University of Western Australia’s Cryogenic Sapphire Resonator-Oscillators

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Cryogenic sapphire oscillator

- The performance of a primary frequency standard is often limited by the stability of the reference (hydrogen maser or voltage-controlled crystal oscillator.)

- The cryogenic sapphire oscillator (CSO), developed in University of Western Australia (UWA) has a short-term frequency stability of about 100 times better than that of the hydrogen maser.

- By using this ultra-stable source as a flywheel, the performance of the primary frequency standards can be improved.

- In this talk:

The Resonator

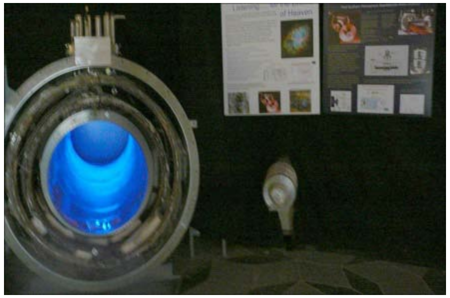
- Construction
- Mode characteristics

The Oscillator and Control Systems

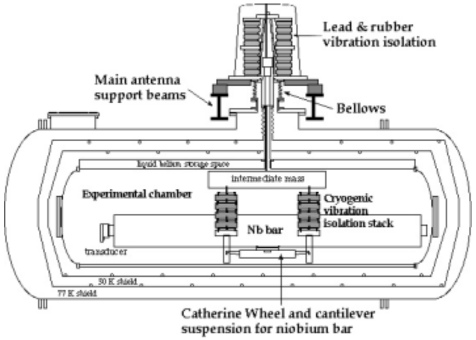
- Noise sources
- Suppression schemes

Some history

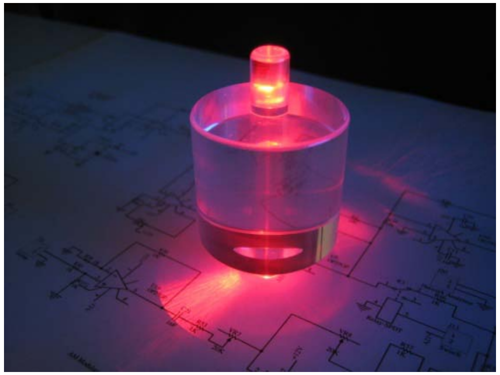
1985: Gravitational wave detection
(1.5 tonne liquid helium cooled
Niobium bar.)
$\Delta f/f = 10^{-14}$



1995: Frequency Standards
and Metrology research group formed
$\Delta f/f = 10^{-15}$



2000: Improved performance
$\Delta f/f = 5x10^{-16}$



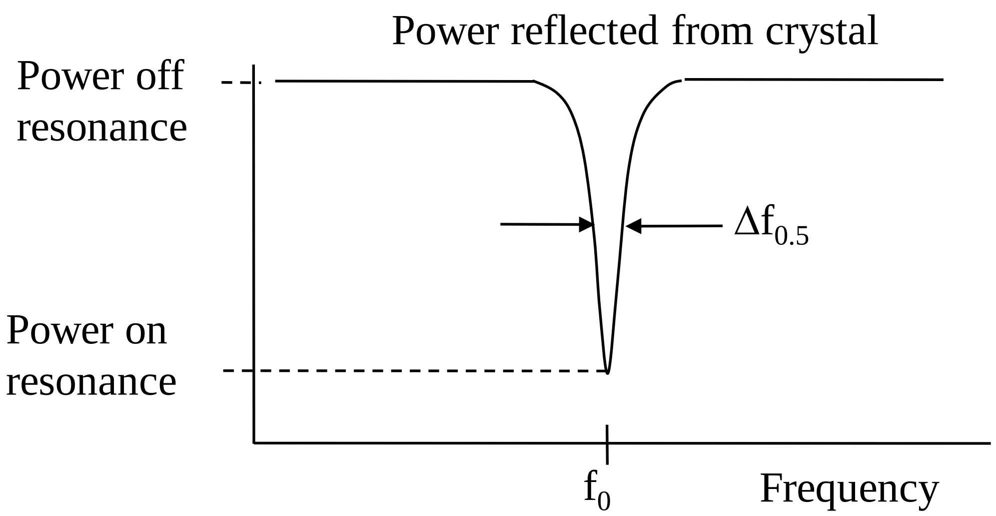
CNES CENTRE NATIONAL D'ÉTUDES SPATIALES

l'Observatoire de Paris

AIST NATIONAL INSTITUTE OF ADVANCED INDUSTRIAL SCIENCE AND TECHNOLOGY (AIST)

NiCT National Institute of Information and Communications Technology

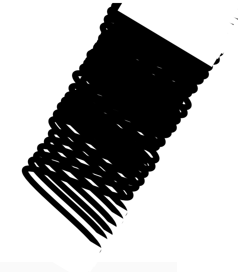
What makes a good frequency determining element?



$$Q \approx \frac{f_0}{\Delta f_{0.5}}$$

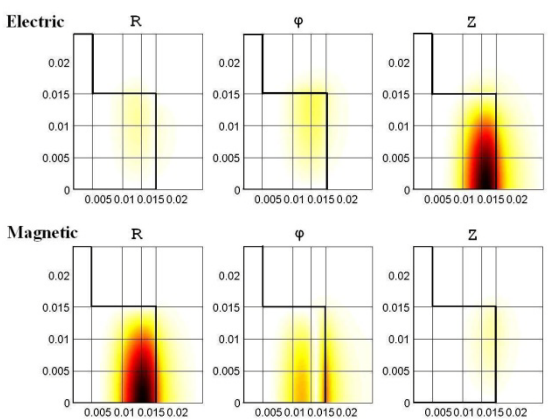
- Need to have a well defined intrinsic frequency
- Need to be stable at this frequency
- For good short term stability need maximum possible Q-factor
- For good medium term stability need good isolation from and low sensitivity to the environment (vibration and temperature)

