AFRL-AFOSR-JP-TR-2022-0027

Relativistic quantum metrology

Terno, Daniel
MACQUARIE UNIVERSITY
BALACLAVA RD
NORTH RYDE, , 2109
AUS

05/20/2022
Final Technical Report

Air Force Research Laboratory
Air Force Office of Scientific Research
Asian Office of Aerospace Research and Development
Unit 45002, APO AP 96338-5002

REPORT DOCUMENTATION PAGE

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION.

1. REPORT DATE	**2. REPORT TYPE**	**3. DATES COVERED**	
20220520	Final	**START DATE** 20170803	**END DATE** 20210702

4. TITLE AND SUBTITLE
Relativistic quantum metrology

5a. CONTRACT NUMBER	**5b. GRANT NUMBER**	**5c. PROGRAM ELEMENT NUMBER**
FA2386-17-1-4015		61102F
5d. PROJECT NUMBER	**5e. TASK NUMBER**	**5f. WORK UNIT NUMBER**

6. AUTHOR(S)
Daniel Terno

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	**8. PERFORMING ORGANIZATION REPORT NUMBER**
MACQUARIE UNIVERSITY BALACLAVA RD NORTH RYDE 2109 AUS	

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	**10. SPONSOR/MONITOR'S ACRONYM(S)**	**11. SPONSOR/MONITOR'S REPORT NUMBER(S)**
AOARD UNIT 45002 APO AP 96338-5002	AFRL/AFOSR IOA	AFRL-AFOSR-JP-TR-2022-0027

12. DISTRIBUTION/AVAILABILITY STATEMENT
A Distribution Unlimited: PB Public Release

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Quantum technologies are getting deployed in space. The target sensitivity, stability and precision of these system may be affected by relativistic effects and in turn allow their use as new probes of fundamental physics. The objectives were to: Characterize localization of photons and effects of gravity in optical interferometry, Identify the effects of spin-gravity couplings in metrology and time keeping, and Design space-based all-optical test of the Einstein Equivalence Principle (EEP). A novel noise-mitigation scheme was developed.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**	SAR	4
U	U	U		

19a. NAME OF RESPONSIBLE PERSON	**19b. PHONE NUMBER** *(Include area code)*
JEREMY KNOPP	315-227-7006

Relativistic quantum metrology

1. EEP all-optical test

Background
Quantum technologies are getting deployed in space. The target sensitivity, stability and precision of these system may be affected by relativistic effects and in turn allow their use as new probes of fundamental physics

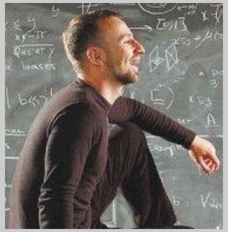
Objectives
- Characterize localization of photons and effects of gravity in optical interferometry
- Identify the effects of spin-gravity couplings in metrology and time keeping
- Design space-based all-optical test of the Einstein Equivalence Principle (EEP)

Impact
Test the basic premises of Einstein's relativity in a new setting

Identify the form & design new test of spin interaction with inertia and acceleration

Funding Profile
AOARD: $36k (2017-2020; extended until 2021/07/02)

Principal Investigator
Dr. Daniel Terno, A/ Prof,
Macquarie University, Sydney, Australia



Key **effect** to look for: gravitational red shift

Key **objective**: interferometric determination of the red shift for light from a single source, without comparison with frequency standards

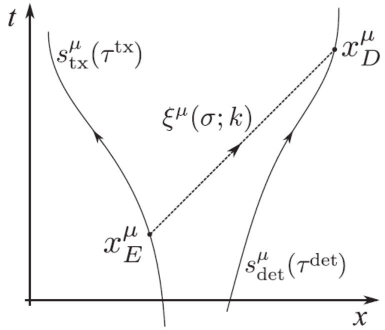
Main **challenge**: the gravitational red shift is dwarfed by the linear Doppler effect by a factor of 100,000

Subproject:
Interferometry in curved spacetime

The necessary calculation tool that had to be devised:
a systematic treatment of the phase difference evaluation

