Design Concept for the Microwave Interrogation Structure in PARCS

G.J. Dick and W.M. Klipstein, Jet Propulsion Laboratory, California Institute of Standards and Technology
T. P. Heavner and S.R. Jefferts, National Institute of Standards and Technology

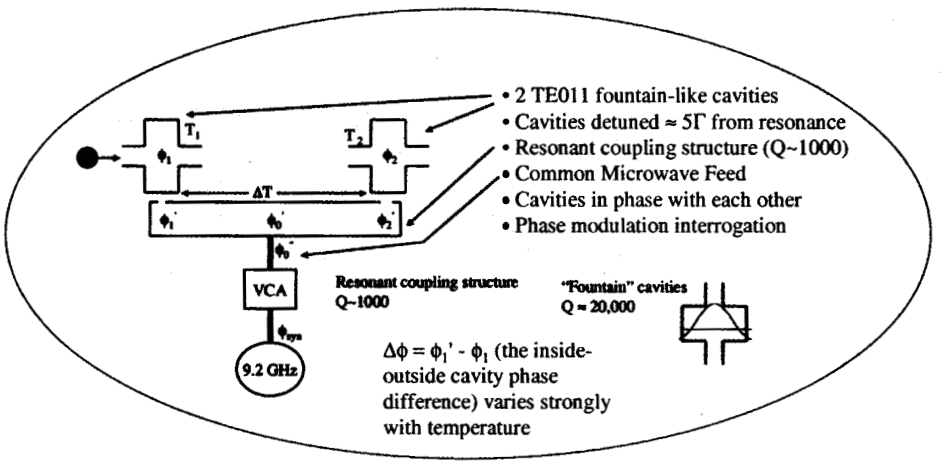
The Problem:

- **Laser-cooled clocks in space reintroduce end-to-end phase shifts absent in fountains**
- **Fountain-like microwave cavities have high sensitivity of phase to temperature, ~1 μrad/μK**
- **Design goals of ~3 μrad stability implies 3 μK temperature stability, which is unachievable**

Our Solution:

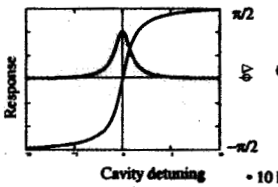
- **Operation of the cavities off of resonance dramatically reduces the required temperature stability**
- **Feeding cavities with a resonant coupling structure keeps phase well matched between the two cavities**

4' x 4'



- 2 TE011 fountain-like cavities
- Cavities detuned ≈ 5Γ from resonance
- Resonant coupling structure (Q~1000)
- Common Microwave Feed
- Cavities in phase with each other
- Phase modulation interrogation

Cavity response and phase angle between drive and cavity response as a function of detuning

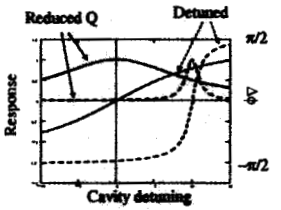


$\Delta\phi = \phi_1 - \phi_1'$ varies strongly with temperature

On resonance, 3 μrad stability ⇒ ~3 μK temperature stability!

$$\frac{d\Delta\phi}{dT} \sim \frac{1}{\text{detuning}^2}$$

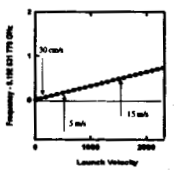
- 10 half-linewidths reduces sensitivity by ~100
- requires 100 times more RF power



$$\frac{d\Delta\phi}{dT} \sim \frac{1}{\text{broadening}}$$

- Reducing the Q by x10 reduces sensitivity by ~10
- requires 100 times more RF power

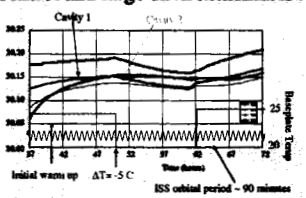
In microgravity the launch velocity is easily tuned, *so the end-to-end phase shift can be evaluated*



...but we do not want to do it frequently

- **quasi-continuous monitoring required**
- **different microwave power settings must have stable phases**

Modeled Thermal Stability of PARCS Cavities shows 30 mK variations with thermostatic control and large environmental ΔT



Temperature rate of change < 1 μK/s

Peter Jim Dulac, JPL, PARCS Thermal Engineer

Reducing the Q is not as effective as detuning the cavities:

Resonating the coupling structure

1) Differential pathlength changes to 2 ends ($\delta\ell_1$-$\delta\ell_2$)
- Mitigated by resonating structure

2) Changes in (ϕ_1' - ϕ_1)
- Eliminated by resonating structure
- Common mode, but not to a single atom $\Delta f = \frac{d\phi}{dt}\Big|_{T_{Resonator}} \frac{dT}{dt}$

For linear temperature slope, Δφ is a fixed (but unknown) frequency error

(30 μK/s is 1 x 10^{-12} in a fountain- average can still be zero)

Distributed cavity phase shift:

- TE_{011} traveling wave phase increases with increased power required (x100)
- TM_{111} component remains approximately unchanged
  - Power into cavity increases by ~100
  - But phase difference between TE and TM modes goes from π/2 to ~ 0

The Bottom Line:

In 1 day we desire 29 microradians average phase:

Maximal phase slope

"worst case" average temperature in 1 day

$\frac{1\ \mu\text{rad}}{1\ \text{mK}} \frac{1}{100}$ • 2 mK = 20 μrad (~ 1 x 10^{-16})

Off-resonant suppression factor

⇒ End-to-end variation is small and can be measured once per day

Part of the research described in this presentation was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.