Performance of an Optical Seismometer from 1 μHz to 10 Hz

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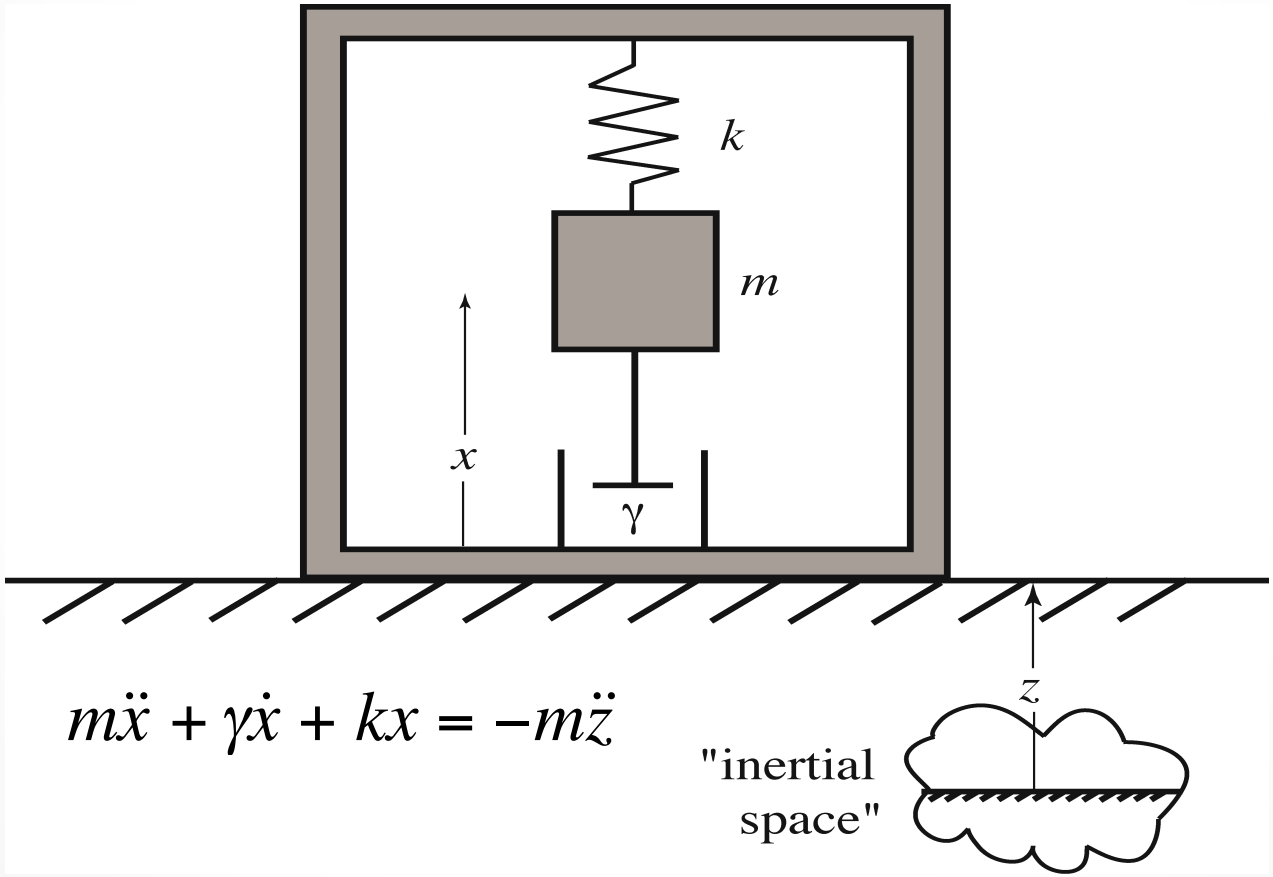
Overview

- Motivation
- STS1 seismometer with interferometric displacement transducer
- Design of interferometric displacement transducer
- Calibration methods: ring down, tides and huddle test
- Vertical and horizontal interferometric STS-1: iSTS-1
- Comparisons with reference instruments: STS-1, STS-2 and SG
- Noise-levels
- Instrument nonlinearities

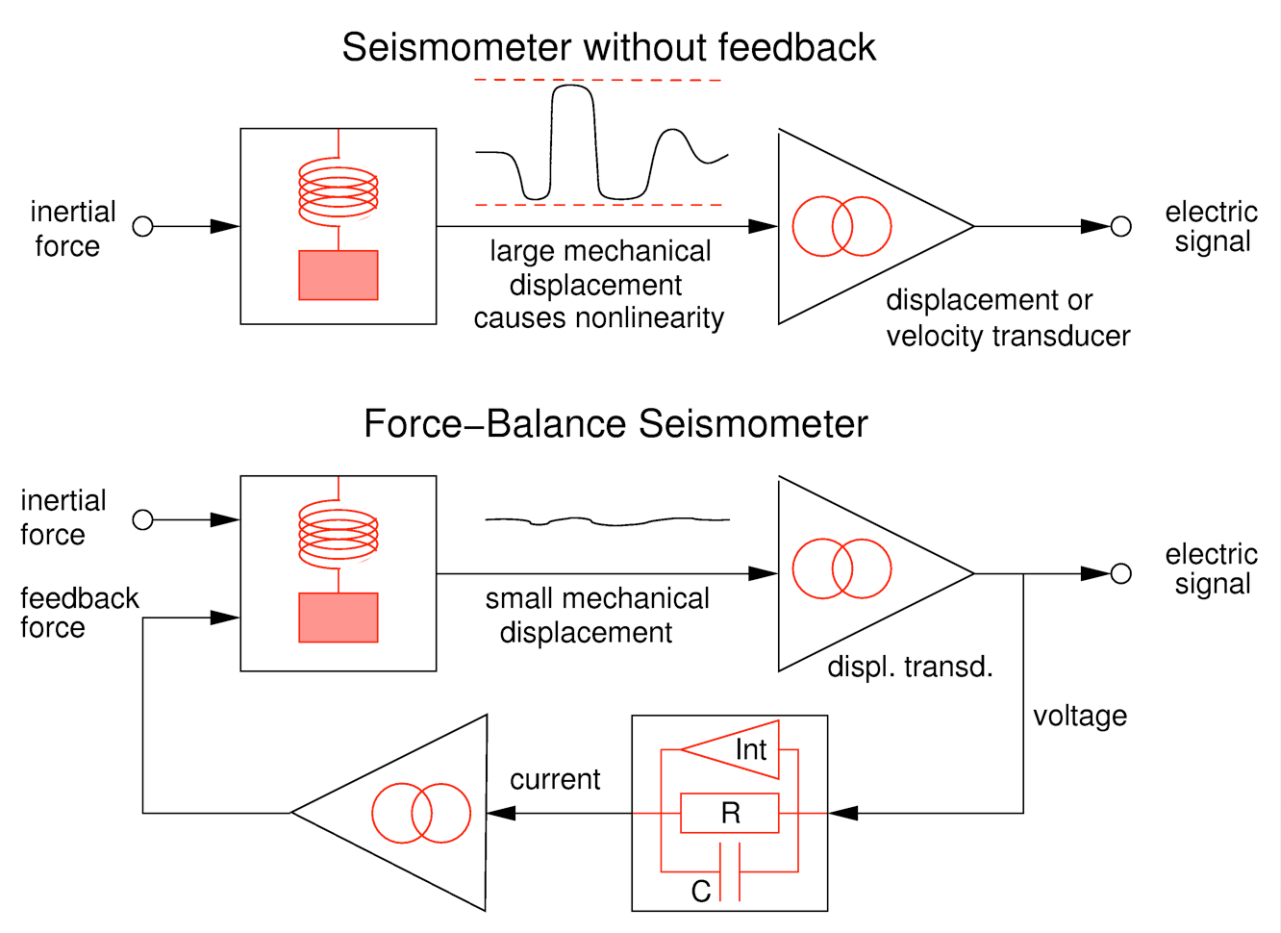
Some basics



$$m\ddot{x} + \gamma\dot{x} + kx = -m\ddot{z}$$

The existing paradigm for broad –band seismometers:

From Erhard Wielandt's "Design Considerations For Broadband Seismometers"



Why build a seismometer with an optical displacement transducer and no force feed-back?

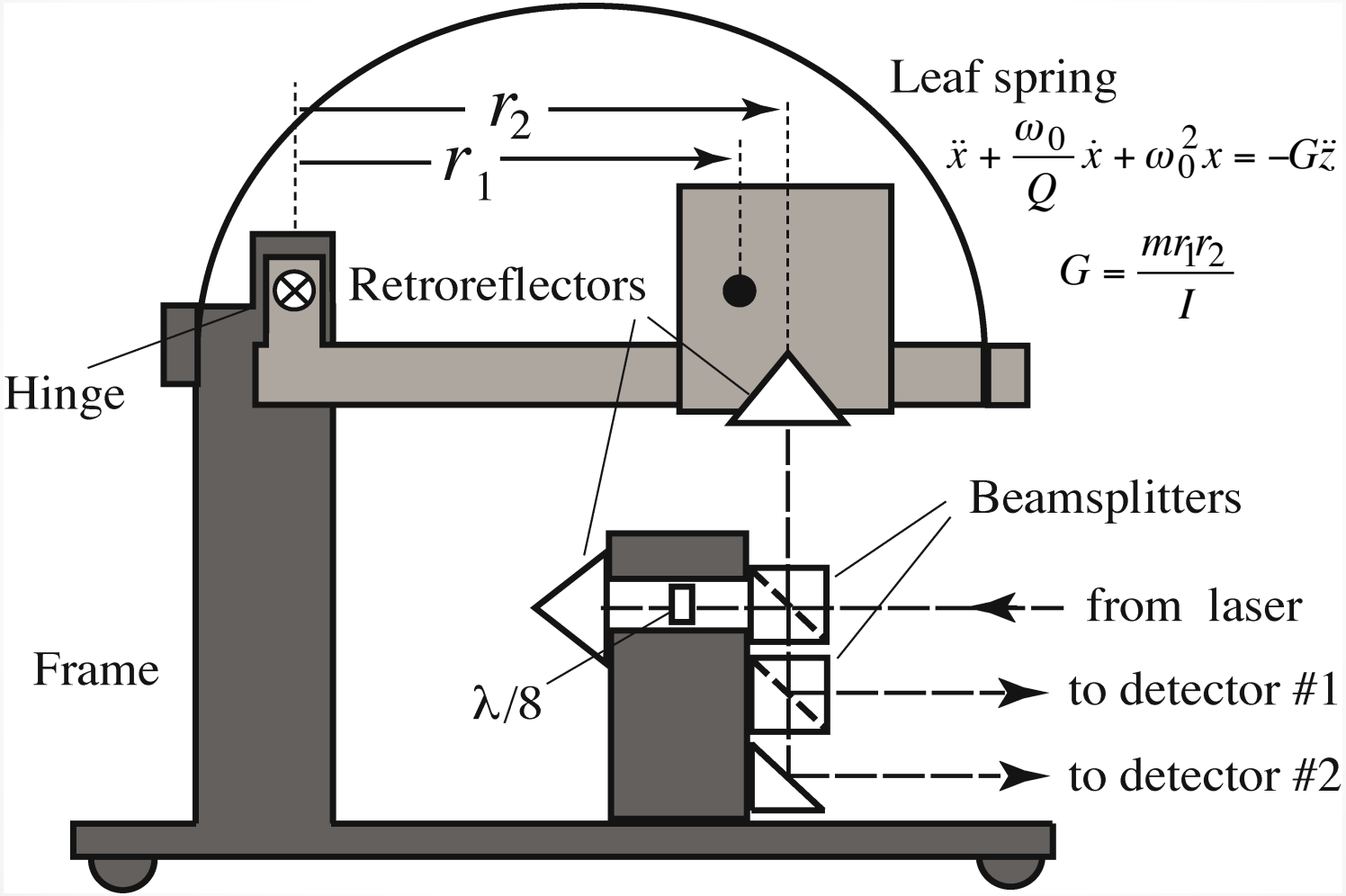
- **deep borehole** :
  - Problems with analog electronics at high temperatures.
  - Lighting protection.

