RÉSULTATS RÉCENTS ET NOUVELLES PROPOSITIONS POUR LE TEST DE L'INVARIANCE DE LORENTZ

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Peter Wolf

BNM-SYRTE, Observatoire de Paris

Bureau International des Poids et Mesures

l'Observatoire de Paris

department of physics

BIPM

cnes

CENTRE NATIONAL D'ETUDES SPATIALES

CONTENTS

INTRODUCTION

- Einstein Equivalence Principle (EEP) is at the heart of special and general relativity.
- EEP $\rightarrow$ WEP, LPI, LLI.
- Most unification theories violate EEP at some level

  $\Rightarrow$ strong motivation to test it.
- Many modern tests of LLI and LPI rely on atomic clocks and macroscopic resonators.
- At the Paris Obs. atomic clocks and cavity resonators are routinely operated for time and frequency metrology. We use that equipment to carry out tests of LLI and LPI (MM, KT experiments, search for variations of fundamental constants), improving significantly on previous results.
- At UWA dedicated experiments for LLI tests using frequency metrology are in process or planned, promising further improvement.

- Numerous Test theories to model LLI violations exist. Here we consider the RMS framework (Robertson 1949, Mansouri & Sexl 1977) and the SME (Colladay & Kostelecký, 1997).

The Standard Model Extension (SME)

- Generalization of the SM Lagrangian including all Lorentz violating terms that can be formed from known fields (photons, p+, e-, n, etc..).
- The photon sector of the SME is equivalent to usual Maxwell equations with:

$$\begin{pmatrix} \vec{D} \\ \vec{H} \end{pmatrix} = \begin{pmatrix} \varepsilon_0\left(\varepsilon_r + \kappa_{DE}\right) & \sqrt{\varepsilon_0/\mu_0}\,\kappa_{DB} \\ \sqrt{\varepsilon_0/\mu_0}\,\kappa_{HE} & \mu_0^{-1}\left(\mu_r^{-1} + \kappa_{HB}\right) \end{pmatrix} \begin{pmatrix} \vec{E} \\ \vec{B} \end{pmatrix}$$

- Experiments generally set limits on linear combinations of the κ tensors:

10 components: limited by astrophysical tests to $\leq 10^{-32}$

$$(\tilde{\kappa}_{e+})^{jk} = \tfrac{1}{2}(\kappa_{DE} + \kappa_{HB})^{jk}; \quad (\tilde{\kappa}_{o-})^{jk} = \tfrac{1}{2}(\kappa_{DB} - \kappa_{HE})^{jk}$$

$$(\tilde{\kappa}_{e-})^{jk} = \tfrac{1}{2}(\kappa_{DE} - \kappa_{HB})^{jk} - \tfrac{1}{3}\delta^{kj}(\kappa_{DE})^{ll}; \quad (\tilde{\kappa}_{o+})^{jk} = \tfrac{1}{2}(\kappa_{DB} + \kappa_{HE})^{jk},$$

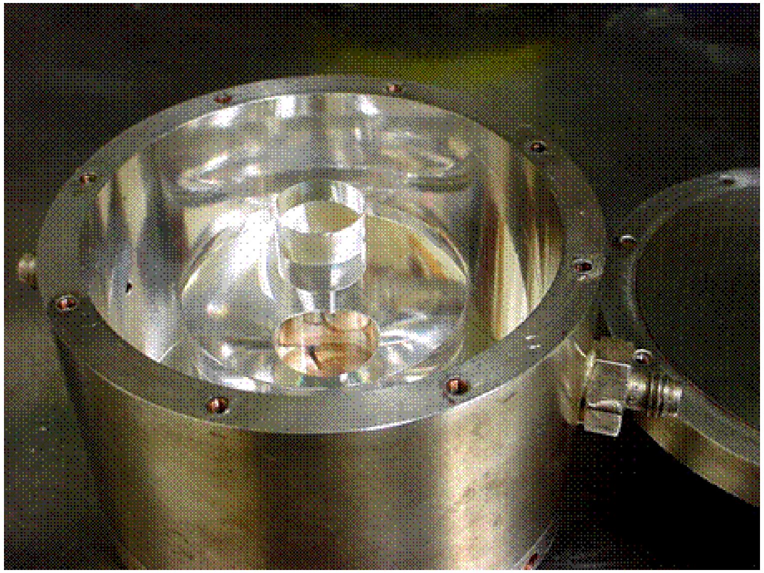
$$\tilde{\kappa}_{tr} = \tfrac{1}{3}(\kappa_{DE})^{ll}.$$