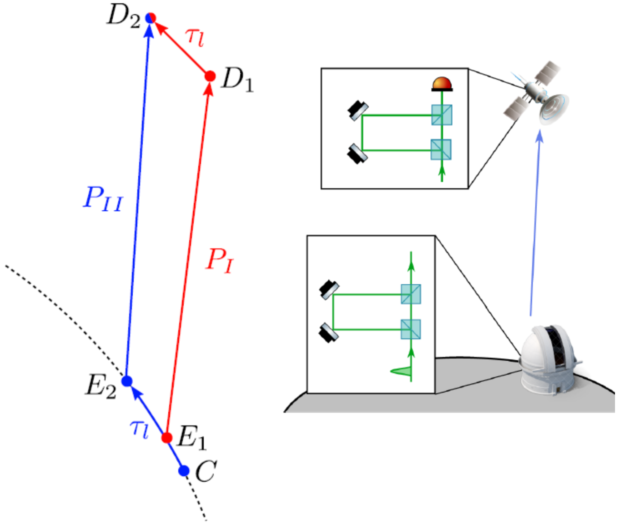
Results:

- A unified scheme to calculate the phase difference for any set-up and any precision of the post-Newtonian approximation



◀The basic idea is very simple:
the phase is constant along the ray

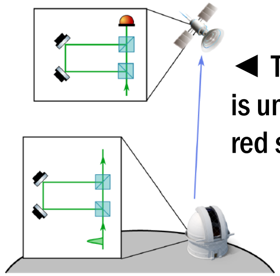
For two pulses from a single stable source the key quantity is the proper delay time between the emissions (E_1 and C) ▶



D. R. Terno, F. Vedovato, G. Vallone, and P. Villoresi,
Large-scale optical interferometry in general spacetimes, Phys. Rev. D **101**, 104052 (2020)

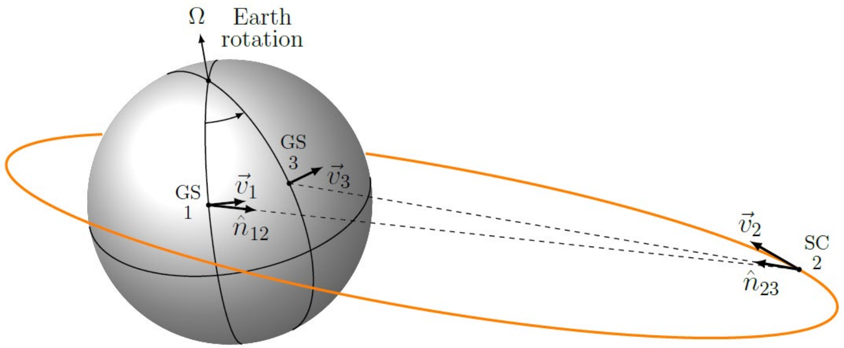
Relativistic quantum metrology

1. EEP all-optical test



◄ The Doppler effect (linear and quadratic) is unavoidably mixed with the gravitational red shift in the original scheme (2012)

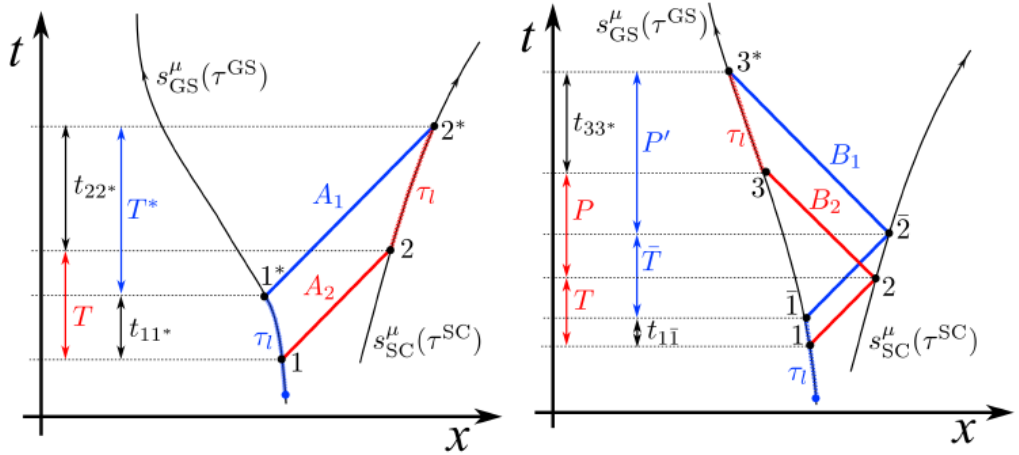
Solution (in principle) (2018)
post-processing of two time-delayed outputs of equal imbalance interferometers