- **Instrumental self-noise:**
  Is residual noise in best seismometers caused by convection due to dissipated heat from analog electronics?

the Plan

- Modify an STS-1 and benefit from its proven suspension.
- Remove feedback electronics.
- Attach corner cube reflector to seismic mass.
- Track motion of seismometer mass with a Michelson interferometer.
- Leave mass centering mechanism in place.

Leaf-spring pendulum

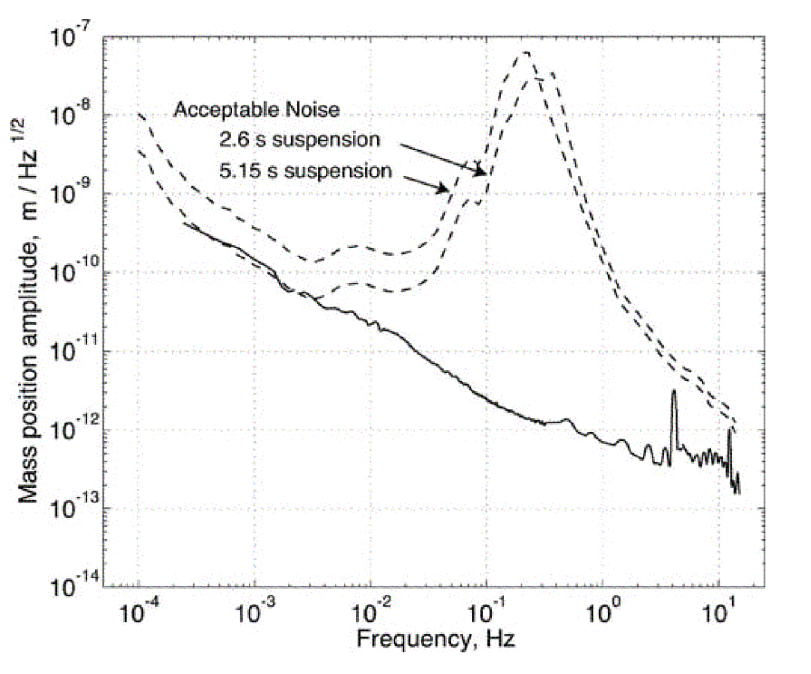


Adjustment of suspension

1. Measure interferometer self-noise by recording locked seismometer

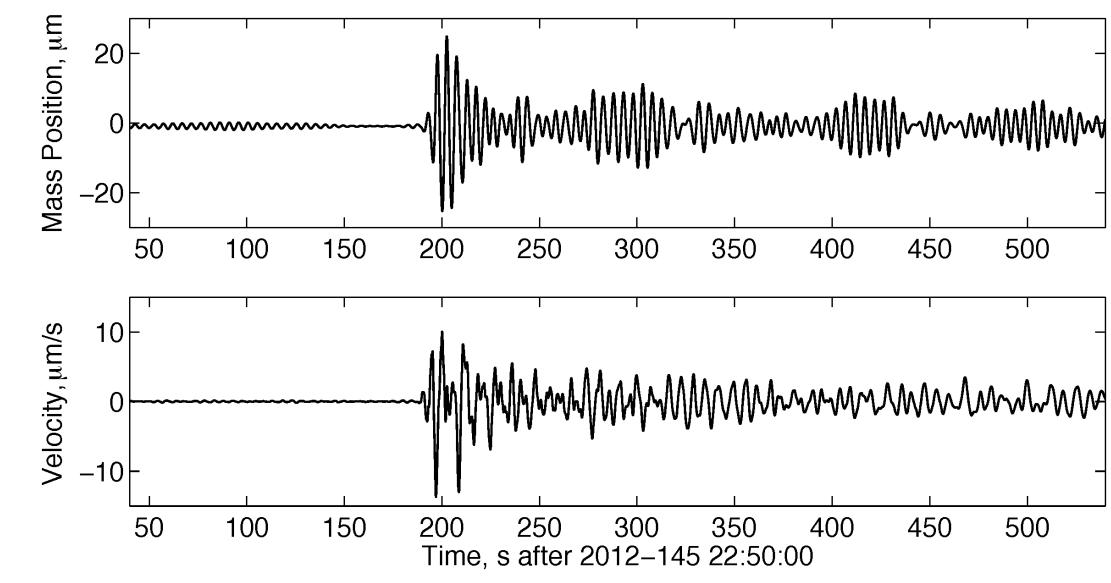
2. Chose free period of pendulum such that NLNM can be resolved in the presence of interferometer self-noise: $T_0 = 5$ sec

$$\Delta x = -\frac{G \cdot T_0^2}{4\pi^2} \cdot \Delta g$$



a first data example:

M6.2 quake in Norwegian sea



=> We need to know instrument transfer function!

Calibration methods

1. Tides
2. Ringdown
3. Comparison with a collocated seismometer
4. Modeling of resonance in noise PSD

(this assumes white excitation spectrum)

Tides

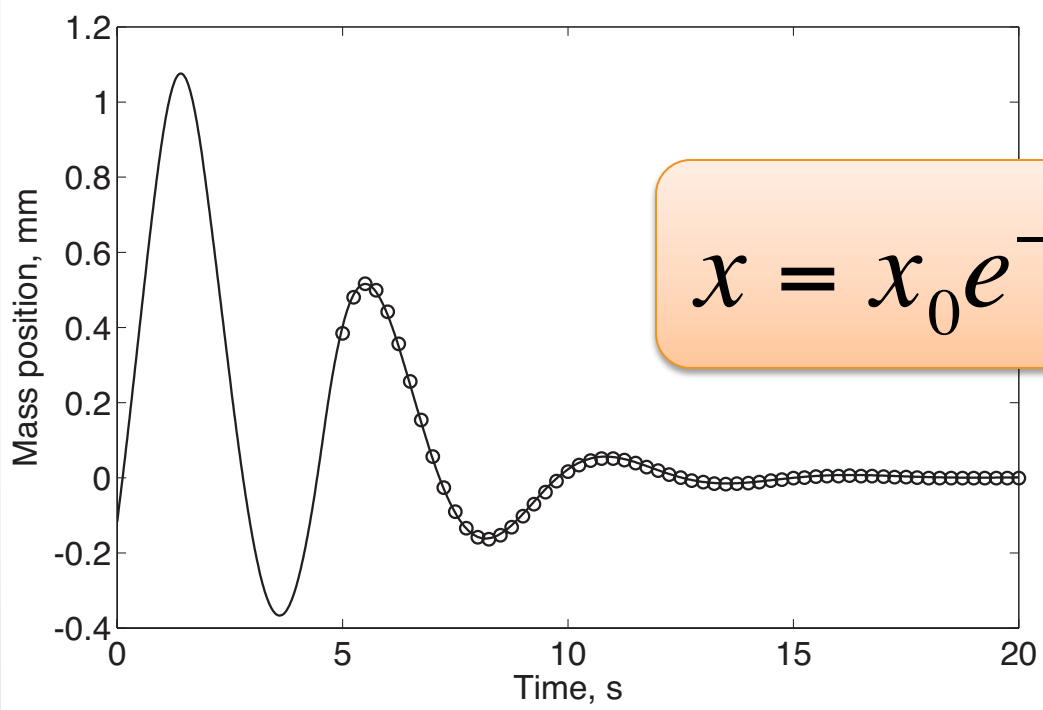
$$\ddot{x} + \frac{\omega_0}{Q}\dot{x} + \omega_0^2 x = -G\ddot{z}$$

$$G = \frac{m r_1 r_2}{I}$$

$$x = -\frac{G}{\omega_0^2}\Delta g$$

Ringdown

$$\ddot{x} + \frac{\omega_0}{Q}\dot{x} + \omega_0^2 x = -G\ddot{z} \qquad G = \frac{m r_1 r_2}{I}$$