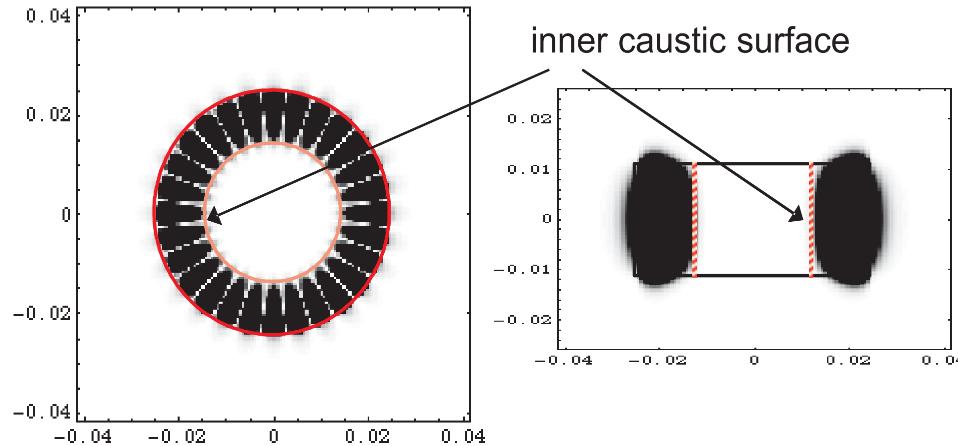
1 component: unmeasured

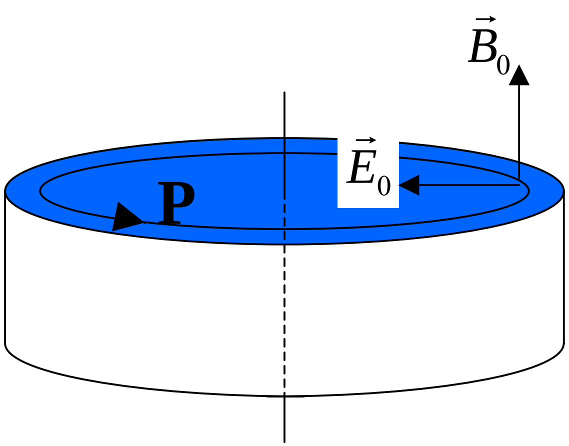
5 components: 4 are limited by resonator tests at ≈ 10^{-15}