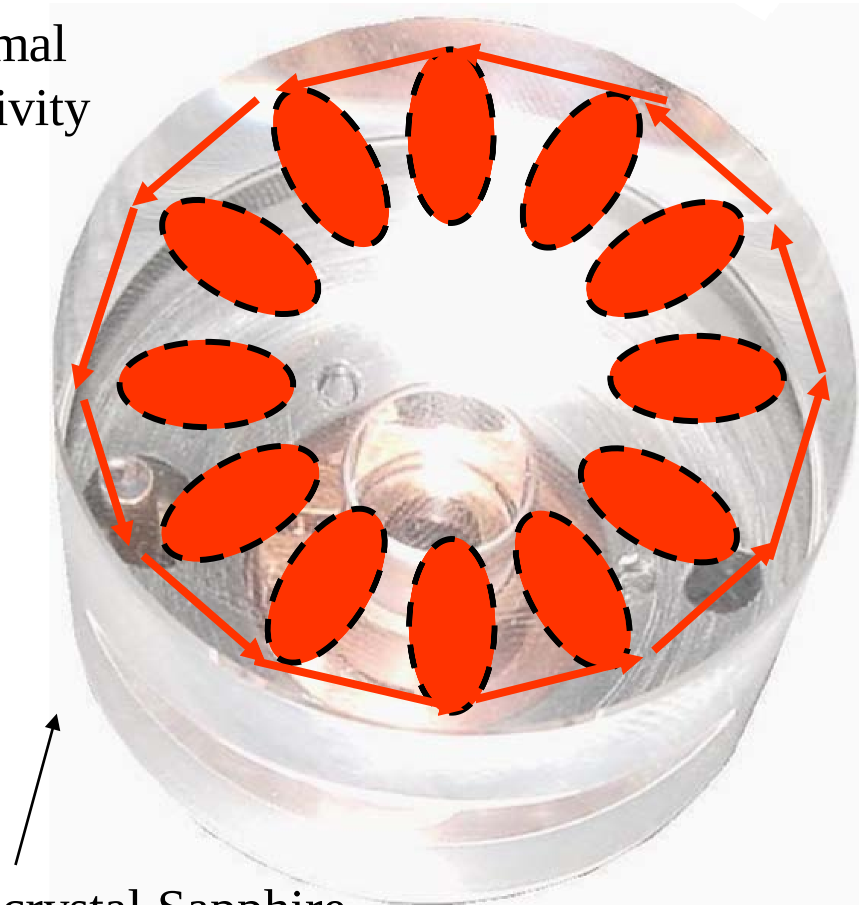
The sapphire cylinder



- ➢Why sapphire? Single crystal sapphire at cryogenic temperature (4~10K) has low defect density, low microwave loss (high Q), a high Young's modulus (vibration and tilt sensitivity reduced), small thermal capacity and high thermal conductivity (easier temperature control.)

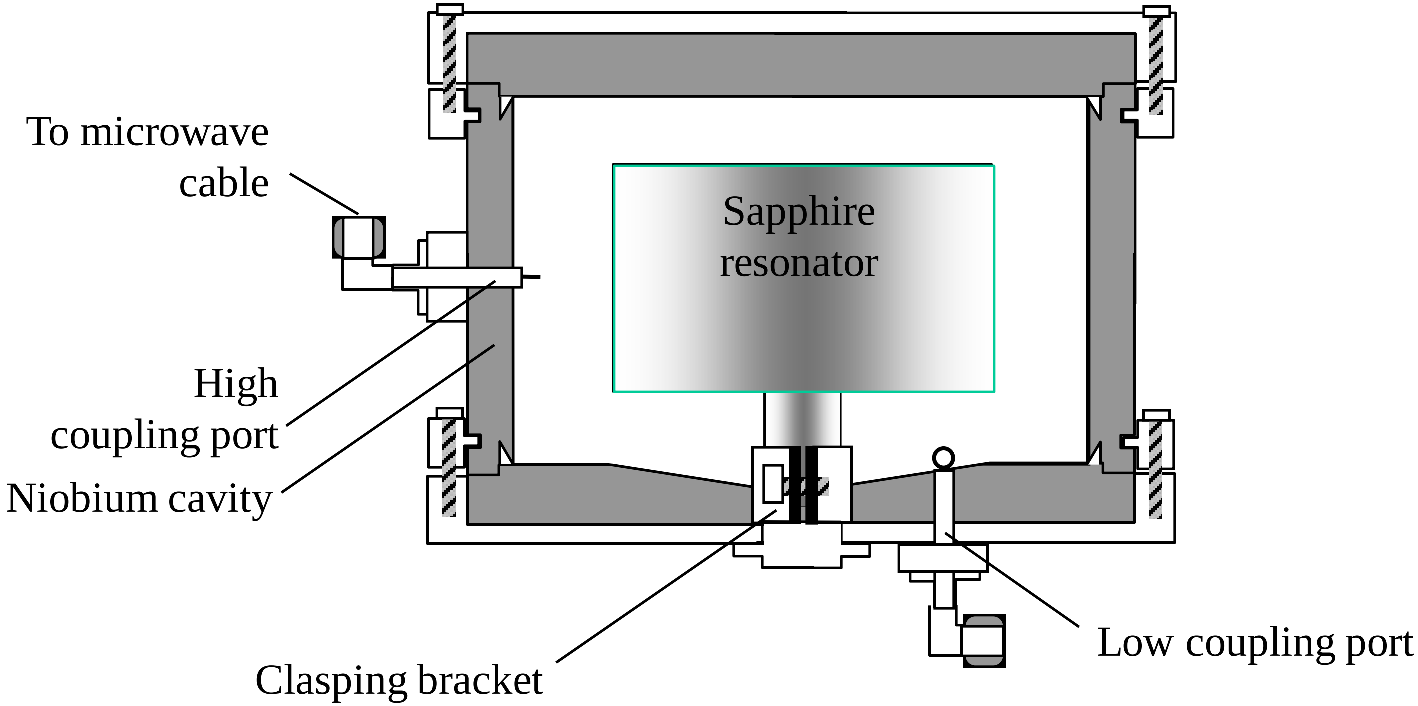
- ➢High Q-factor whispering gallery modes (high azimuthal number improves electro-magnetic confinement)