$$x = x_0 e^{-\omega_0 t / 2Q} \cos \omega_r t$$

Comparison with a collocated seismometer

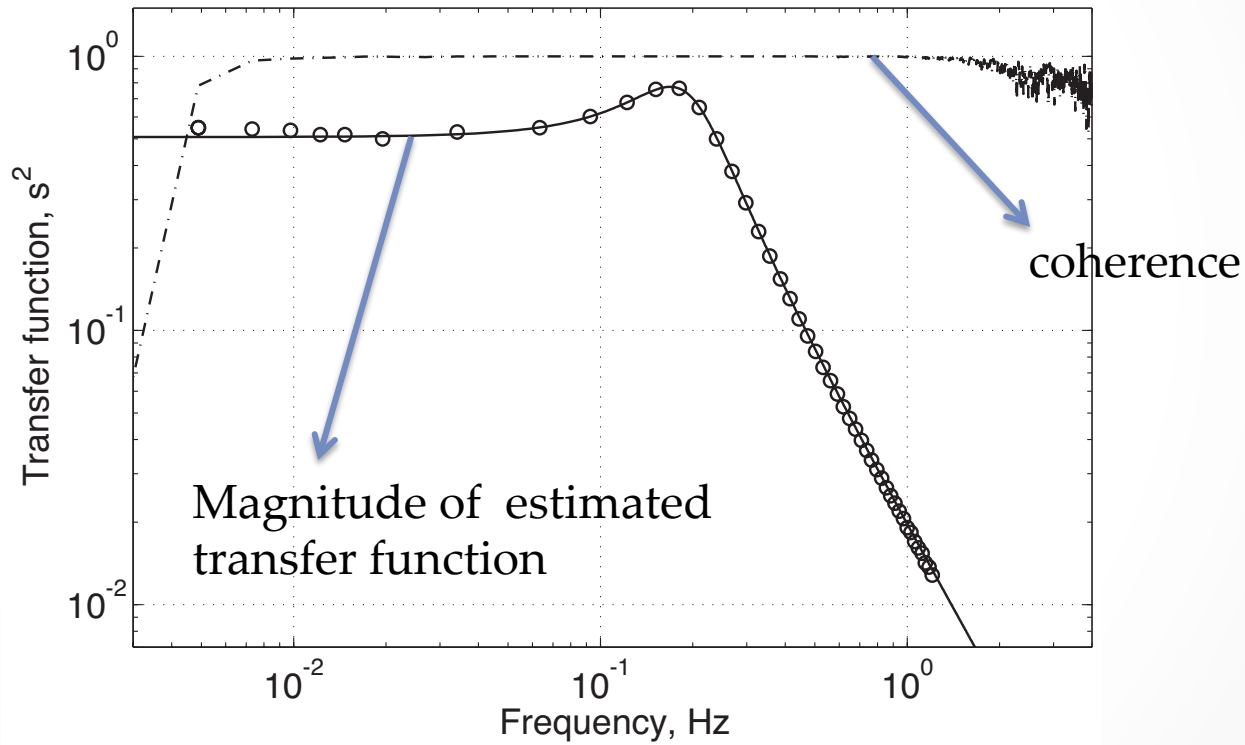
$$\ddot{x} + \frac{\omega_0}{Q}\dot{x} + \omega_0^2 x = -G\ddot{z}$$

$$G = \frac{m r_1 r_2}{I}$$

$$|T(\omega)| = \left|\frac{X(\omega)}{\omega^2 Z(\omega)}\right| = \frac{G}{\left[(\omega^2 - \omega_0^2)^2 + \frac{\omega^2\omega_0^2}{Q^2}\right]^{1/2}}$$

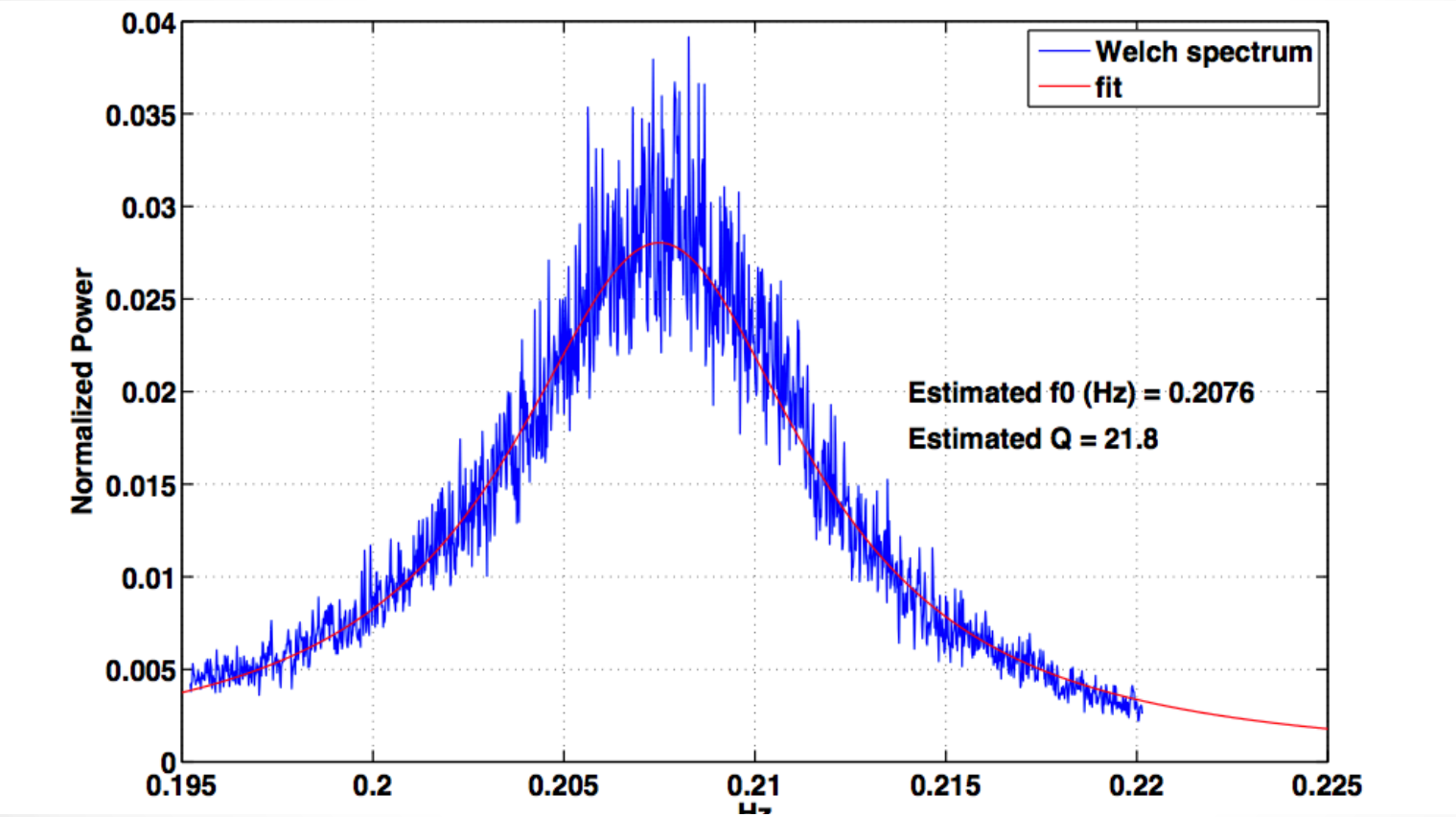
Obtain mass displacement from iSTS1 and ground acceleration from colocated seismometer.

Comparison with a collocated seismometer



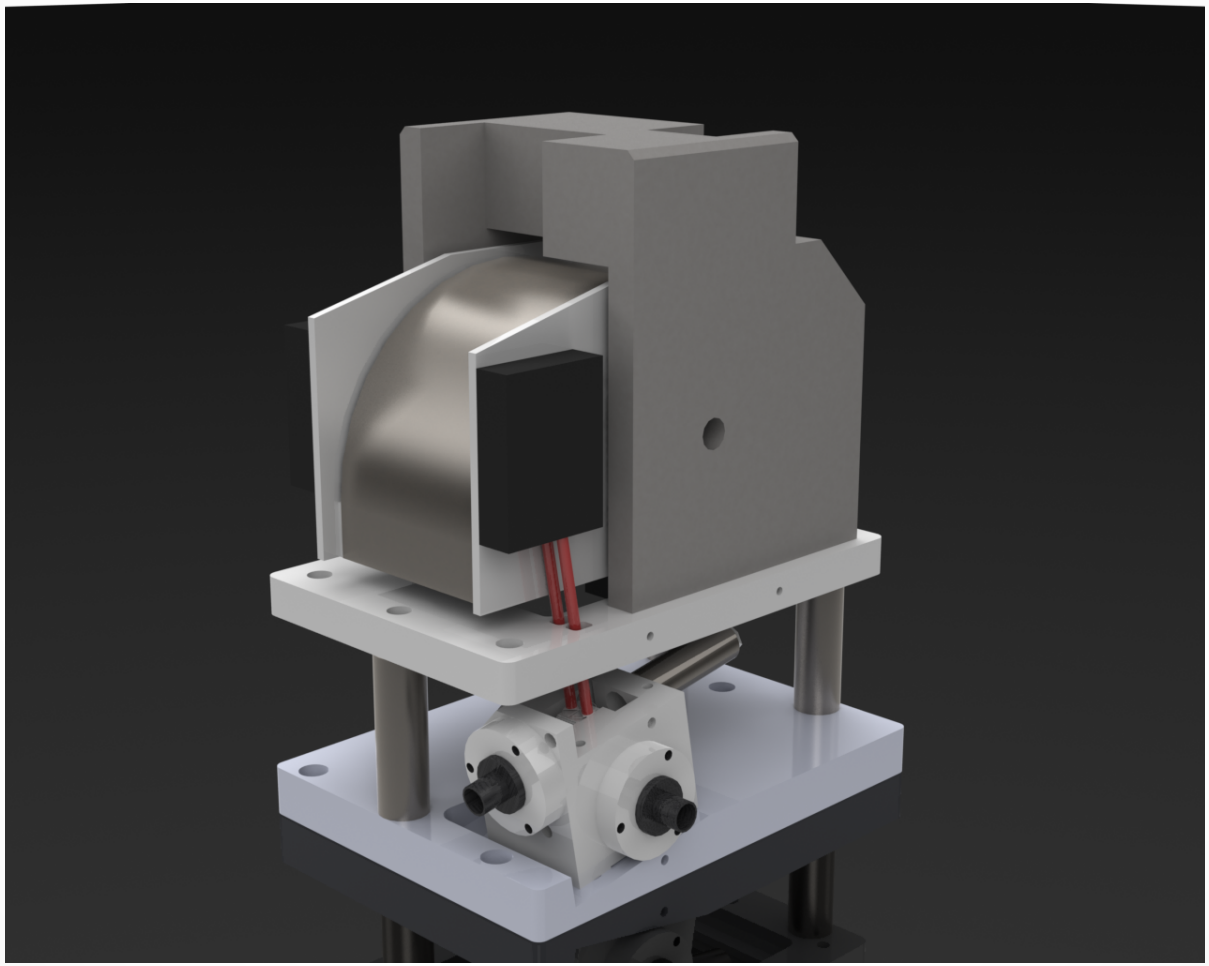
T_0=5.15s, Q=1.45
iSTS1 at PFO: damping via shorted feedback coil

