OHP Colloquium
2013. 9. 26. (Thursday)

Laser ranging by time-of-flight measurement of femtosecond light pulses

Korea Advanced Institute of Science and Technology (KAIST)
Department of Mechanical Engineering

Young-Jin Kim, Ph. D

Keunwoo Lee, Joohyung Lee, Sanghyun Lee and Seung-Woo Kim

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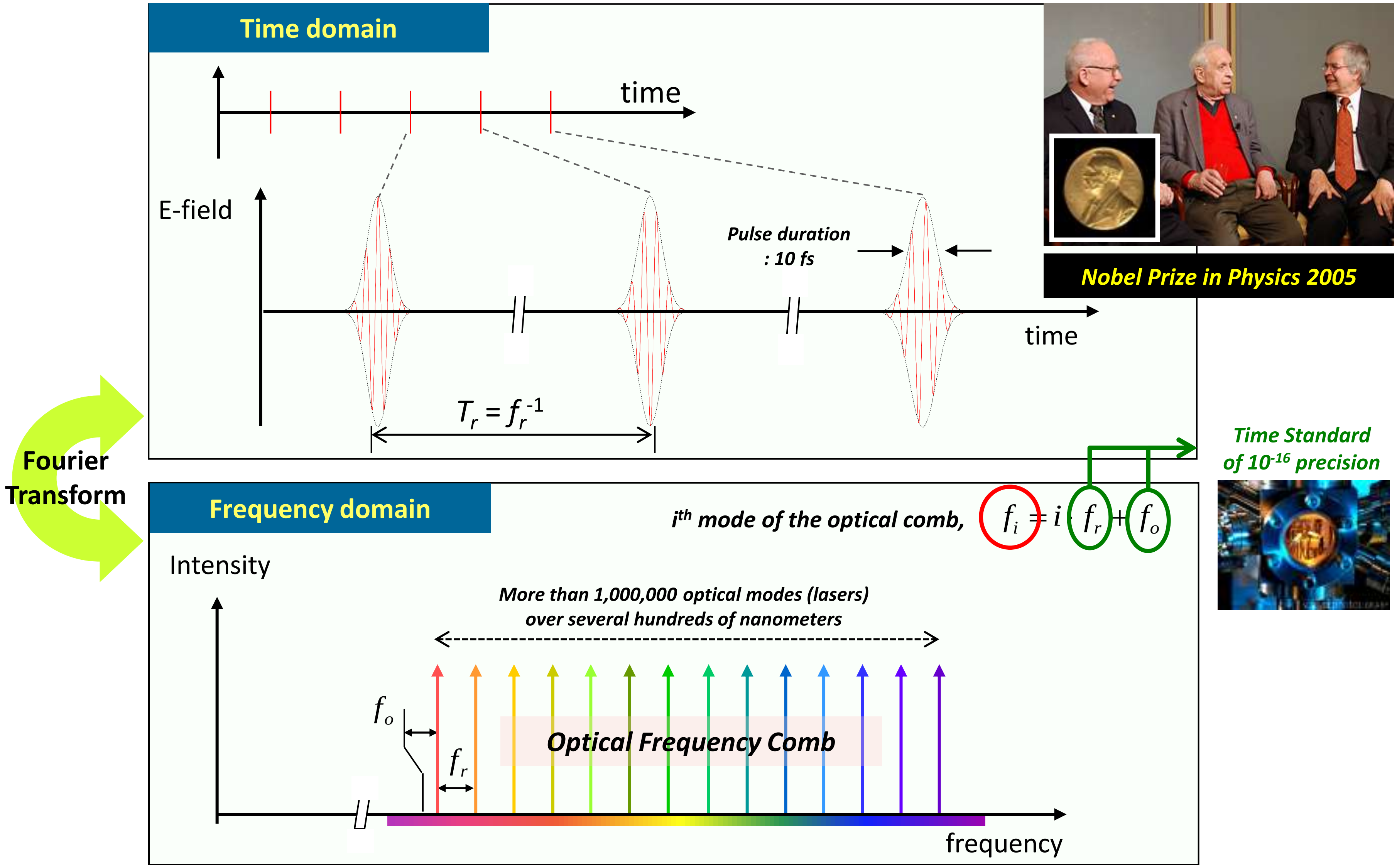
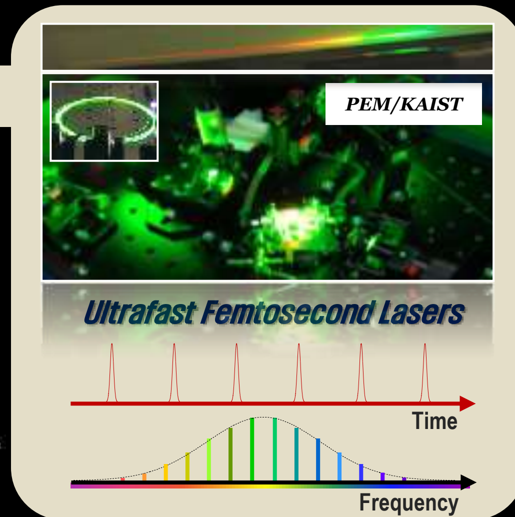
What is Femtosecond Pulse Laser?