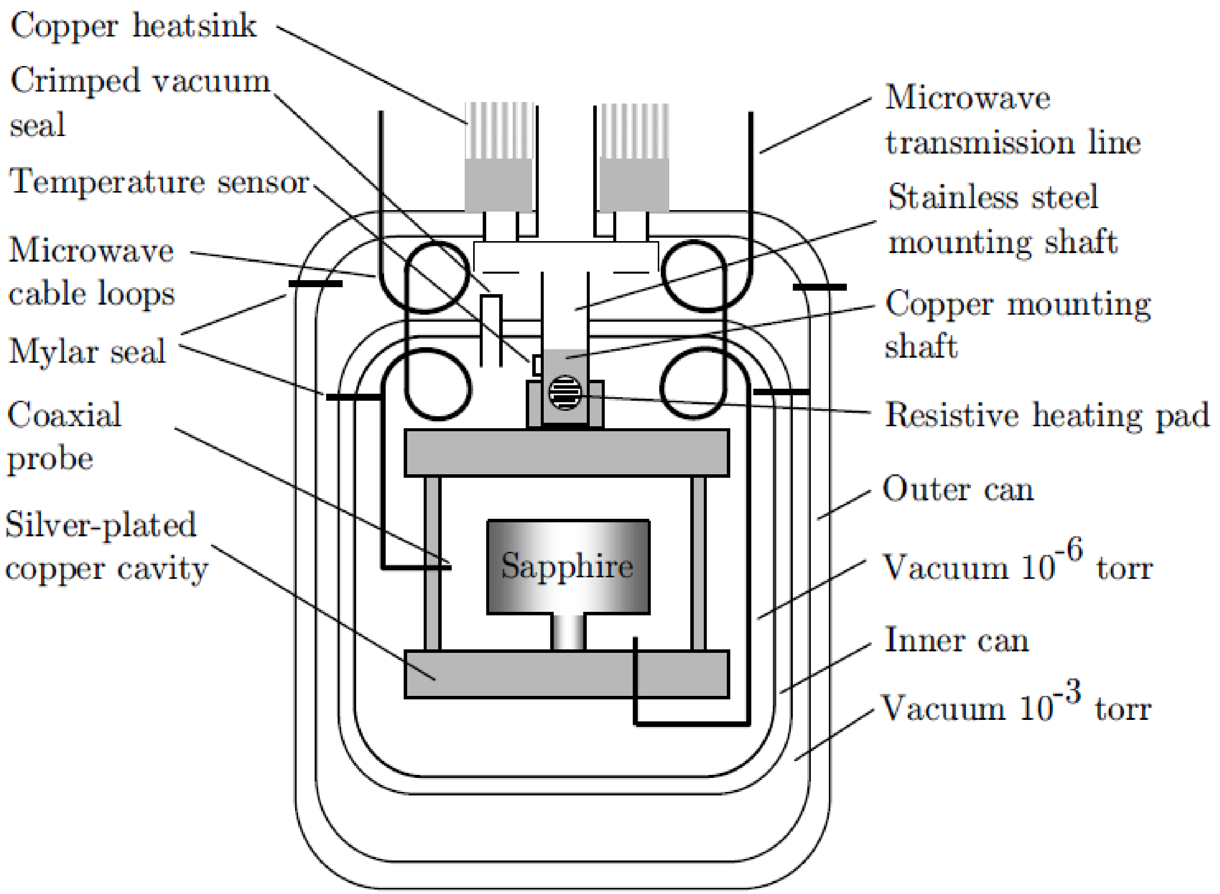


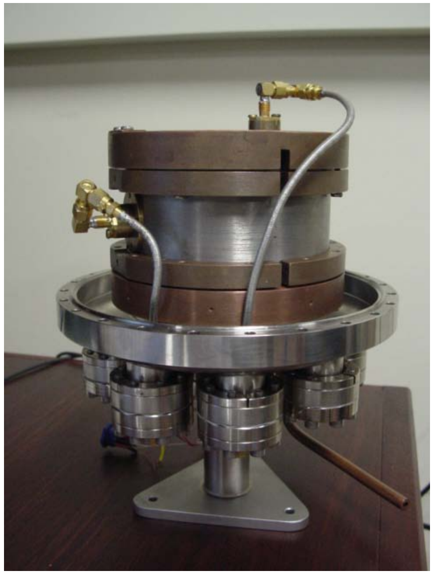
Single crystal Sapphire Resonator (top view)

The Cavity

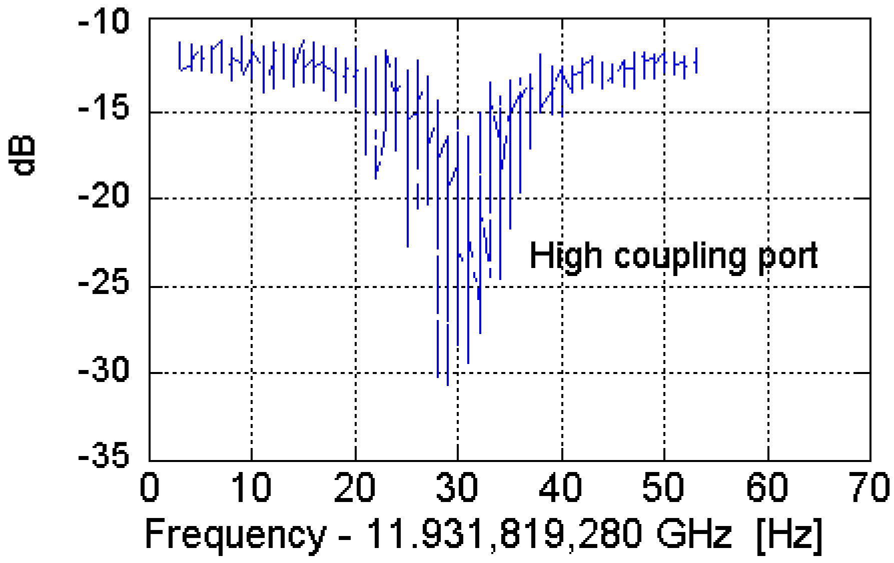

To microwave cable
Sapphire resonator
High coupling port
Niobium cavity
Clasping bracket
Low coupling port