Vertical iSTS1 at BFO



iSTS1-Z at BFO: only mechanical damping of pendulum

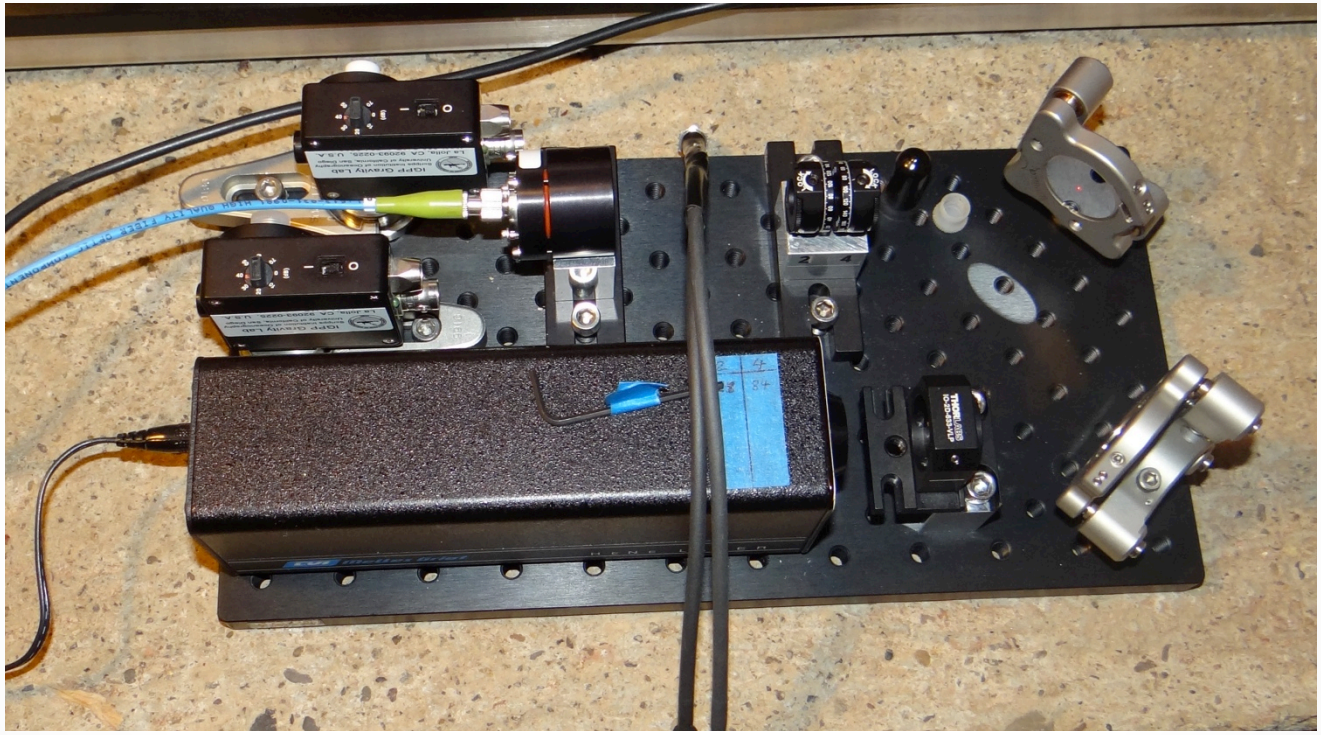
Converted STS1 (*i*STS1)