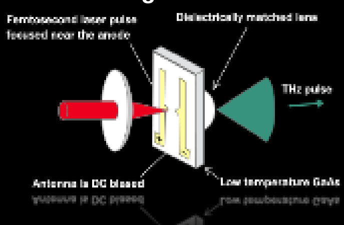
f_r : repetition rate

f_o : carrier-envelope offset frequency

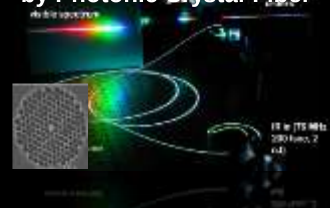
Ultrafast Optics for Ultra Precision



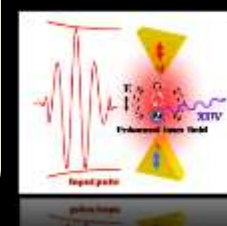
THz generation



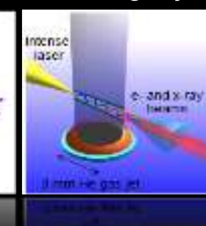
Supercontinuum generated by Photonic Crystal Fiber



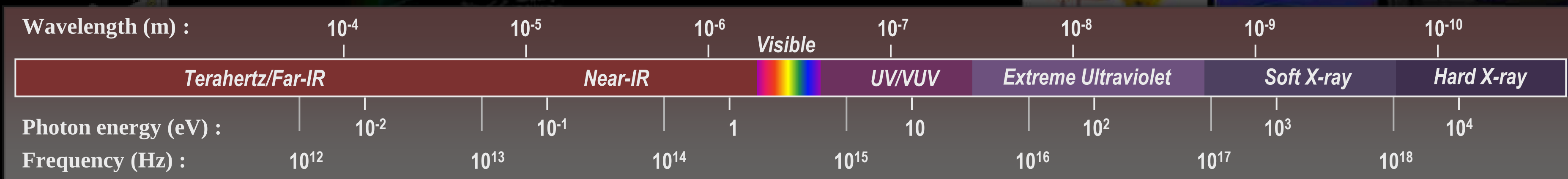
SP based HHG



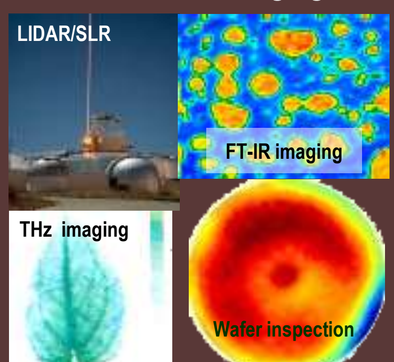
HHG in gas jet



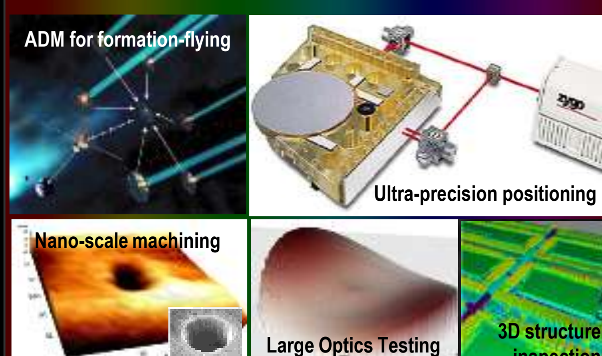
Laser-produced plasma X-ray



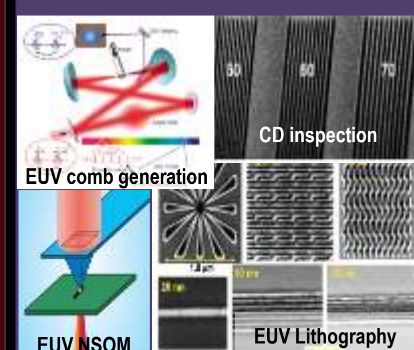
- LIDAR/SLR
- IR non-destructive inspection
- FT-IR spectroscopy
- Terahertz wave imaging