The Outer Can



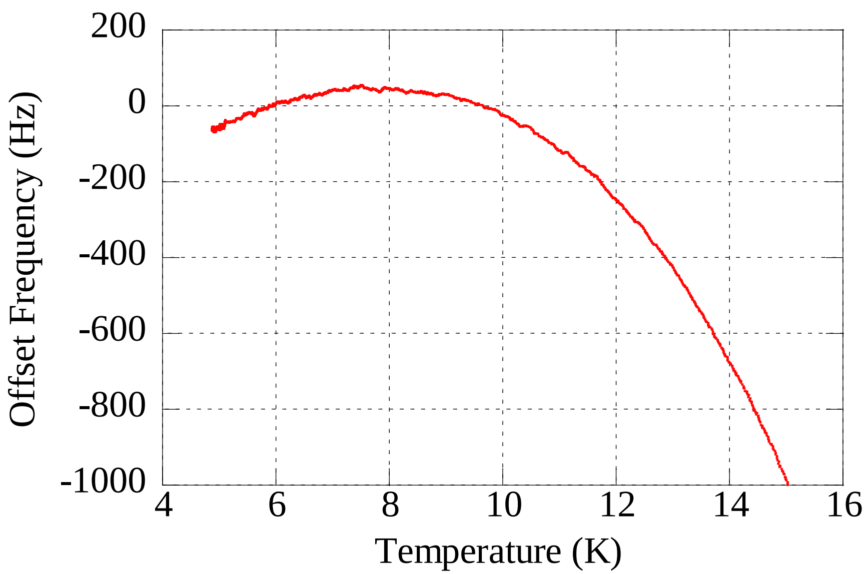


Mode characteristics at 4K



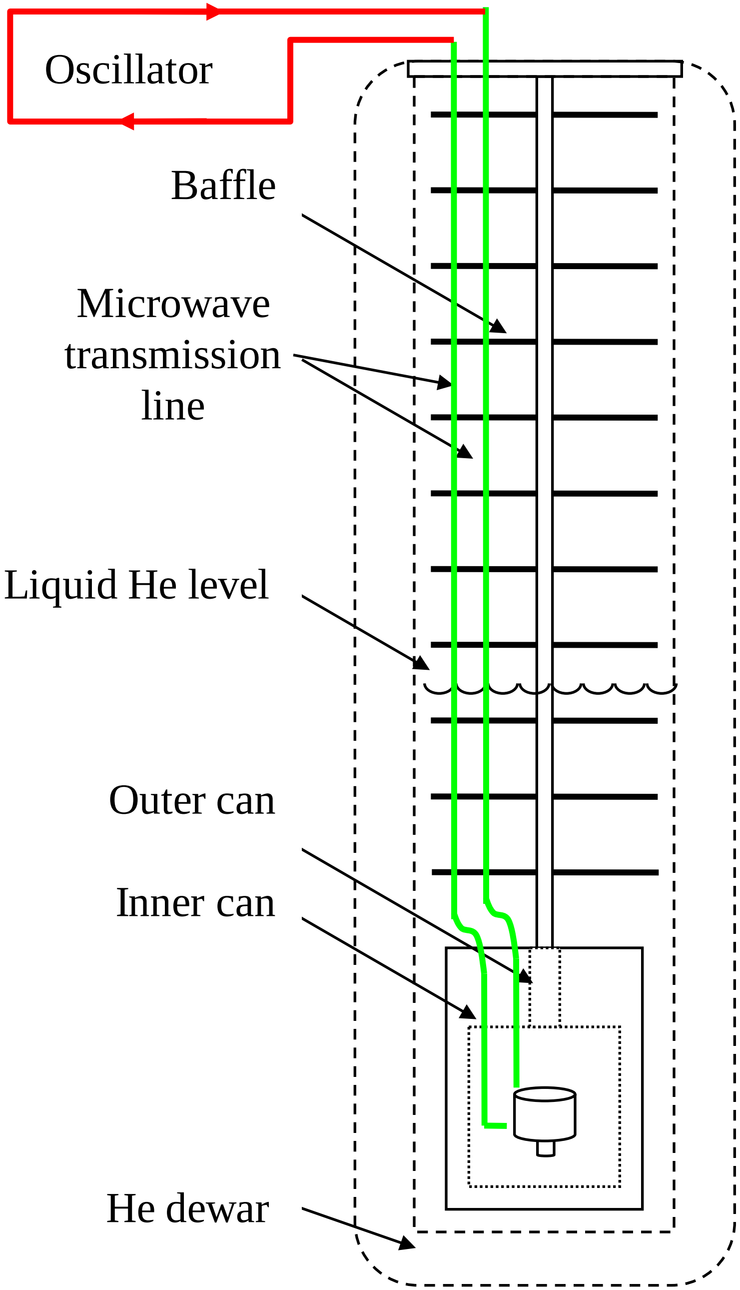
- Resonant frequency 11.931 819 GHz ($H_{14,1,\delta}$ mode)
- Q-factor ~ $2x10^9$

Frequency-temperature turning point

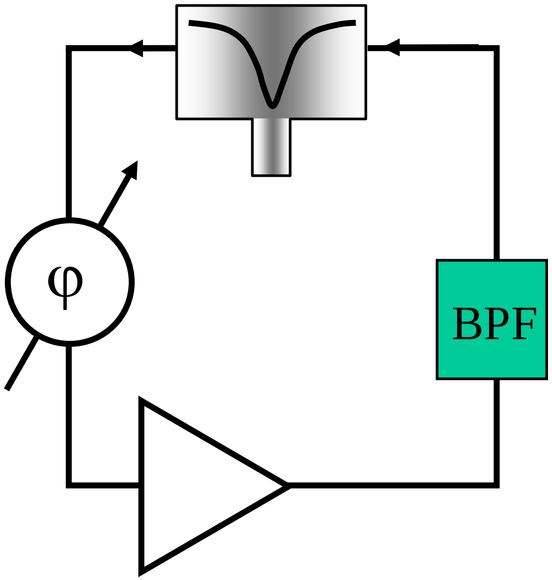


- ~7.5K turning point in frequency-temperature dependence (due to Ti^{+3} and Mo^{+3} ions)
- Curvature $\kappa=(1/f_0)d^2f/dT^2$. For sapphire, $\kappa = 10^{-9}K^{-2}$
- To achieve fractional frequency stability of 10^{-16} at 1 mK offset from the turning point, need 0.1mK temperature stability
- These conditions are not difficult to meet for liquid-helium-cooled resonators due to the availability of high-sensitivity low-noise carbon-glass temperature sensors.

