundamental physics
- ➢Earthquake detection



Ultrastable laser interferometry for earthquake detection with terrestrial and submarine cables

GIUSEPPE MARRA, CECILIA CLIVATI, RICHARD LUCKETT, ANNA TAMPELLINI, JOCHEN KRONJÄGER, LOUISE WRIGHT, ALBERTO MURA, FILIPPO LEVI, STEPHEN ROBINSON, ANDRÉ XUEREB, BRIAN BAPTIE, DAVIDE CALONICO

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Thank you for your attention

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CLONETS – CLock NETwork Services

Strategy and innovation for clock services over optical-fibre networks

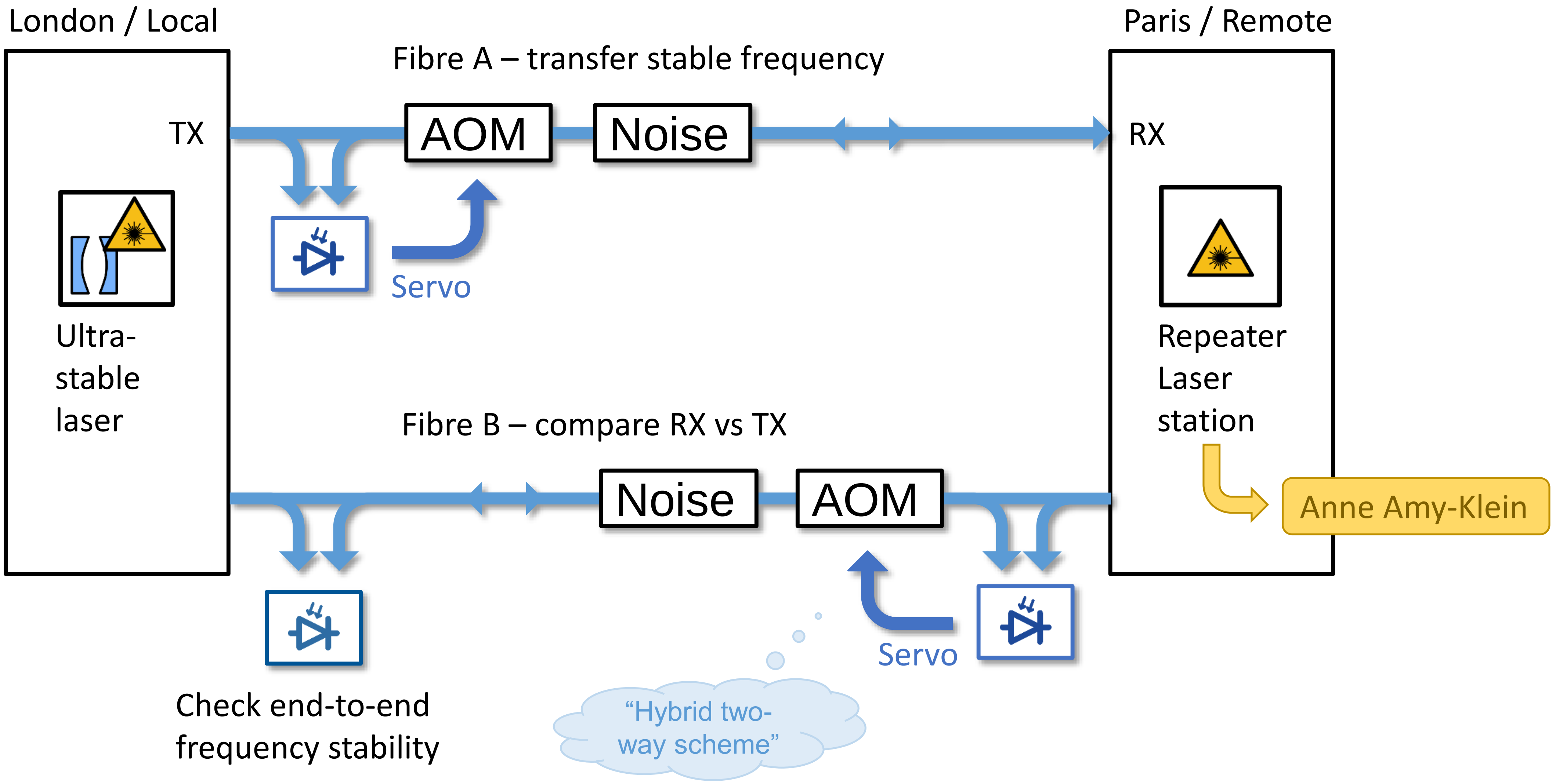
Proposal ID: **731107**
Topic: **INFRAINNOV-2016**
Duration: **30 months**
Start date: **1st January 2017**
Web page: **http://www.clonets.eu**