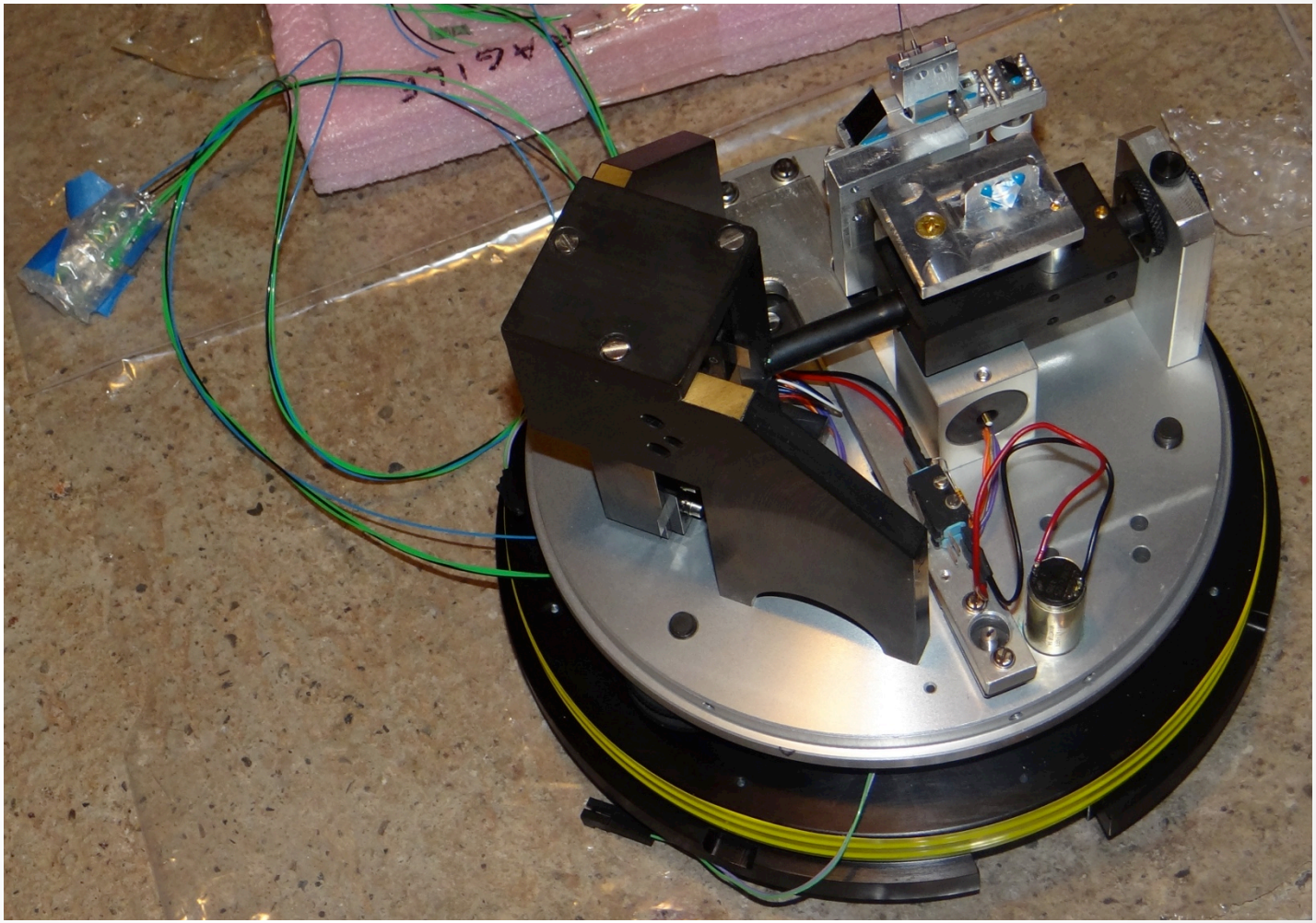
*i*STS1-V

*i*STS1-V in pressure vessel

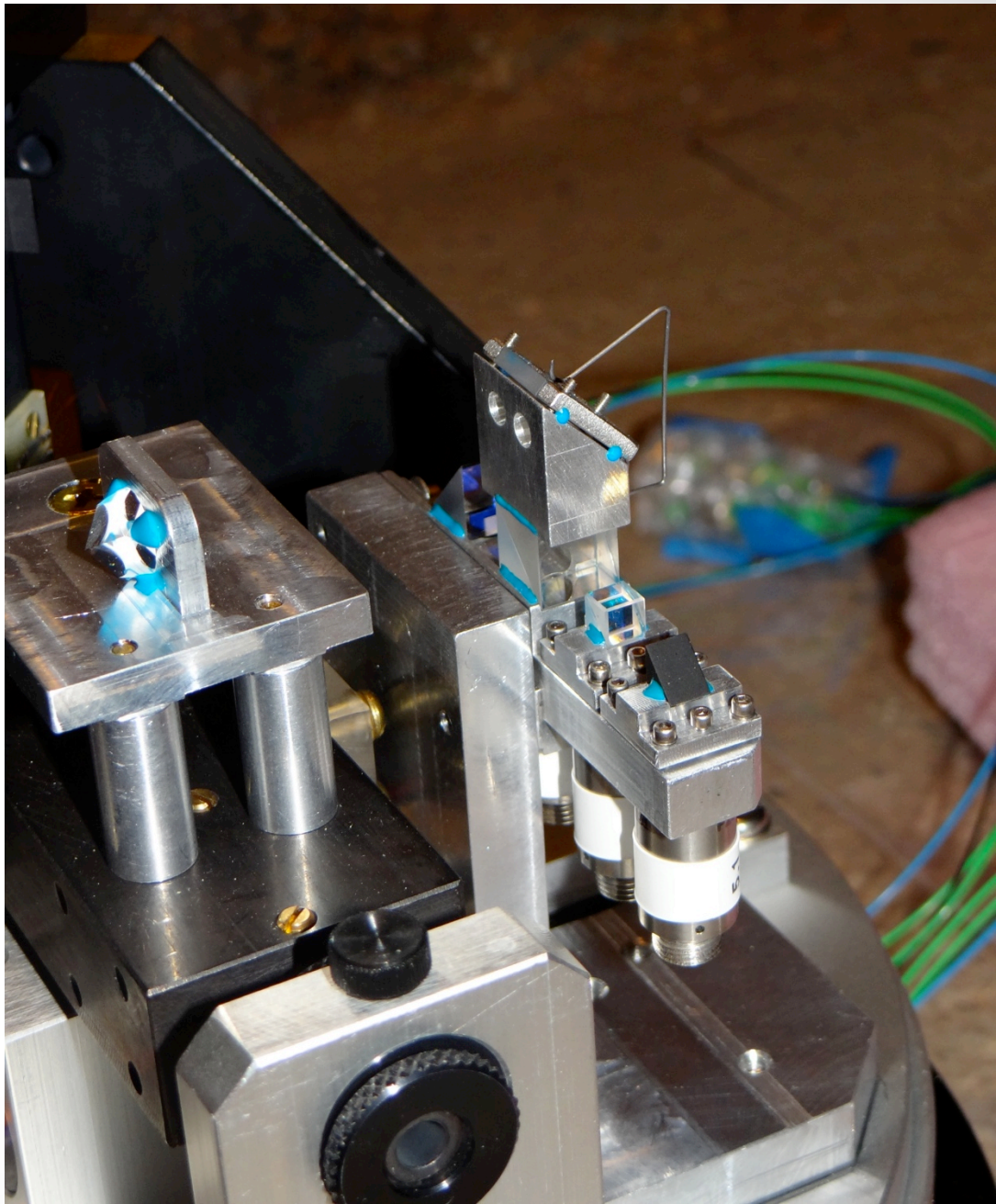
Optics table for *i*STS1-V



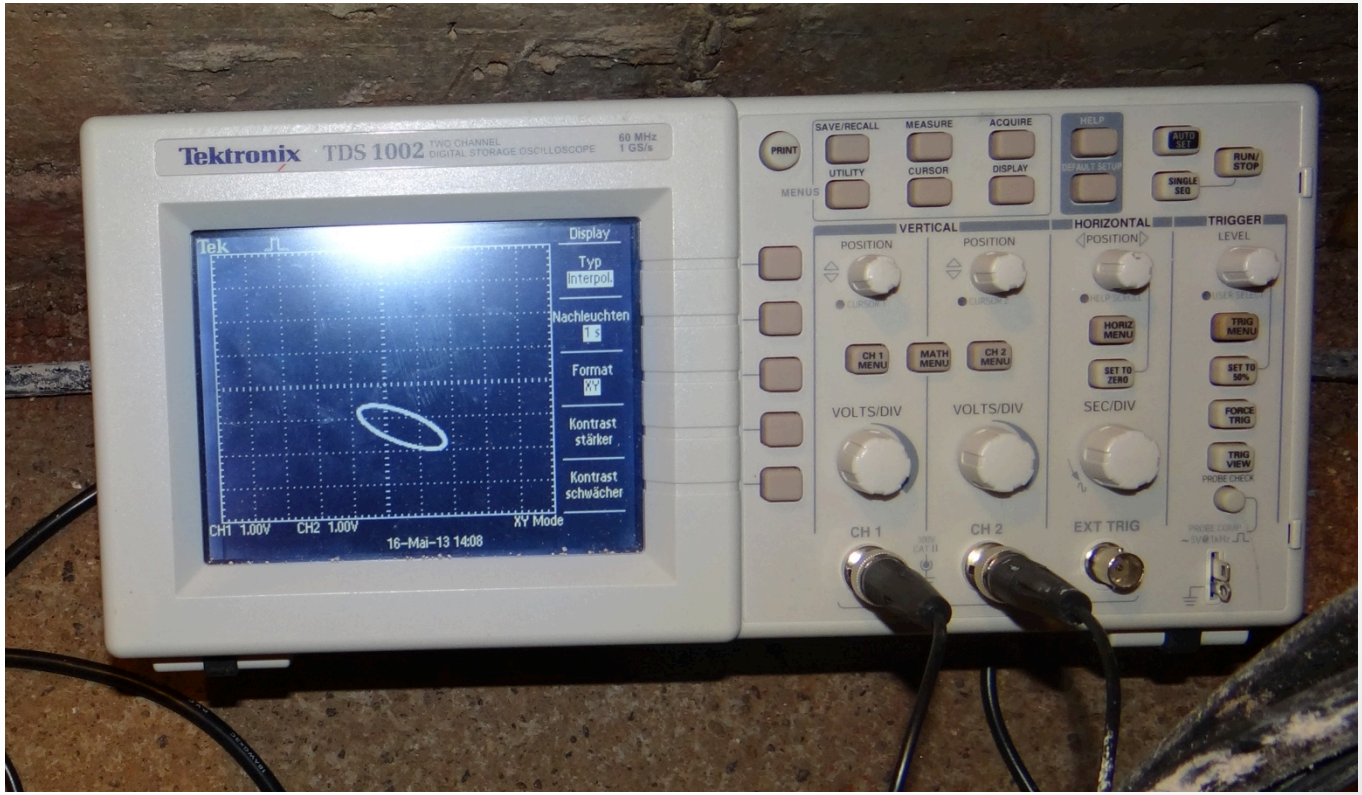
*i*STS1-H



*i*STS1-H interferometer

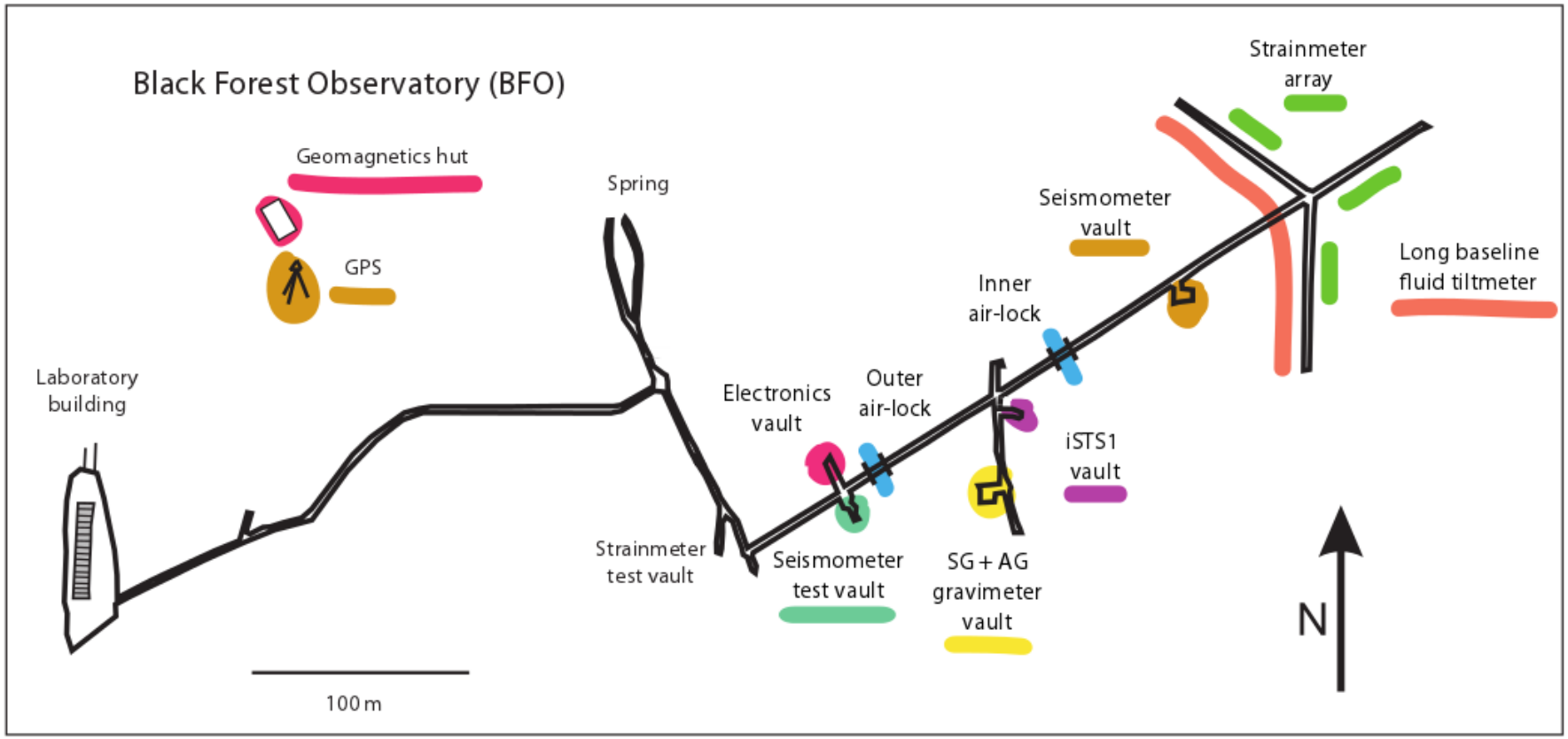


Raw interferometer signal

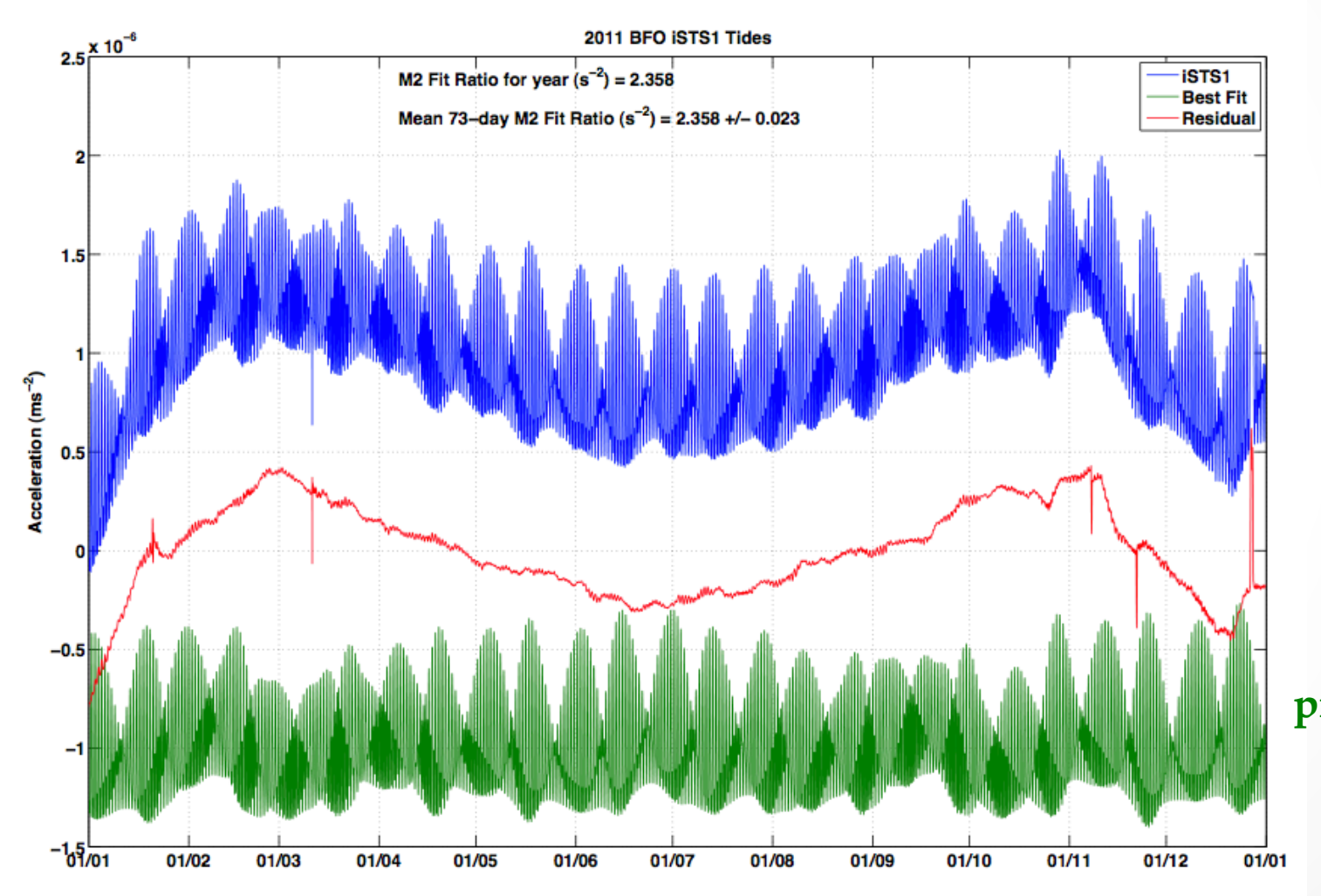



WARNING

Installation in BFO mine



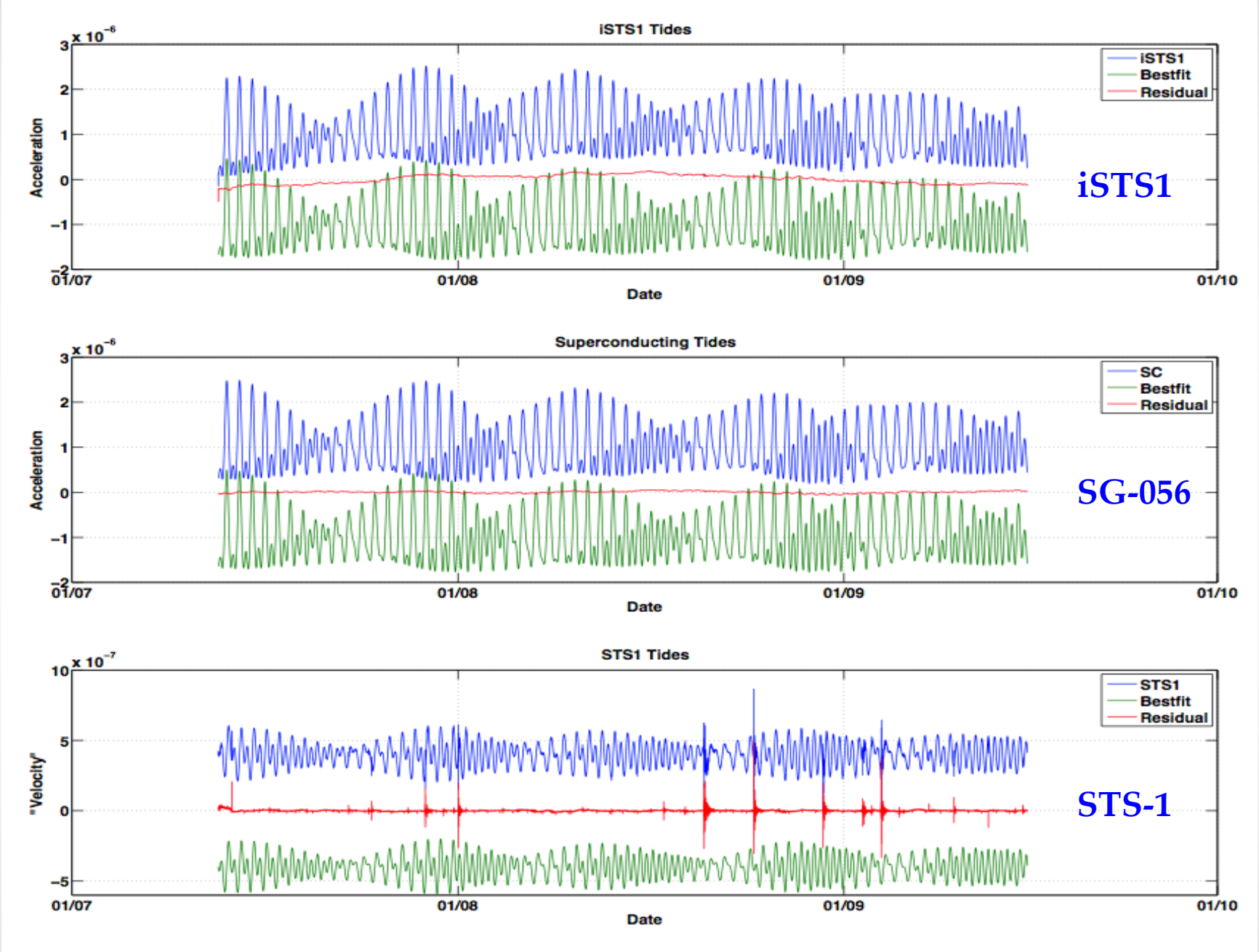
Calibration with predicted tides