The Oscillator



The Oscillator

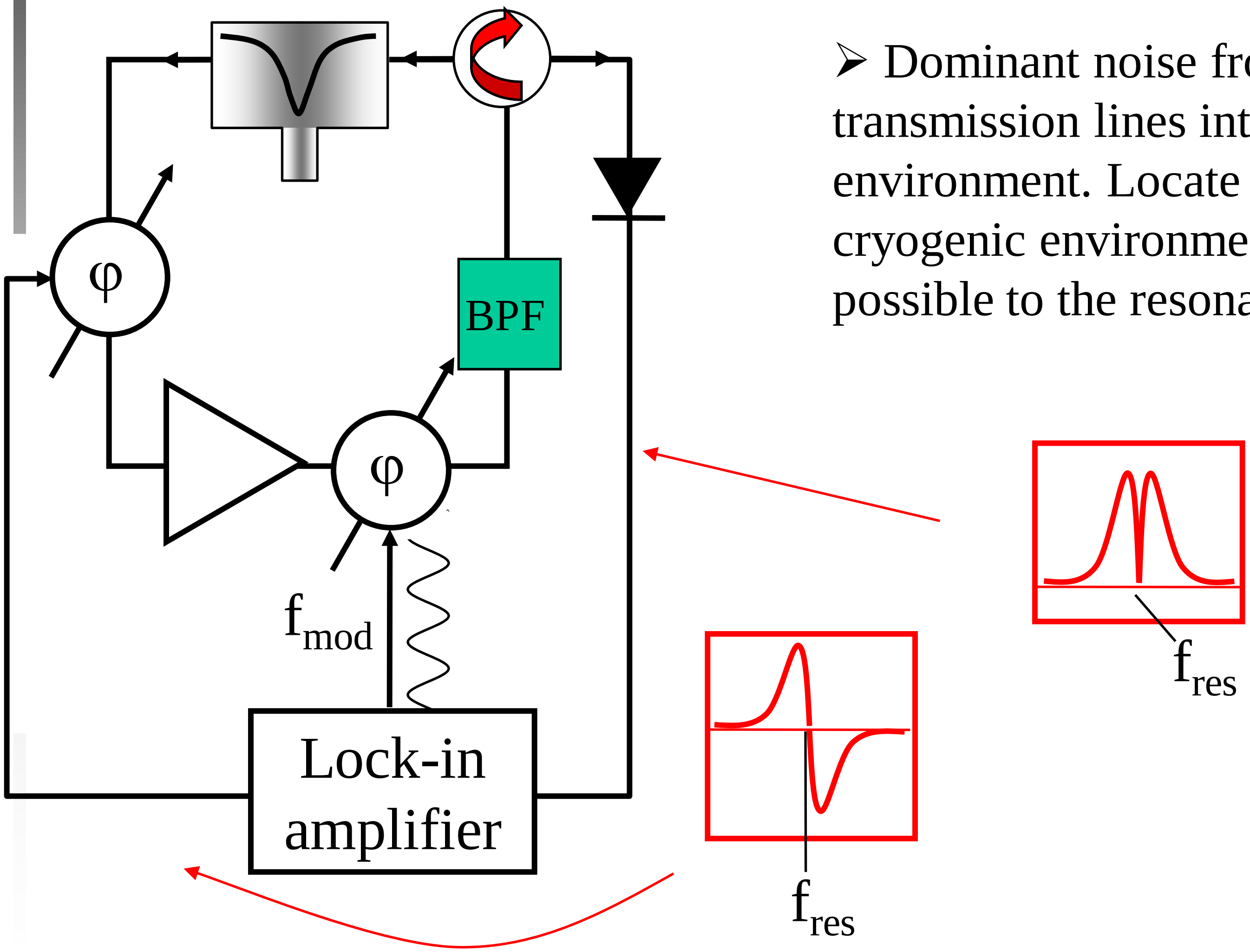


- Sapphire – high Q bandpass filter in the oscillator
- Amplifier → gain for oscillation
- Phase shifter → integer wavelengths
- Sapphire is multi-mode, need a band pass filter

Control systems required;

- Frequency control system to lock oscillator frequency to resonator frequency
- Power control

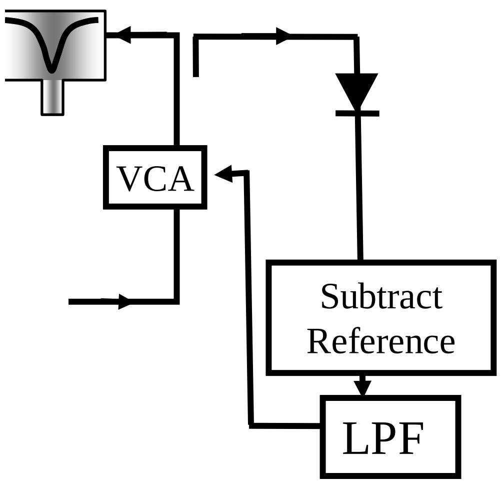
1. Frequency Control

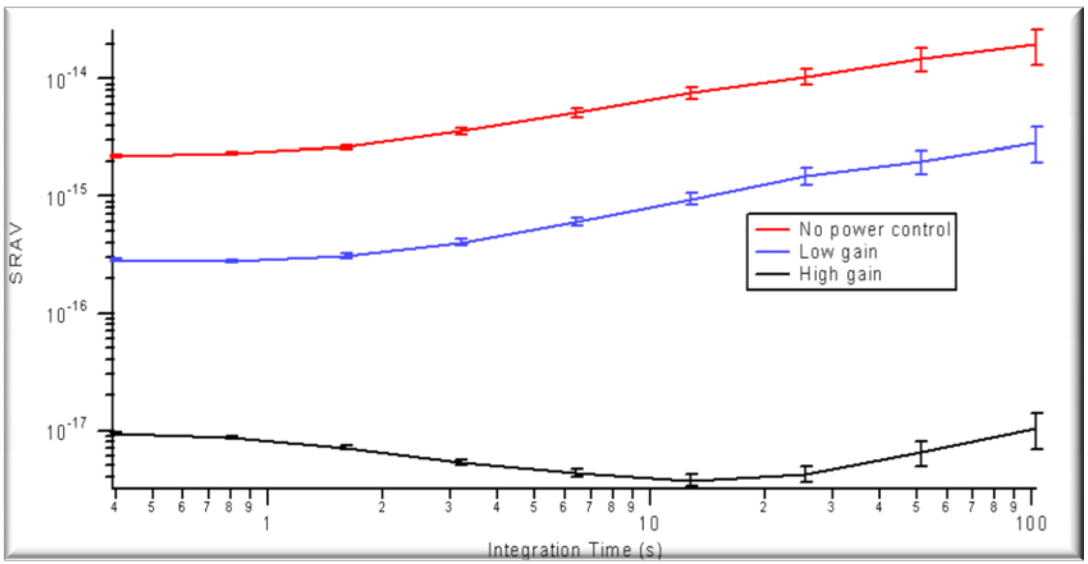


- Modulate signal and use Pound-lock control system
- Dominant noise from long transmission lines into cryogenic environment. Locate detectors in cryogenic environment as close as possible to the resonator