3 components: limited by resonator tests at ≈ 10^{-11}

THE EXPERIMENT AT THE PARIS OBSERVATORY

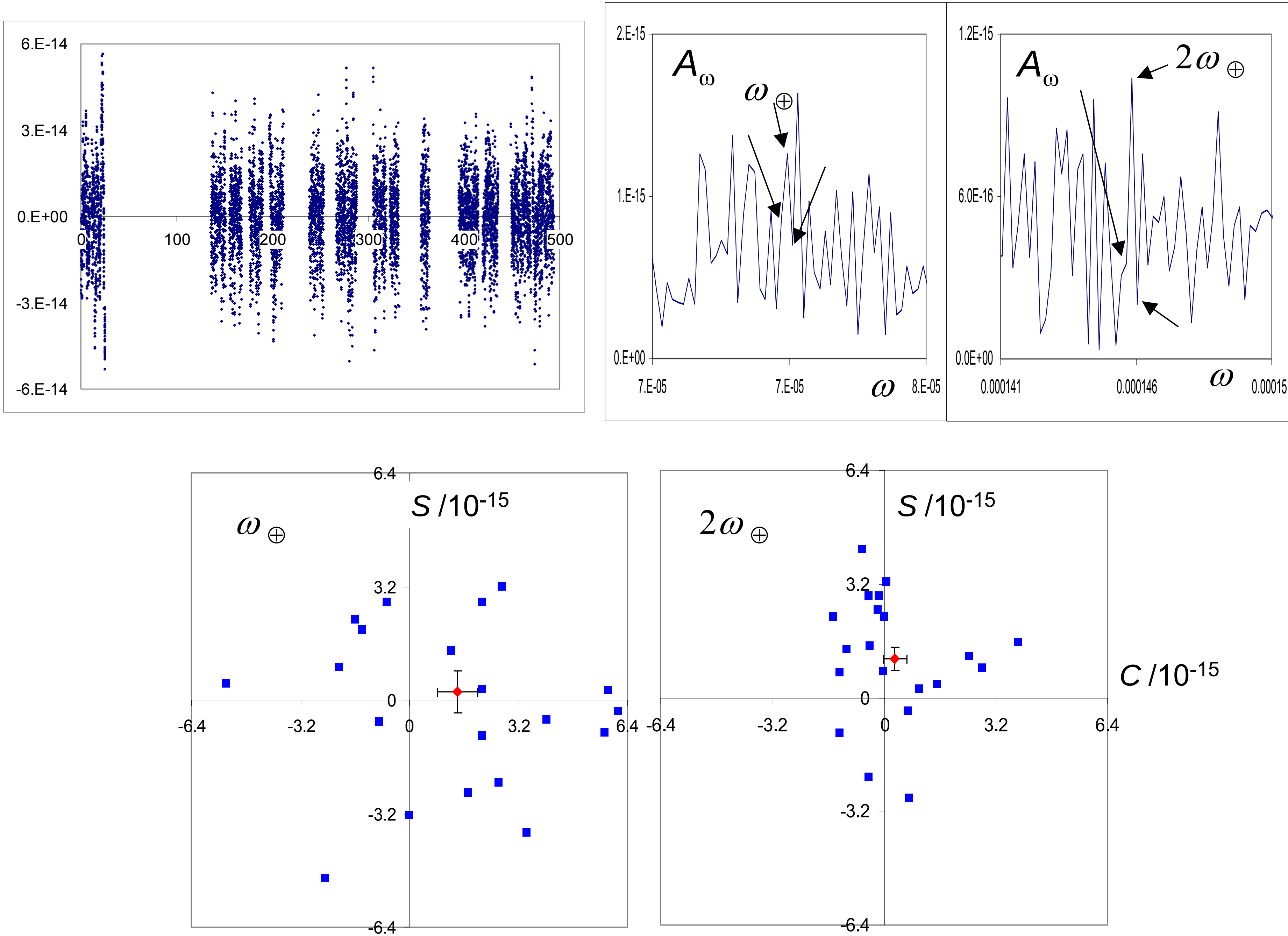






- Compare CSO frequency to H-maser
- In the SME the frequency of the CSO depends on the orientation of E and B fields

  $\Rightarrow$ time variation due to rotation and orbit of Earth.
- Negligible effect on H-maser (m_F = 0 states) and sapphire crystal (few %).
- Look for variations at $\omega \pm \Omega$, $2\omega \pm \Omega$.


6.E-14
3.E-14
0.E+00
-3.E-14
-6.E-14
0
100
200
300
400
500
2.E-15
1.E-15
0.E+00
7.E-05
7.E-05
8.E-05
A_ω
$\omega_\oplus$
ω
1.2E-15
6.0E-16
0.0E+00
0.000141
0.000146
0.000151
A_ω
$2\omega_\oplus$
ω
$\omega_\oplus$
$S/10^{-15}$
6.4
3.2
0
-3.2
-6.4
-6.4
-3.2
0
3.2
6.4
$2\omega_\oplus$
$S/10^{-15}$
6.4
3.2
0
-3.2
-6.4
-6.4
-3.2
0
3.2
6.4
$C/10^{-15}$

Systematic Effects

Effect	ω - Ω	ω	2ω
H-maser	$< 5\times10^{-16}$	$< 5\times10^{-16}$	$< 5\times10^{-16}$
Tilt	3×10^{-16}	3×10^{-16}	1×10^{-16}
g	3×10^{-17}	3×10^{-17}	3×10^{-17}
B-field	$< 10^{-18}$	$< 10^{-18}$	$< 10^{-18}$
Temperature	$< 1\times10^{-16}$	$< 1\times10^{-16}$	$< 1\times10^{-16}$
Atm. Pressure	2.3×10^{-16}	0.3×10^{-16}	0.4×10^{-16}
Total	$\mathbf{6.4\times10^{-16}}$	$\mathbf{5.9\times10^{-16}}$	$\mathbf{5.2\times10^{-16}}$