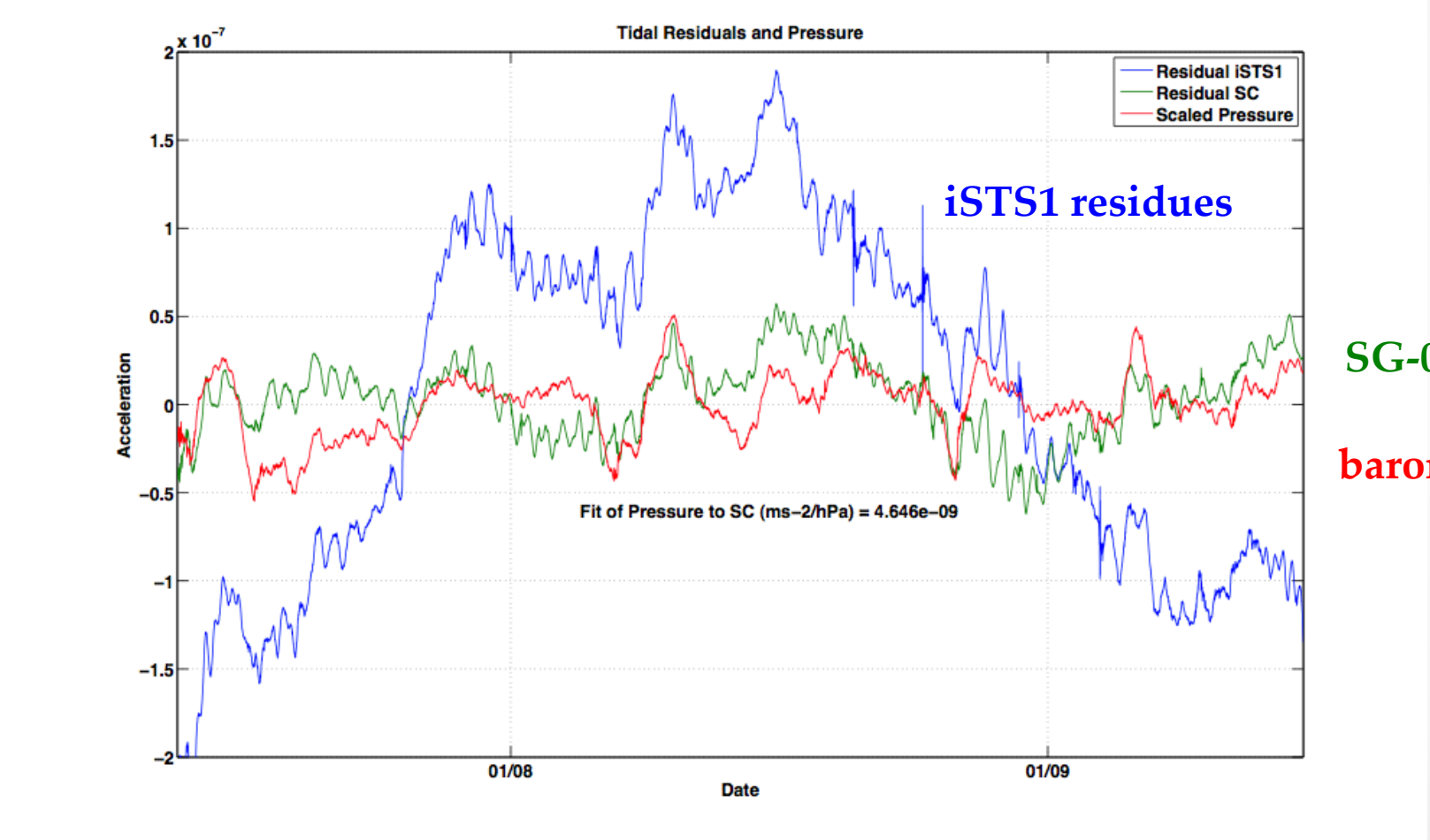
iSTS1-Z

residues

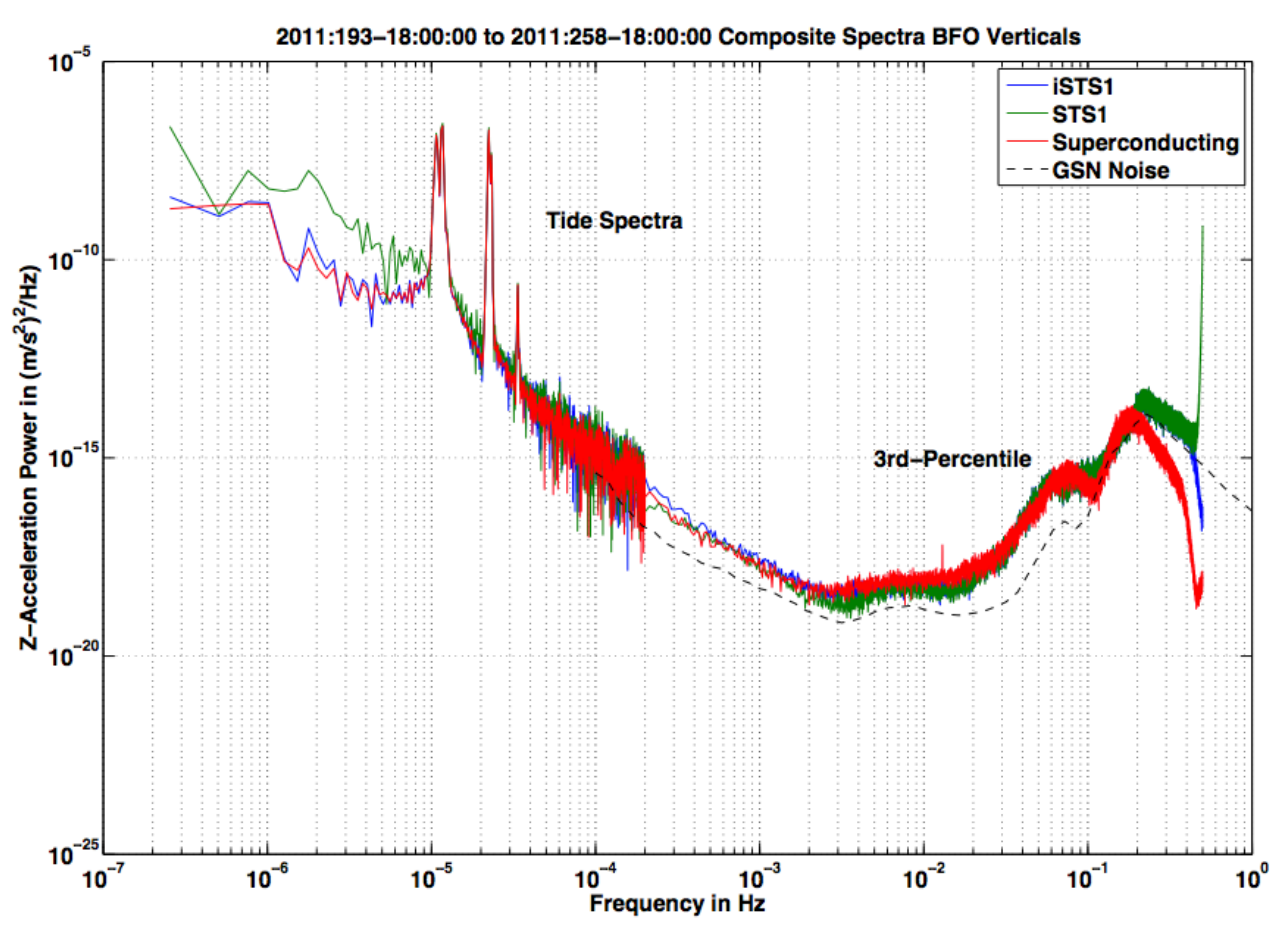
predicted tides


iSTS1 Tides
x 10^-6
Acceleration
iSTS1
Bestfit
Residual
iSTS1
01/07
01/08
01/09
01/10
Date
Superconducting Tides
x 10^-6
Acceleration
SC
Bestfit
Residual
SG-056
01/07
01/08
01/09
01/10
Date
STS1 Tides
x 10^-7
"Velocity"
STS1
Bestfit
Residual
STS-1
01/07
01/08
01/09
01/10
Date

Comparison of tidal residues



Composite low-frequency noise spectra