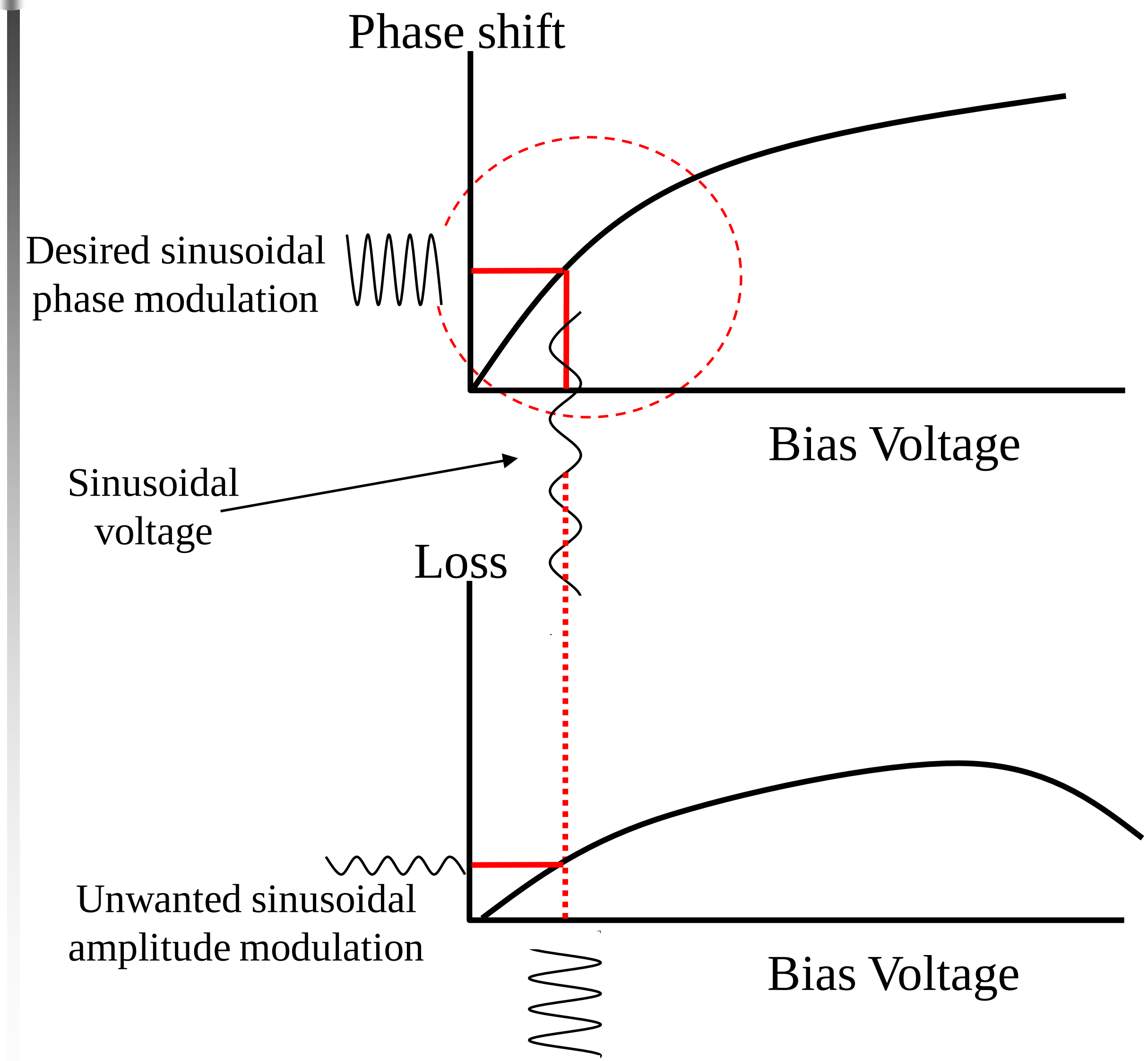
2 .Power control system

- Dominant effect of power variations is radiation pressure-induced permittivity change in sapphire
- Previously measured (Luiten) fractional frequency stability ~ 5 x 10^{-11}/(mW dissipated)