Results in the SME

	Müller et al.(2003)	This work
$\widetilde{\kappa}_{e-}^{XZ} \ /10^{-15}$	**-6.3 ± 12.4**	**-3.2 ± 1.3**
$\widetilde{\kappa}_{e-}^{YZ} \ /10^{-15}$	**3.6 ± 9.0**	**-0.5 ± 1.3**
$\widetilde{\kappa}_{e-}^{XY} \ /10^{-15}$	1.7 ± 2.6	-5.7 ± 2.3
$(\widetilde{\kappa}_{e-}^{XX} - \widetilde{\kappa}_{e-}^{YY}) \ /10^{-15}$	8.9 ± 4.9	-3.2 ± 4.6
$\widetilde{\kappa}_{o+}^{XZ} \ /10^{-11}$	-1.2 ± 2.6	-1.4 ± 2.3
$\widetilde{\kappa}_{o+}^{YZ} \ /10^{-11}$	0.1 ± 2.7	2.7 ± 2.2
$\widetilde{\kappa}_{o+}^{XY} \ /10^{-11}$	**14 ± 14**	**-1.8 ± 1.5**

Results in the RMS framework

Wolf & Petit (1997) Saathoff et al. (2003)	$\lvert\alpha + \frac{1}{2}\rvert < 8 \times 10^{-7}$ $\lvert\alpha + \frac{1}{2}\rvert < 2.2 \times 10^{-7}$
Braxmaier et al. (2002) Hils & Hall (1990) Wolf et al. (2003) Present results	$\lvert\beta - \alpha - 1\rvert < 2.1 \times 10^{-5}$ $\lvert\beta - \alpha - 1\rvert < 6.9 \times 10^{-7}$ $\beta - \alpha - 1 = (2.0 \pm 2.8) \times 10^{-7}$
Brillet & Hall (1979) Müller et al. (2003) Wolf et al. (2003) Present results	$\lvert\delta - \beta + \frac{1}{2}\rvert < 5 \times 10^{-9}$ $\delta - \beta + \frac{1}{2} = (2.2 \pm 1.5) \times 10^{-9}$ $\delta - \beta + \frac{1}{2} = (1.5 \pm 4.2) \times 10^{-9}$ $\delta - \beta + \frac{1}{2} = (-0.05 \pm 3.2) \times 10^{-9}$

Discussion and Conclusion

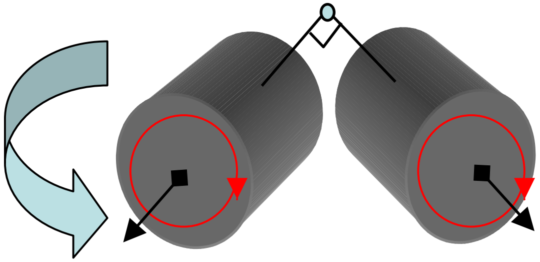
RMS framework:

- Improvement (factor 2) on our previously published results.
- Up to 70 times more stringent than best other KT experiment.
- About factor two short of best other MM test.
- No significant (at 1σ) deviation from Lorentz invariance.

Standard Model Extension (SME)

- Improvement by about an order of magnitude for three SME parameters.
- Significant ($\approx 2\sigma$) results for two parameters.
- Not consistent with Müller et al. (except for $\tilde{\kappa}_{e-}^{XZ}$).
- Not supported by distribution of individual points, or fits at neighbouring frequencies.
- Most likely a statistical coincidence or an underestimated or neglected systematic effect.
- $\Rightarrow$ Experiment is continued….
- $\Rightarrow$ Rotating experiment at UWA (potentially > order of magnitude improvement).