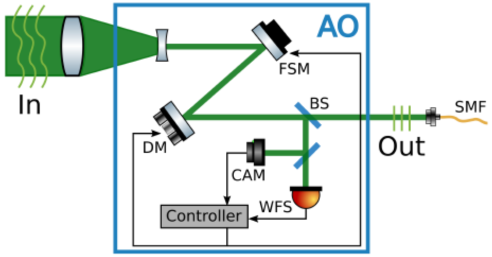


$$S = \varphi_{SC} - \tfrac{1}{2}\varphi_{GS}$$

◄ the signal, includes gravity and the 2nd order effects of relative velocity

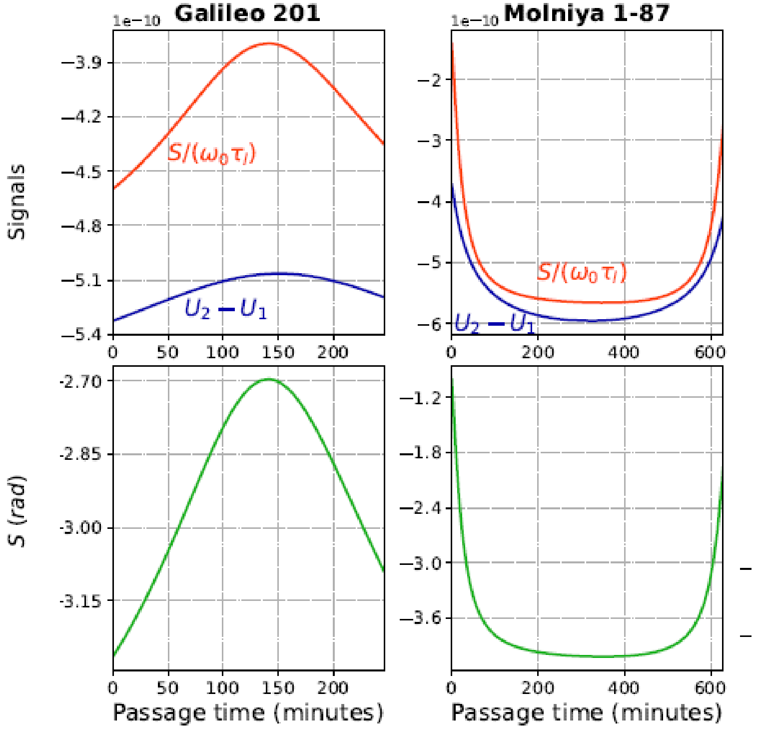
The pulse scheme used to evaluate the phases (2019-20) ▼





▲ Adaptive optics scheme free space - fiber (2019-21)

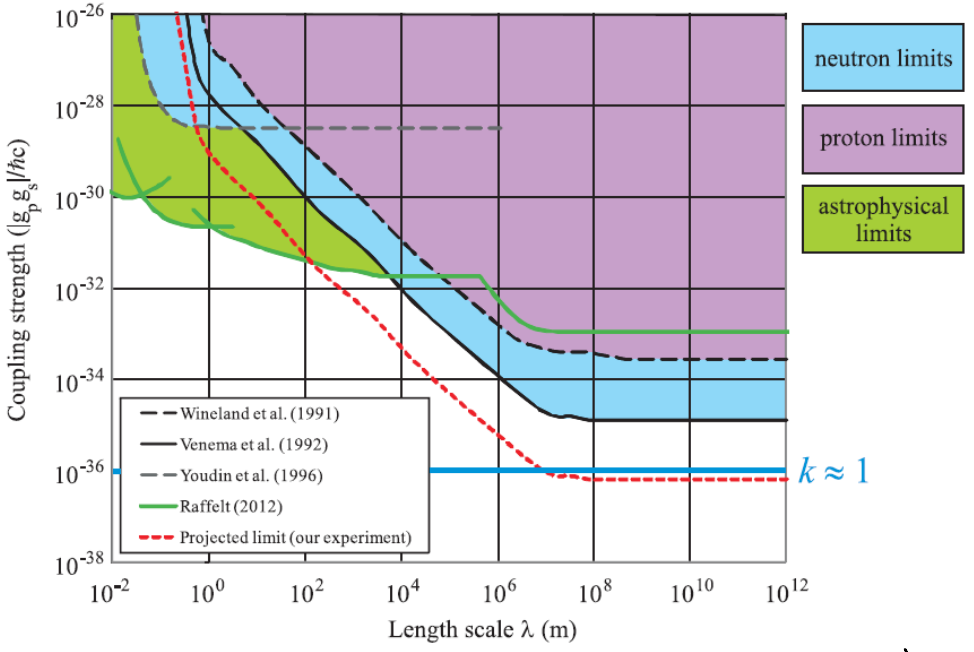
2nd order phase shift and the extracted signal (blue), for optimal orbits (2021)