STS-1 Z

iSTS1

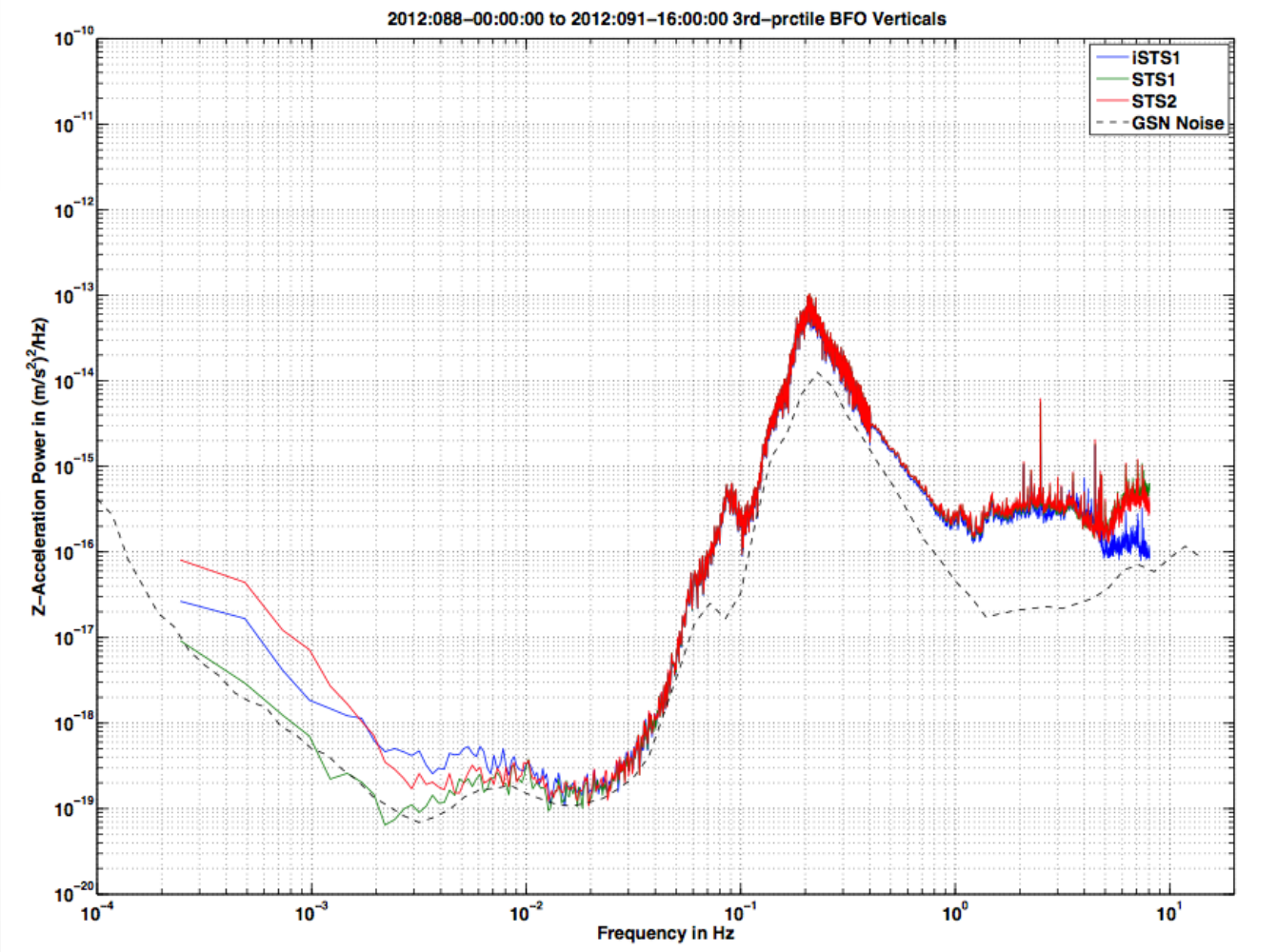
SG-056

Noise at seismic frequencies

STS-2 Z

iSTS1

STS-1 Z

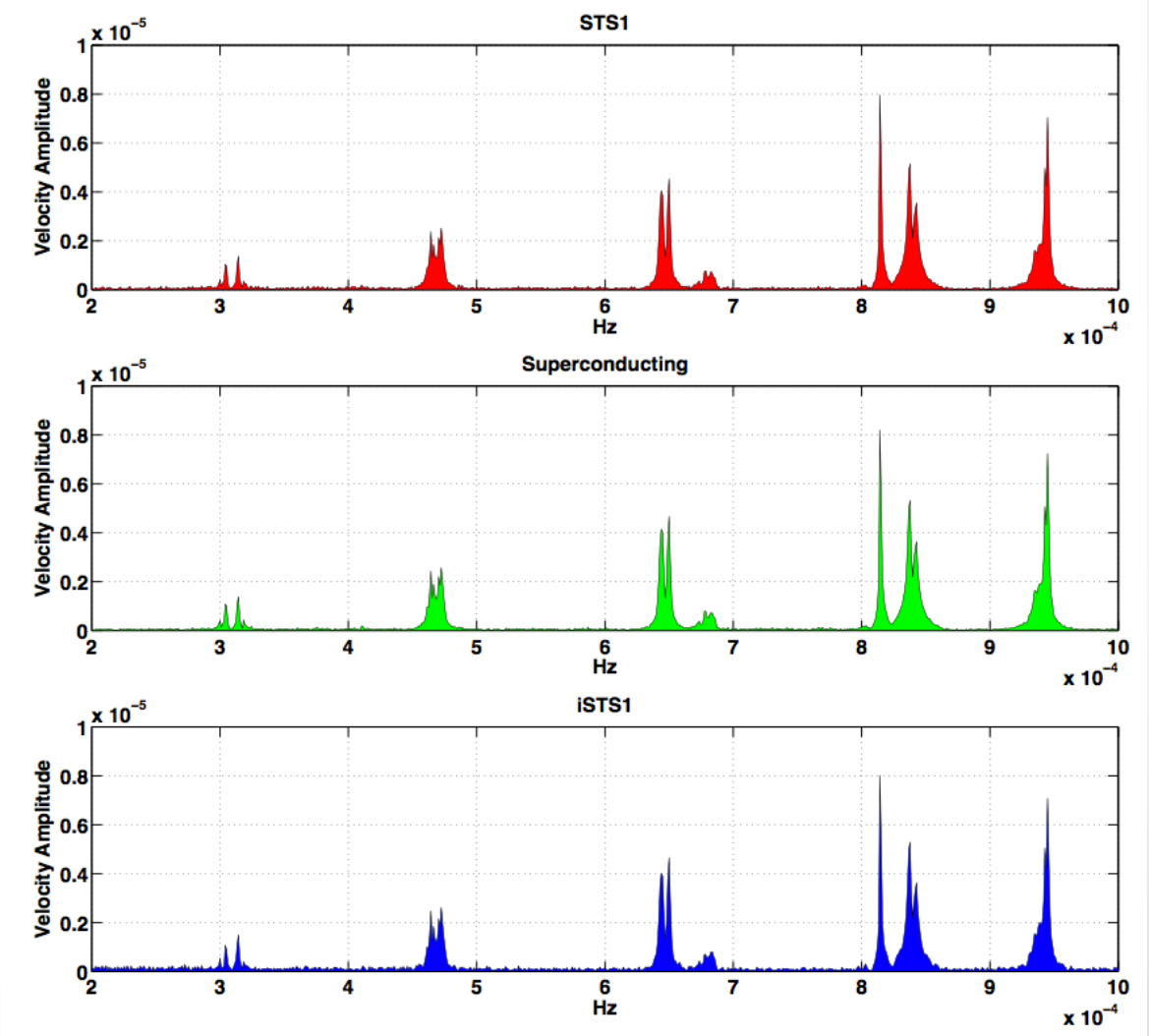


Free mode spectra Tohoku-Oki quake

STS-1 Z

SG-056

iSTS1 Z



Modeling iSTS-1 non-linearities

For large ground accelerations we anticipate non-linear behavior of the seismometer suspension:

$$-G\ddot{z} = \ddot{x} + \frac{\omega_0}{Q}\dot{x} + \omega_0^2 x + c_1 x + c_2 x^2$$