ROTATING EXPERIMENT AT UWA

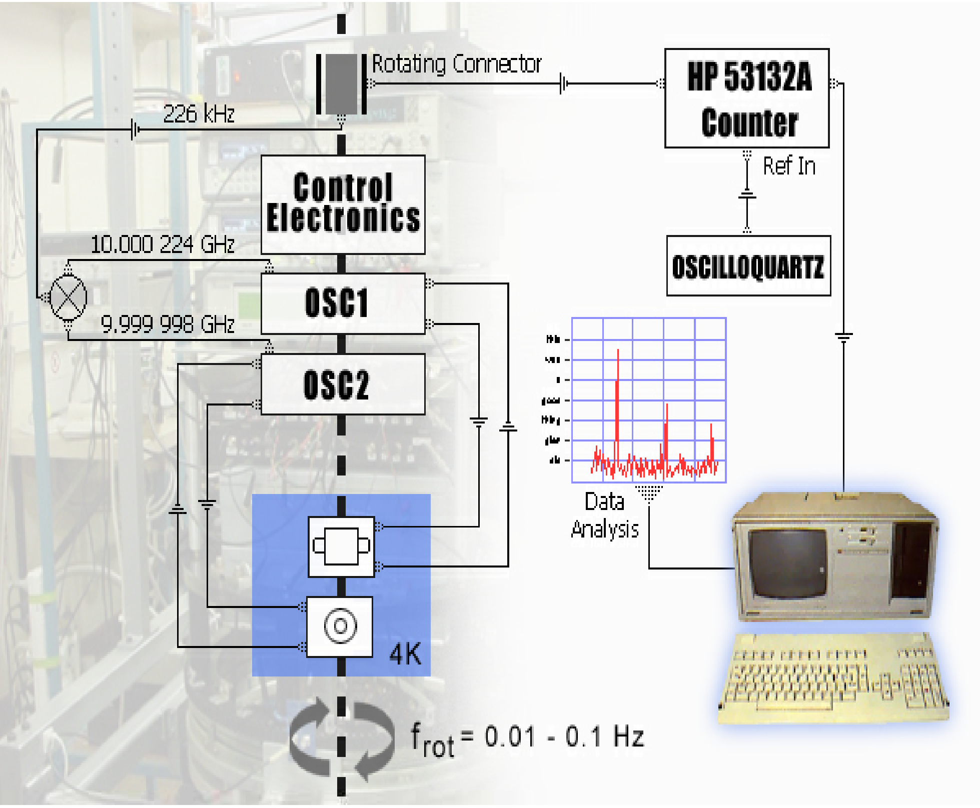


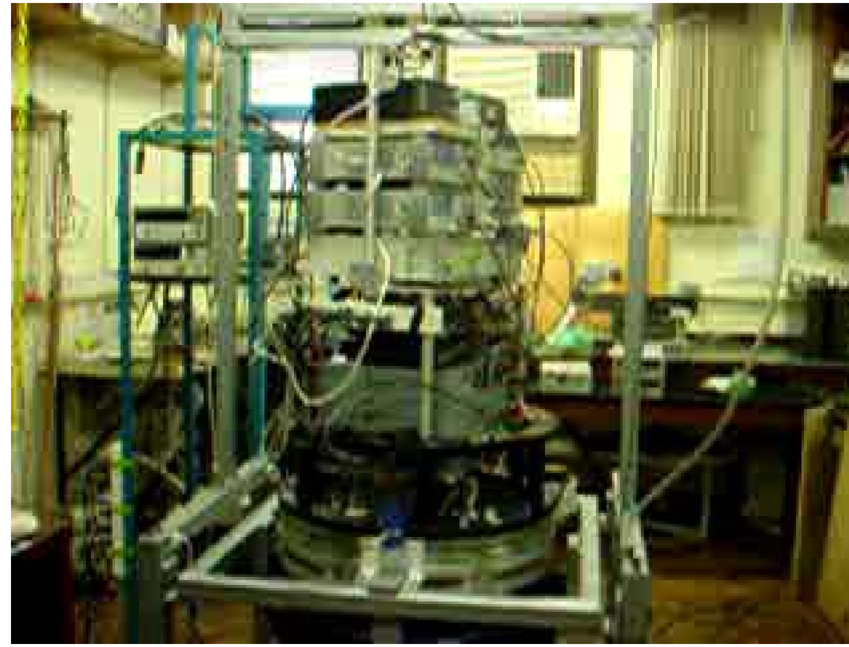
-two orthogonal CSOs (Michelson-Morley set-up).