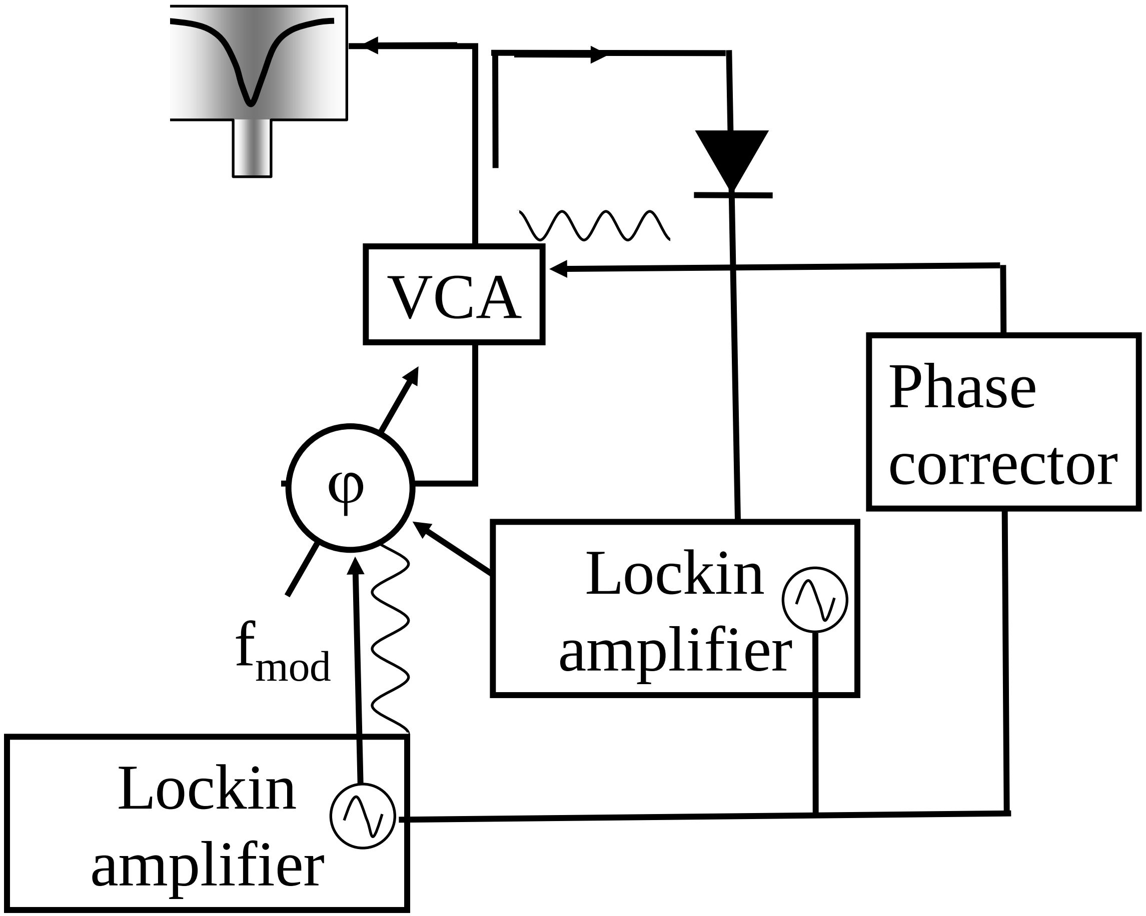


3. Amplitude modulation

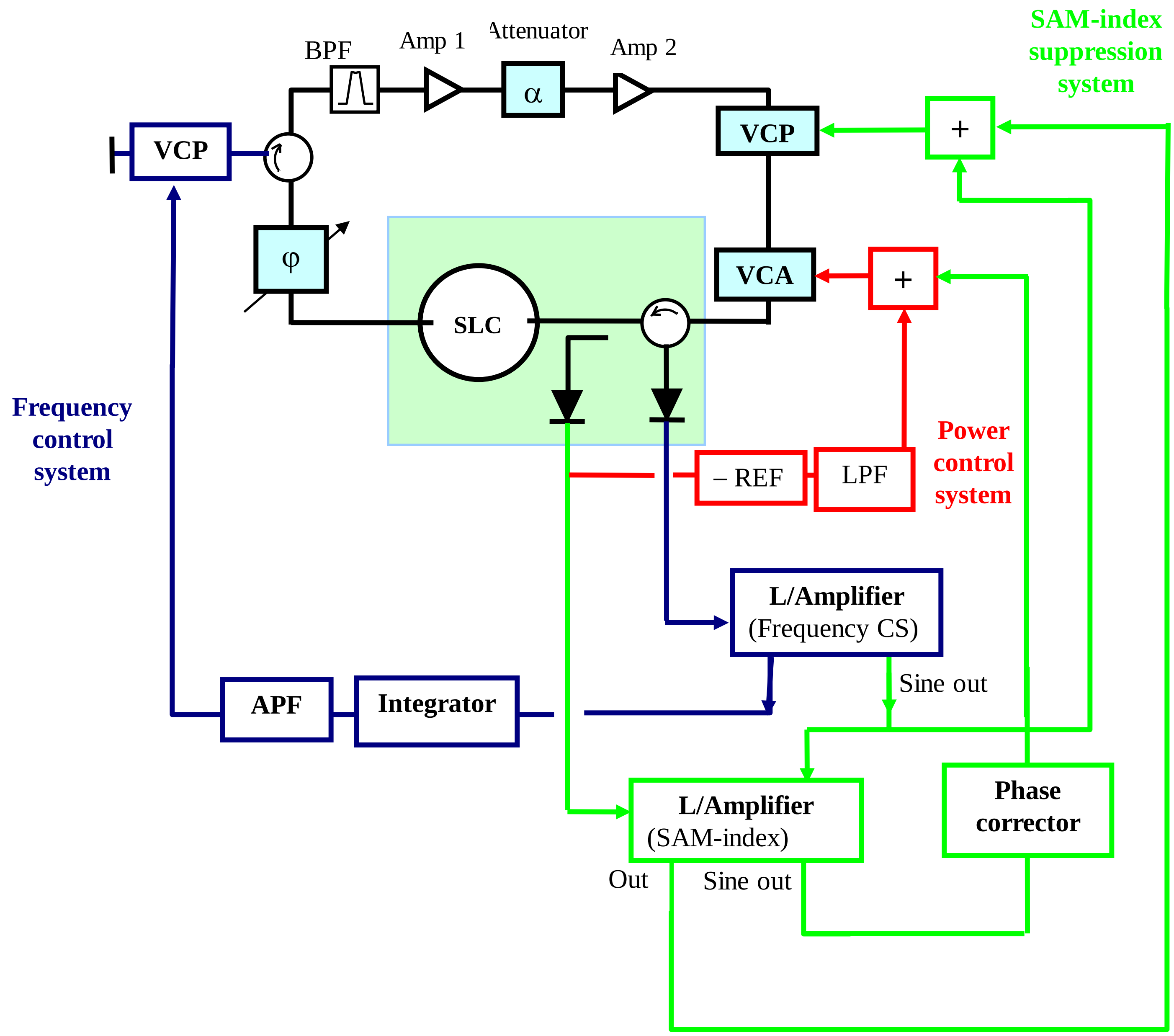


Amplitude Modulation Suppression

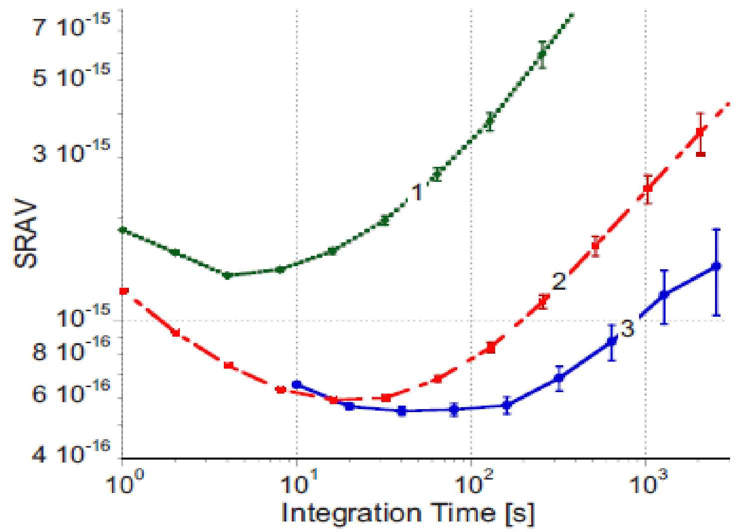
Introduce AM to cancel AM from phase modulator.