Coordinator

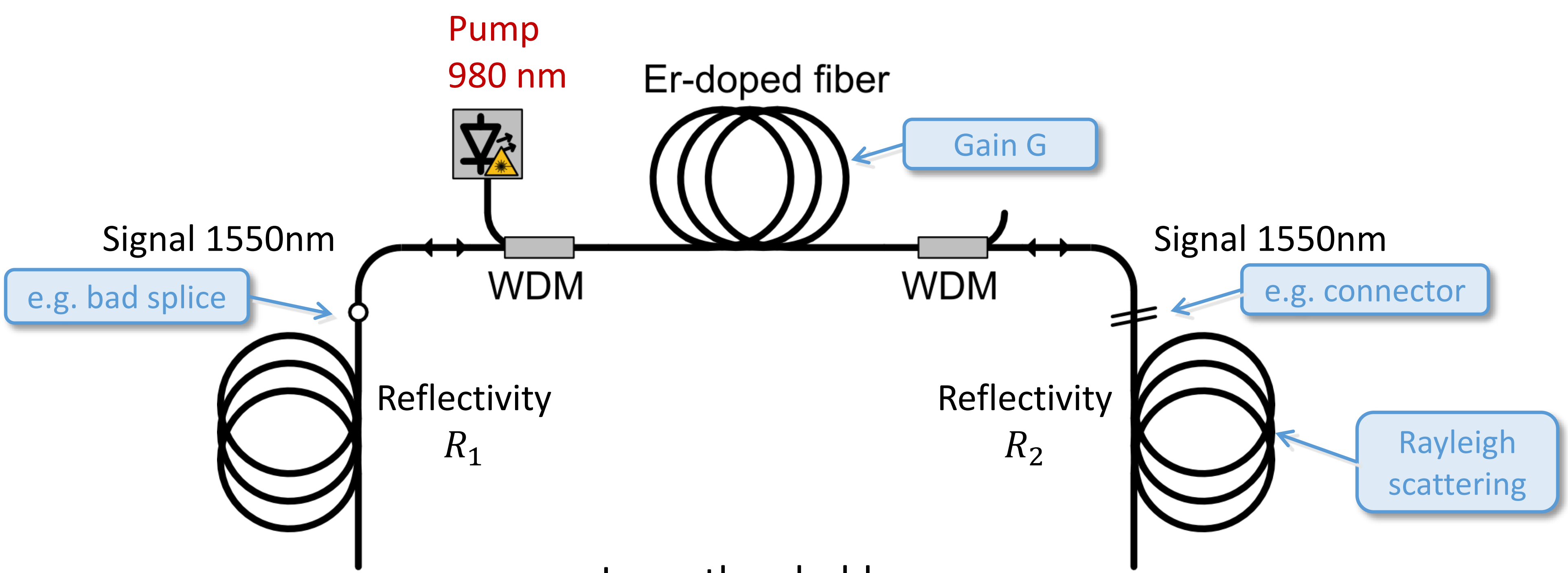
Participants

Third Parties

London-Paris link – Topology



Spurious lasing of bidirectional EDFAs



Laser threshold

$$G^2 R_1 R_2 = 1$$

E.g. Rayleigh scattering -35 dB – occasionally much higher

In practice G = 15…20 dB max