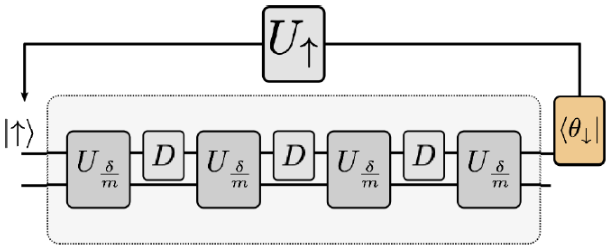
D. R. Terno, F. Vedovato, M. Schiavon, A. R. H. Smith, P. Magnani, G. Vallone, and P. Villoresi, *Proposal for an optical test of the Einstein Equivalence Principle*
arXiv: 1811.04835v2 (2018);
Detailed optical scheme and simulations (in preparation)

Relativistic quantum metrology

Subproject: spin-gravity coupling



▲ Known limits on k . Kimball et al, Ann. Phys. (Berlin) **525**, 514 (2013)



◄ the noise cancellation scheme

■ The direct acceleration/gravity–spin coupling is a possible feature of modified theories of gravity. The value of parameter k is unknown

$$H_{\text{ext}} = \frac{\hbar k}{2c} \vec{a} \cdot \vec{\sigma}$$

Fundamental **science** challenge: what is there beyond general relativity?

Space **technology** challenge: if such effects exist, they have to be taken into account/countered in ord to achieve the proposed performance targets

Key idea (2019): The effect looks like coupling of spin to magnetic field. Method of *weak measurement* allows to trade the size of the effect for low probability of success of the measurement.

Key innovation (2020-21): Quantum Zeno effect (the result of appropriately tailed pulse sequences) is used to reduce the effects of noise

Results:

A proposal for optical magnetometry for fields up to 10^{-19}T (two orders of magnitude improvement) that is robust against the typical sources of noise (2019-20)

S. Ghosh, L.-C. Kwek, D. R. Terno, and S. Vinjanampathy, *Weak-value magnetometry for precision tests of fundamental physics*, arXiv: 1912.10693

P. Magnani, M. Schiavon, A. R. H. Smith, D. R. Terno, G. Vallone, F. Vedovato, P. Villoresi, and S. Vinjanampathy, *Quantum satellites and tests of relativity*, in *Proceedings of the Fifteenth Marcel Grossman Meeting on General Relativity* (World Scientific, Singapore, 2021)

Future:

A novel scheme for error-mitigation that is based on quantum Zeno effect, potentially applicable in a variety of system. This is subject of the current (20021-) Macquarie U/IIT Bombay collaboration

Brief Narrative

1. We introduce a convenient formalism to evaluate the phase of a light signal propagating on a general curved background. It allows us to obtain a transparent relation between the frequency-shift and the phase difference in large-scale optical interferometry for a general relativistic setting, as well as to derive compact expressions generalizing the Doppler effect in one-way and two-way schemes. Our recipe is easily applicable to stationary spacetimes, and in particular to the near-Earth experiments where the geometry is described in the parametrized post-Newtonian approximation.

2. The local position invariance of non-gravitational experiments, which entails the gravitational red-shift is the key element of the Einstein Equivalence Principle (EEP). Precision measurements of the gravitational red-shift tightly bound violations of the EEP only in the fermionic sector of the Standard Model. Proposals exploiting light interferometry suffer from the first-order Doppler effect, which dominates the weak gravitational signal necessary to test the EEP, making them unfeasible. Here, we propose a novel scheme to test the EEP, which is based on a double large-distance optical interferometric measurement. By manipulating the phase-shifts detected at two locations at different gravitational potentials it is possible to cancel-out the first-order Doppler effect and observe the gravitational red-shift implied by the EEP, bounding its potential violation to it natural precision limit of $\sim 10^{-5}$. We present the detailed analysis of the proposal within the post-Newtonian framework and the simulations of the expected signals, particularly focusing on high-excentricity orbits that allow to differentiate between the signal and the Doppler shift.

3. Progress in testing fundamental physics relies on our ability to measure exceedingly small physical quantities. Using a $^{40}Ca^{+}$ trapped ion system as an example we show that an exceedingly weak synthetic magnetic field (at the scale of 10^{-19} T) can be measured with current technology. This improved sensitivity can be used to test the effects of spin coupling that affect the equivalence principle and, if present, may impact the performance of the proposed entangled optical clocks arrays. The novel noise-mitigation scheme is based on the quantum Zeno effect and will be investigated as a part of error correction protocols in certain classes of quantum optimisation algorithms.