All control systems

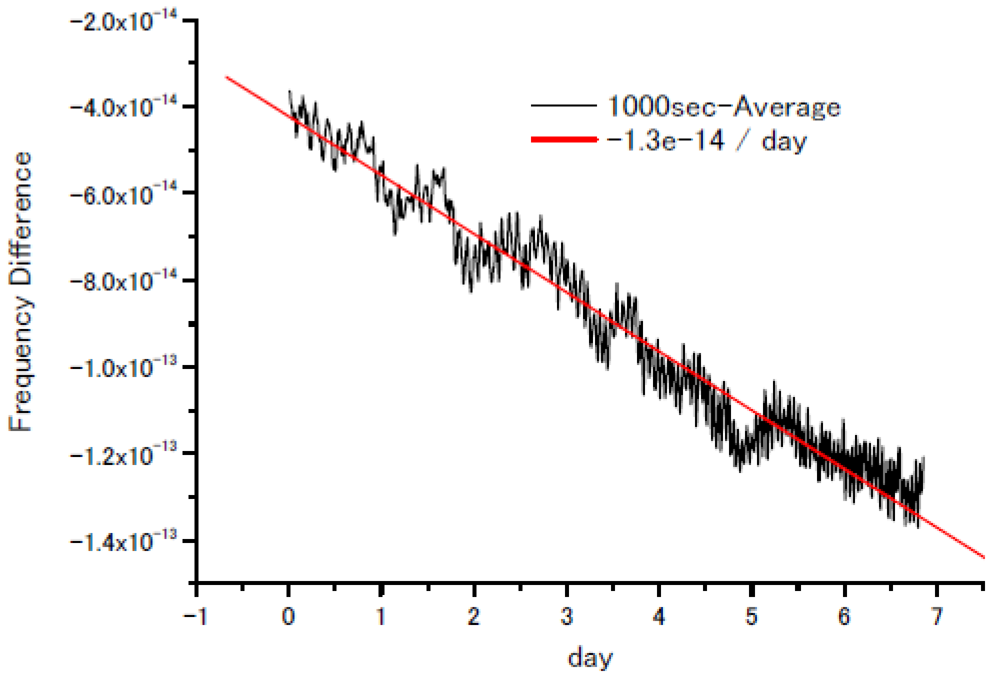


Measured Allan deviation



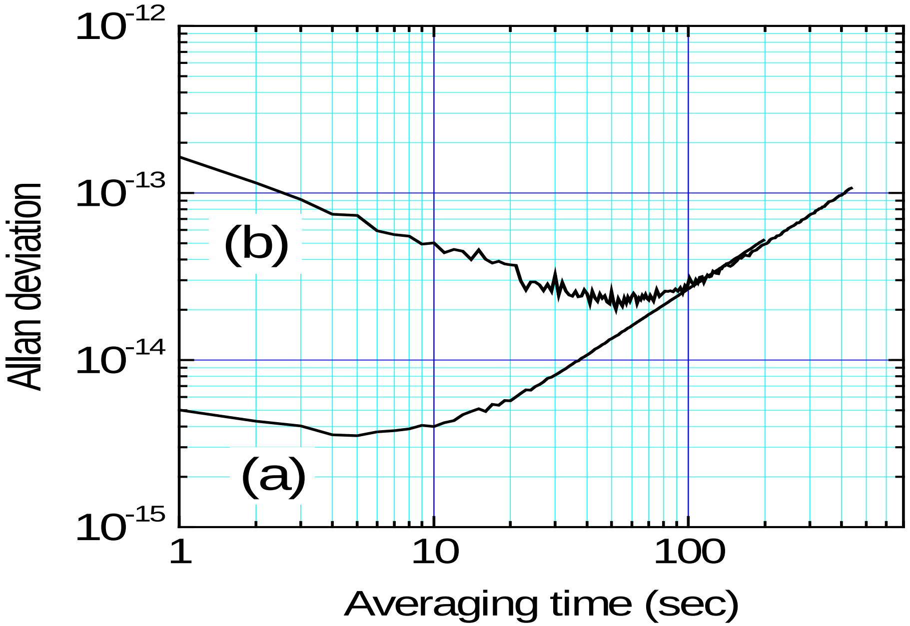
Beat between two nominally identical cryogenic sapphire oscillators; one oscillator acted as a reference oscillator with all control systems operational.
In the second oscillator
  curve 1: power control off, AM suppression off
  curve 2: power control on, AM suppression off
  curve 3: power control on, AM suppression on
The values were directly calculated from the raw data without any removal of the linear frequency drift.

Drift



Low drift rate due to
-optimal geometry of the shielded sapphire resonator characterized by a relatively sparse spectrum of cavity modes in the vicinity of the operational one
-CSO is maintained in a temperature-controlled room (+/- 0.2^{o}C) and other than two brief periods of maintenance, it has been kept at or below 77K for over four years.

Applications at NICT



At NICT an optical frequency comb (femtosecond pulse mode-locked Ti:sapphire laser) was used to perform frequency stability measurements of an ultra-narrow linewidth 729nm clock laser.

The repetition rate of the optical comb was phase-locked to the 1GHz signal derived from either the CSO (a) or a hydrogen maser (b).

When the ultra-stable CSO reference was used, a fractional frequency stability of 10^{-15} at 1 second was observed.

Conclusion/Future directions

Recent work at UWA has used a low-vibration pulse-tube cryo-cooler instead of liquid helium

NICT has developed synthesis chains to down-convert the 11.2GHz output frequency of the CSO to 1GHz signal and to up-convert the resulting 1GHz signal to 9.192GHz. The 1GHz down-converters are loosely locked to the hydrogen masers, which are traceable to Japan Standard Time.

An optical comb has been referenced to this highly stable signal and used in stability measurements of a clock laser

The CSO signal will be used as a reference for the atomic fountain NICT-CsF1.