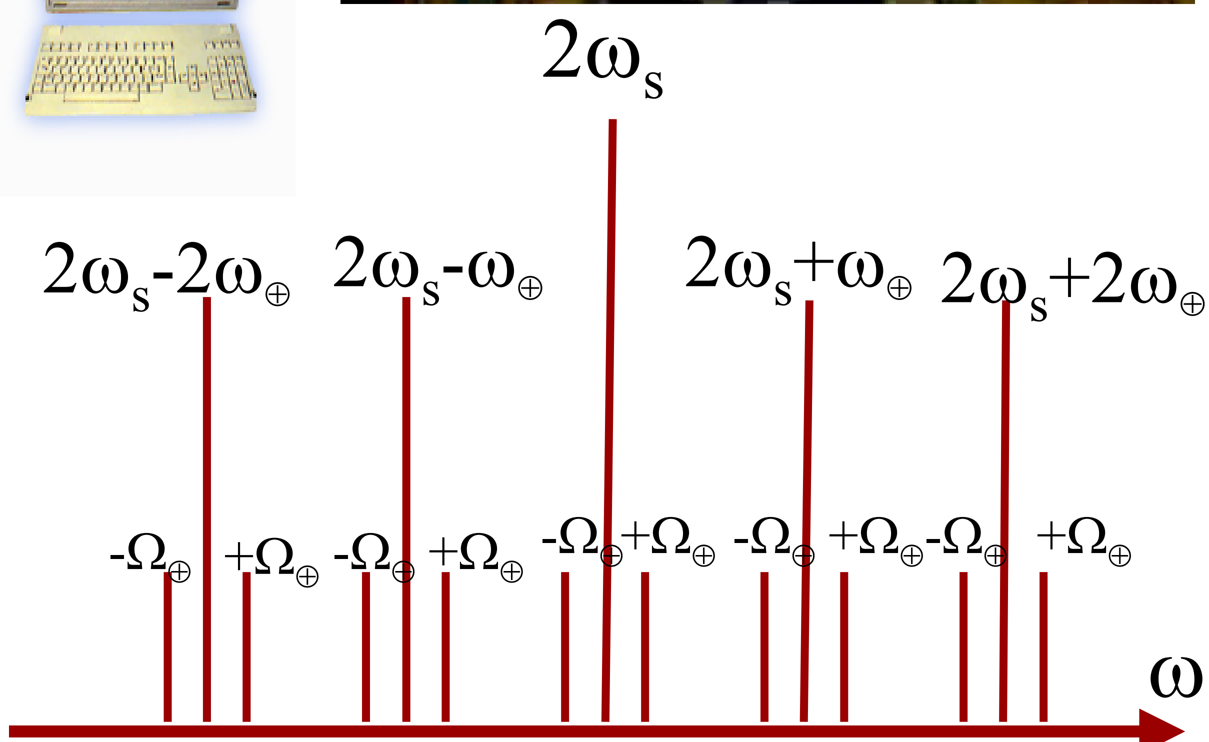
-rotation at approx. 20 s period.

-lower noise level, faster data integration, common mode systematics.

-expect order of magnitude improvements over best present limits and access to a yet unmeasured SME parameter.







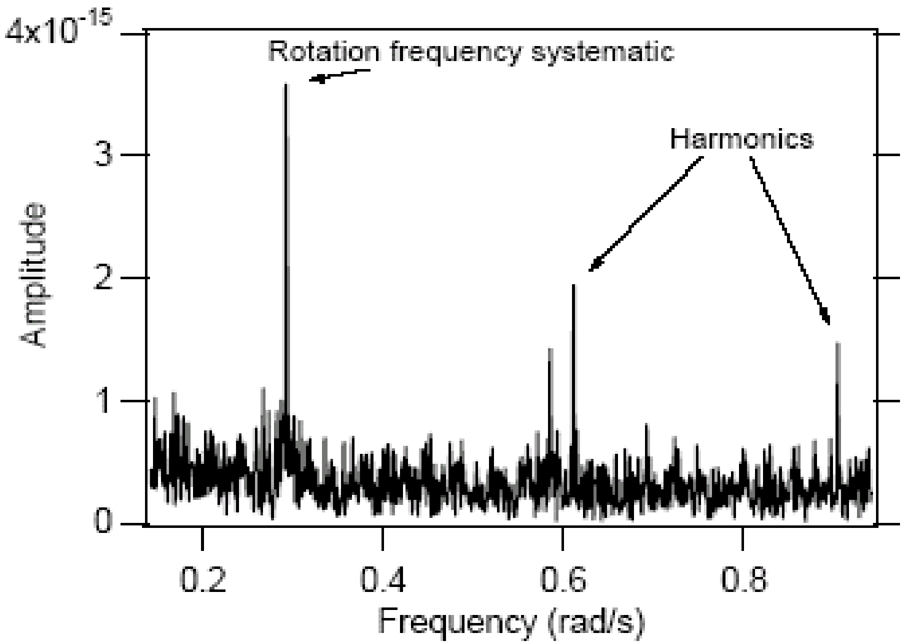
ω_s:Spin

$\omega_\oplus$:Sidereal

$\Omega_\oplus$:Annual

- 15 frequencies

First Results and Future Plans



- first run (June 2004), 16 h operation, ≈ 2 s sampling.
- noise level is equivalent to Paris results with 500 days of data.
- but large, at present uncontrolled, systematic effect(s).
- still possible to analyse side-bands to get first estimate of some parameters.