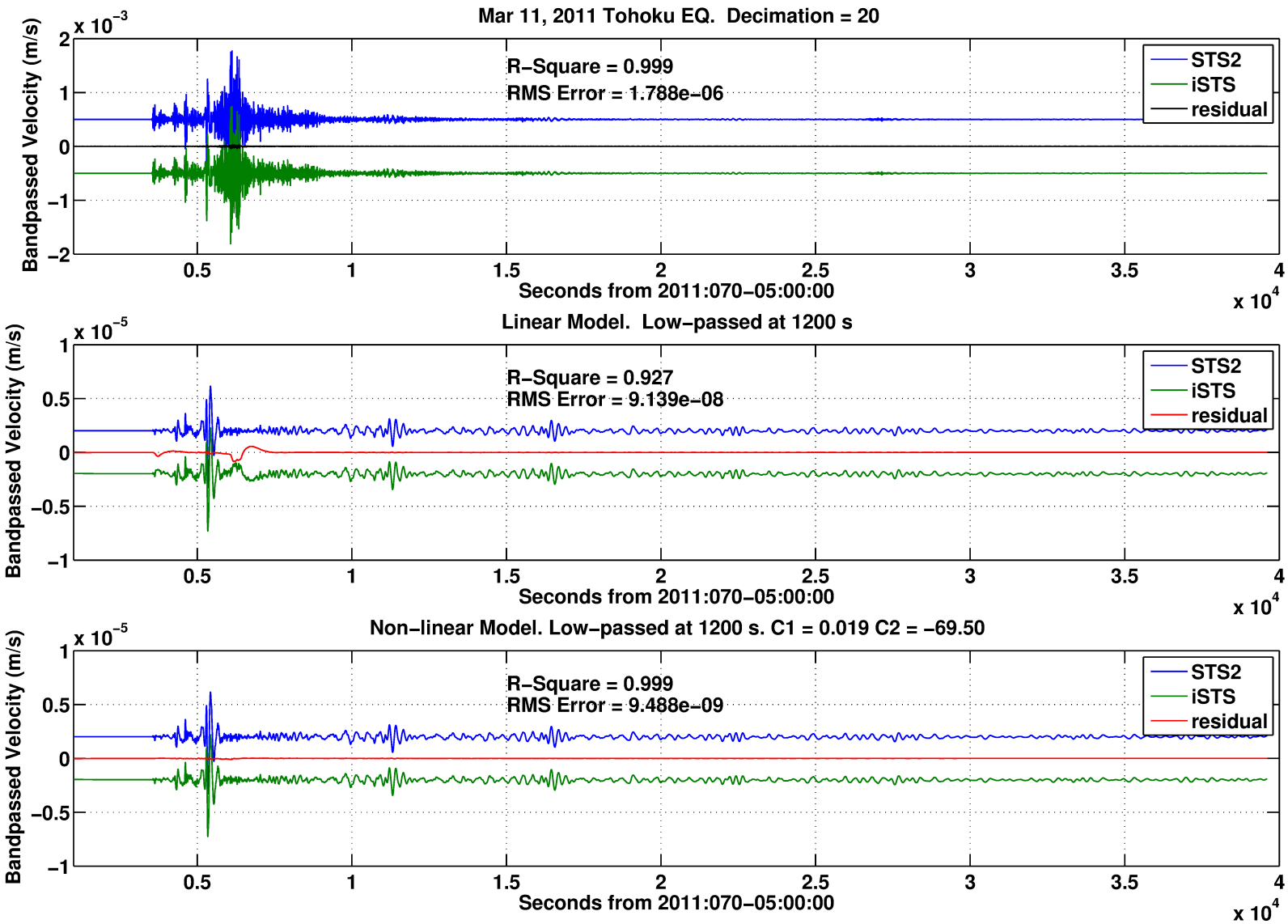
We estimate c_1 and c_2 by comparison with a collocated STS-2 seismometer

Mw9.1 Tohoku-Oki quake

STS-2Z

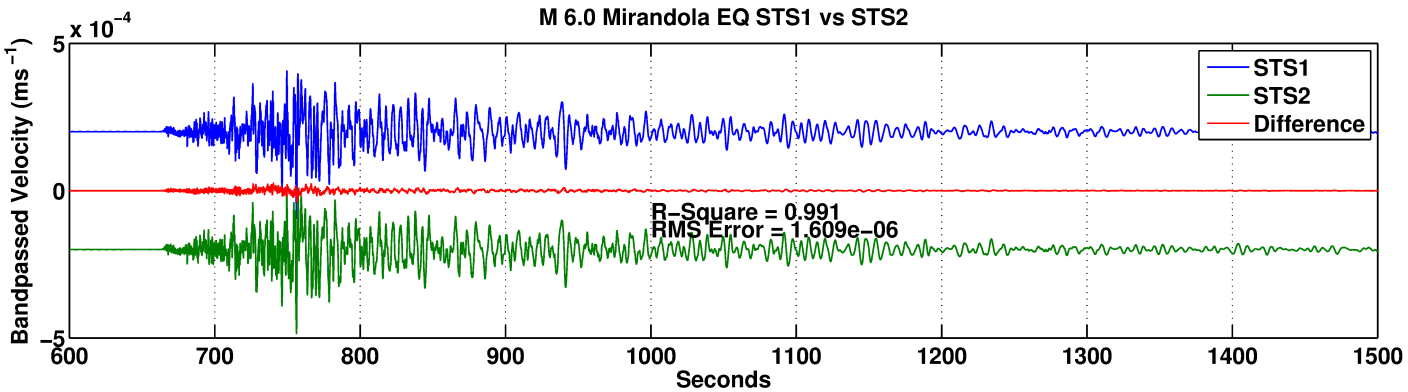
iSTS1

residue

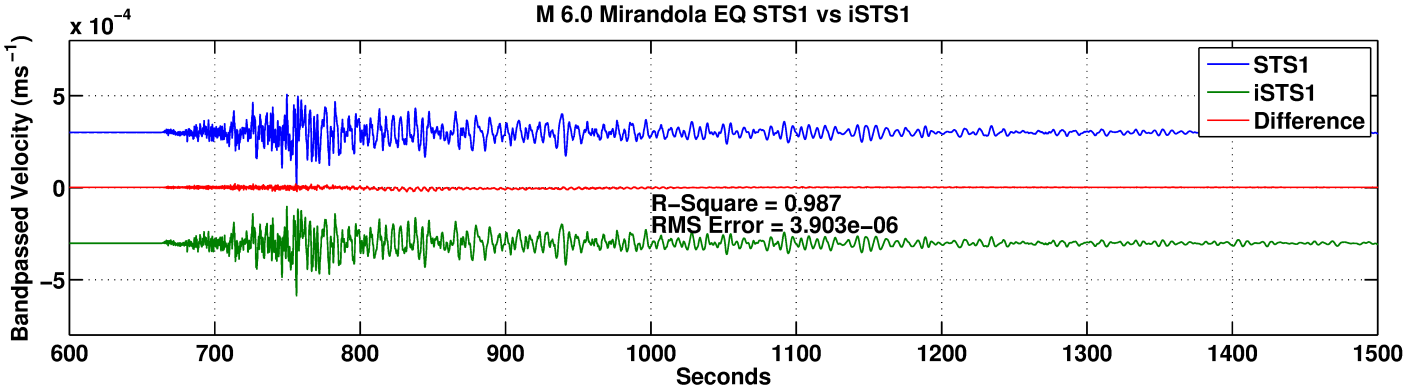


M6.0 Mirandola quake

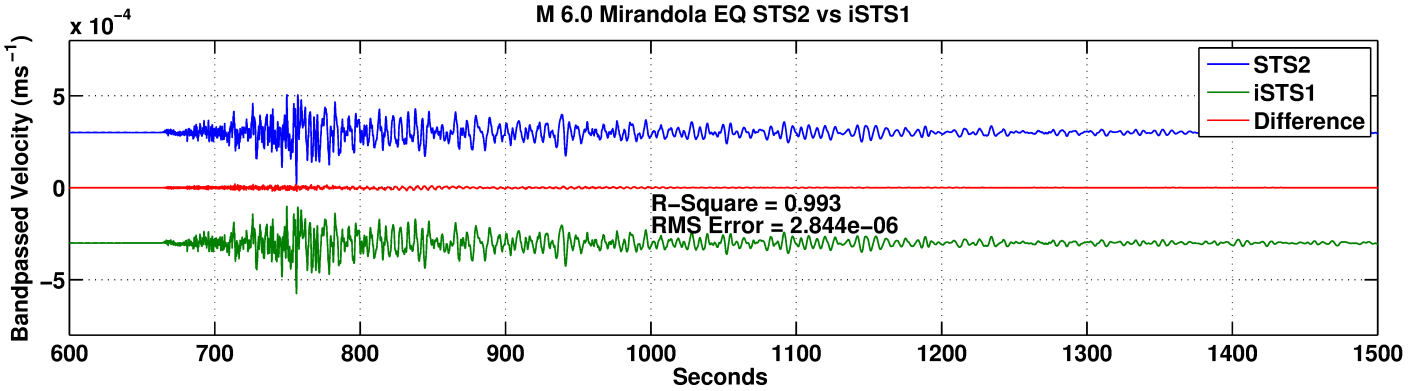
STS1 vs. STS2



STS1 vs. iSTS1



STS2 vs. iSTS1



Conclusions

- This comparison of the Superconducting Gravimeter, the standard STS1 and STS2 seismometers, and the optical iSTS1_seismometer shows that the optical seismometer can provide data of nearly equal quality over a bandwidth spanning that of the other instruments, 0 to nearly 100 Hz.
- The coefficients of both the linear and non-linear response of the iSTS1 are constant at least over the 4 year epoch studied.
- So far the optical displacement transducer has not led to a lowering of the self-noise in the mHz-band (but we are working on it).
- The dynamic range of the iSTS1 is large enough that it did not clip for Mw9.1 Tohoku-Oki event at 9000km epicentral distance.

References

- Zumberge, Berger, Otero & Wielandt. *An optical seismometer without force feedback*, **BSSA**, 2010.
- Zumberge, Berger, Dzieciuch & Parker. *Resolving quadrature fringes in real time*, **Appl. Optics**, 2004
- Berger, Davis, Widmer-Schnidrig and Zumberge. *Performance of an Optical Seismometer from 1 μHz to 10 Hz*, **BSSA**, 2014
- Zumberge, Berger, Hedlin, Husmann, Nooner, Hilt and Widmer-Schnidrig. *An optical fiber infrasound sensor: a new lower limit on atmospheric pressure noise between 1 and 10 Hz*. **J. Acoust. Soc. Am.** 2003.