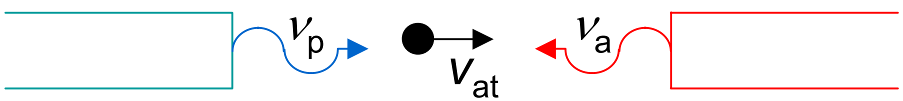
Future Plans:

- new Helium transfer tube => faster turn around time and less disturbance to experiment.
- additional rotating connector and data acquisition card to monitor tilt, temp in and out of experiment, helium level, control systems.
- shield against magnetic fields.

NEW METHODS OF TESTING LORENTZ VIOLATION IN ELECTRODYNAMICS

• Search for methods to measure the remaining SME photon parameter $\tilde{\kappa}_{tr}$ (scalar) and a better method to measure the 3 components of $\tilde{\kappa}_{o+}^{jk}$ (anti-symmetric).

• We found that Ives-Stilwell experiments are sensitive to $\tilde{\kappa}_{tr}$:



Ives – Stilwell experiment

$$\frac{\nu_a \nu_p}{\nu_0^2} = 1 + 4\tilde{\kappa}_{tr} \frac{v_{at}}{c} \frac{v_\oplus}{c} F(\phi, \chi, \eta, t, \omega_\oplus, \Omega_\oplus)$$

with $F(\phi,\chi,\eta,t,\omega,\Omega) = O(1)$

• The most recent version (Saathoff et al. 2003) uses $^7Li^+$ ions at $v_{at} = 0.064\, c$ and sets a limit:

$$\frac{\nu_a \nu_p}{\nu_0^2} = 1 + \varepsilon \quad \text{with} \quad |\varepsilon| \leq 1.8 \times 10^{-9} \quad \Rightarrow \quad \boxed{|\tilde{\kappa}_{tr}| < 10^{-4}}$$

• Analysing other experiments of this type (Two photon spectroscopy, GPS clock comparisons, etc…) in the SME yields additional, but less stringent limits on $\tilde{\kappa}_{tr}$.

The Standard Model Extension (SME)

- Generalization of the SM Lagrangian including all Lorentz violating terms that can be formed from known fields (photons, p+, e-, n, etc..).
- The photon sector of the SME is equivalent to usual Maxwell equations with:

$$\begin{pmatrix} \vec{D} \\ \vec{H} \end{pmatrix} = \begin{pmatrix} \varepsilon_0(\varepsilon_r + \kappa_{DE}) & \sqrt{\varepsilon_0/\mu_0}\,\kappa_{DB} \\ \sqrt{\varepsilon_0/\mu_0}\,\kappa_{HE} & \mu_0^{-1}(\mu_r^{-1} + \kappa_{HB}) \end{pmatrix} \begin{pmatrix} \vec{E} \\ \vec{B} \end{pmatrix}$$

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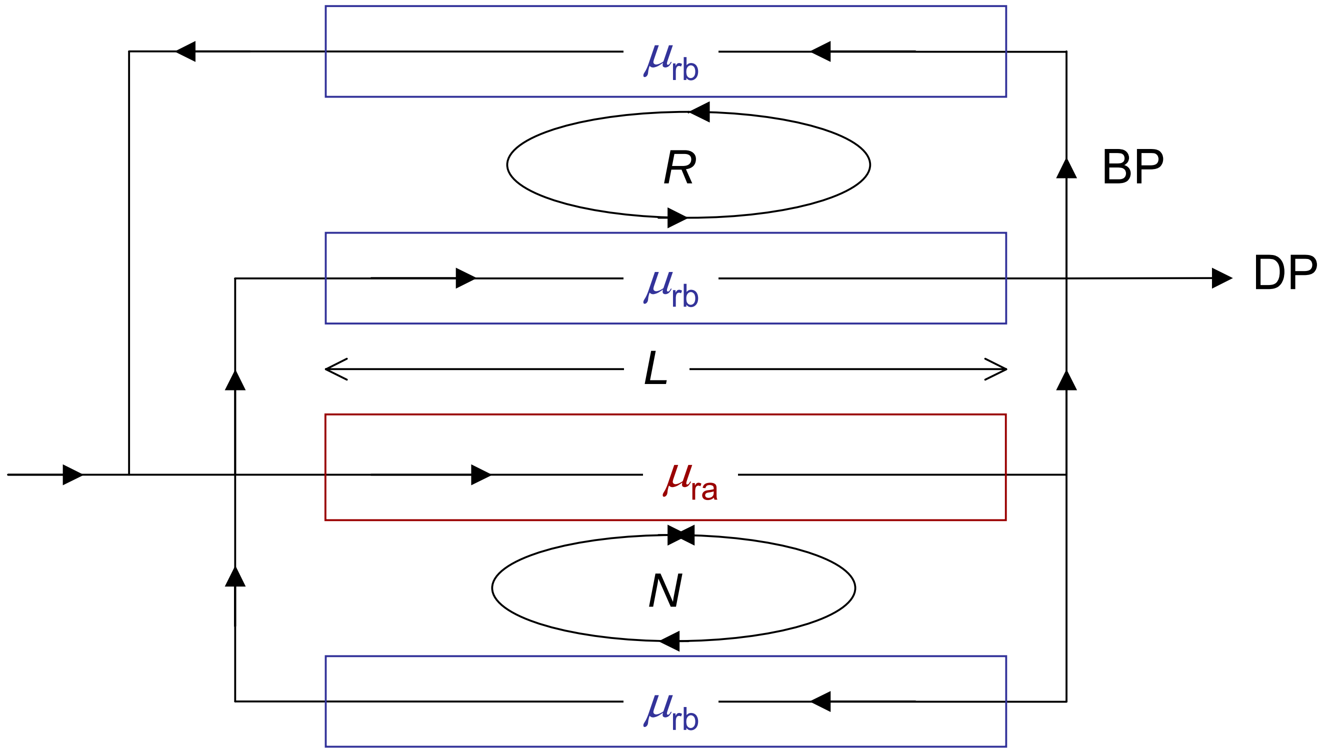
$$\tilde{\kappa}_{tr} = \tfrac{1}{3}(\kappa_{DE})^{ll}.$$

Proposed Interferometer Experiment

- Interferometer with materials of different permeability in each arm:



- In the SME:

$$\Delta\varphi = \frac{2\pi L}{\lambda}(\mu_{ra} - \mu_{rb})\left(\tilde{\kappa}_{o+}^{jk} F(t) + \frac{v_{\oplus}}{c}\tilde{\kappa}_{tr} G(t)\right)(N+1)(R+1)$$

with $F(t)$, $G(\mathrm{t}) = O(1)$

• Requires, low loss, magnetic material.

• For example, at microwave frequencies, use YIG (Yttrium Iron Garnet) in one arm and vacuum in the other.

$$\delta\left(\frac{v_{\oplus}}{c}\tilde{\kappa}_{tr}, \tilde{\kappa}_{o+}^{jk}\right)\Bigg|_{SNR=1} \approx \frac{\lambda}{2\pi L(R+1)(N+1)(1-\mu_r)} \frac{\sqrt{S_{\varphi}}}{\sqrt{N_c \tau_{obs}}}$$

• For example: L = 1m; ν = 10 GHz; (R+1) = 100; (N+1) = 50; μ_r = 0.9;

• Assume rotation at 20 s period: N_c = 0.05; $\sqrt{S_\varphi} = 10^{-9}$ rad/$\sqrt{\text{Hz}}$;

$\Rightarrow$ With τ_{obs} = 2000 s you can expect:

$\delta(\tilde{\kappa}_{o+}^{jk}) \leq 10^{-15}$	Improvement by 4 orders of magnitude
$\delta(\tilde{\kappa}_{tr}) \leq 10^{-11}$	Improvement by 7 orders of magnitude

CONCLUSION

Experiment at the Paris Observatory:

- Improves our previous results in the RMS framework by a factor ≈ 2.
- Improves best previous results in the SME by about one order of magnitude.
- Significant (≈ 2σ) results for two parameters, most likely a statistical coincidence or an underestimated or neglected systematic effect.

Rotating experiment at UWA:

- First operation shows promising noise level, but uncontrolled systematics.
- Even in the presence of that systematic some limits can be obtained from analysis of the sidebands.
- Ultimately we expect order(s) of magnitude improvement in sensitivity over previous experiments.

Proposed Interferometer experiment at UWA:

- Derived first limit $\left|\tilde{\kappa}_{tr}\right| < 10^{-4}$ (Saathoff et al. 2003).
- Proposed interferometer experiment, promises several orders of magnitude improvement on measurement of $\tilde{\kappa}_{tr}$ and $\tilde{\kappa}_{o+}^{jk}$.
- Prototype recently finished, shows expected phase noise level down to 1 Hz.