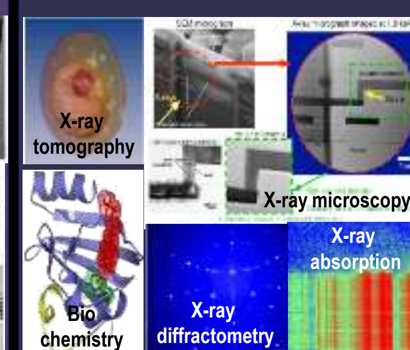
- Absolute distance metrology
- 3D profile/thickness metrology
- Optical frequency synthesizer
- Ultra-precision positioning

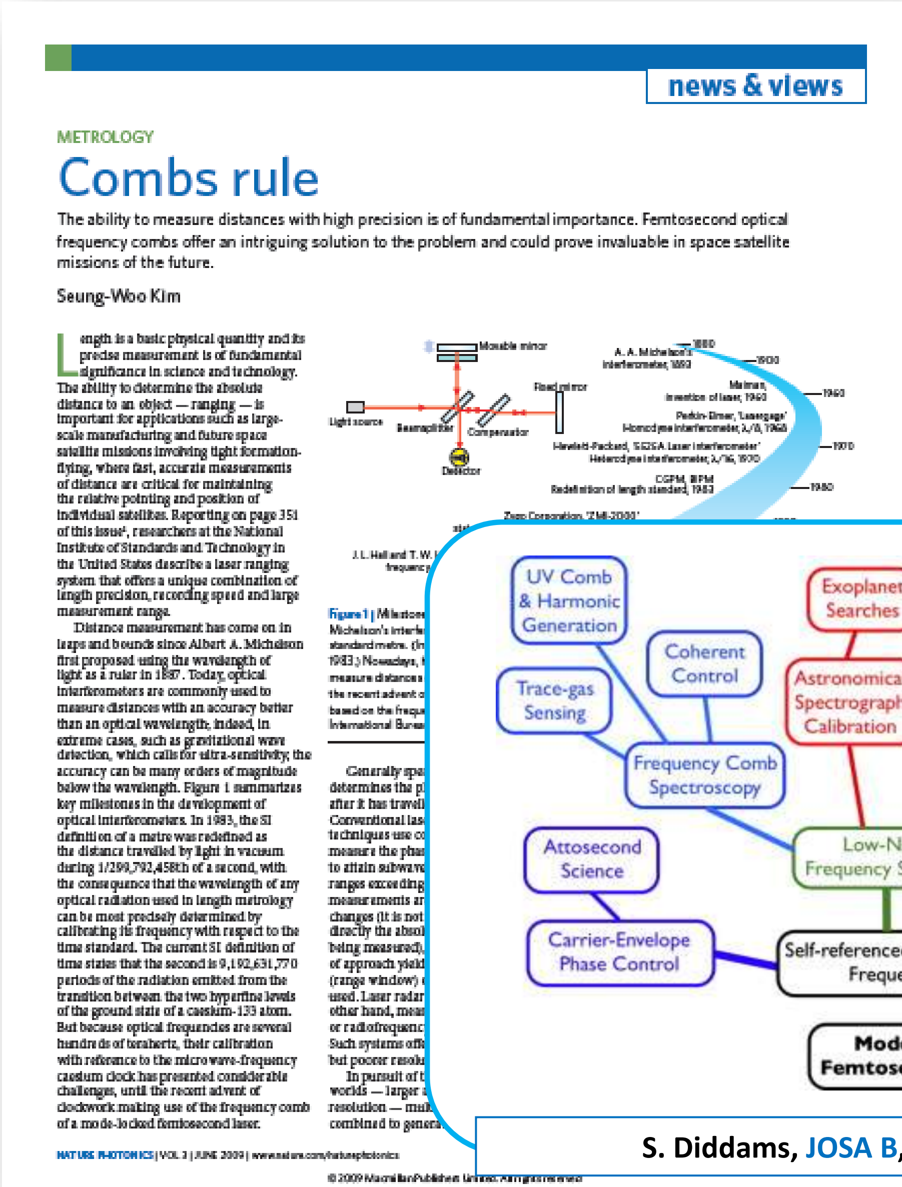


- EUV comb generation
- Thin-film thickness metrology
- Critical dimensions inspection
- Nano-scale material imaging



- Coherent X-ray generation
- X-ray microscopy
- X-ray non-destructive inspection
- X-ray imaging/interferometry





news & views

METROLOGY

Combs rule

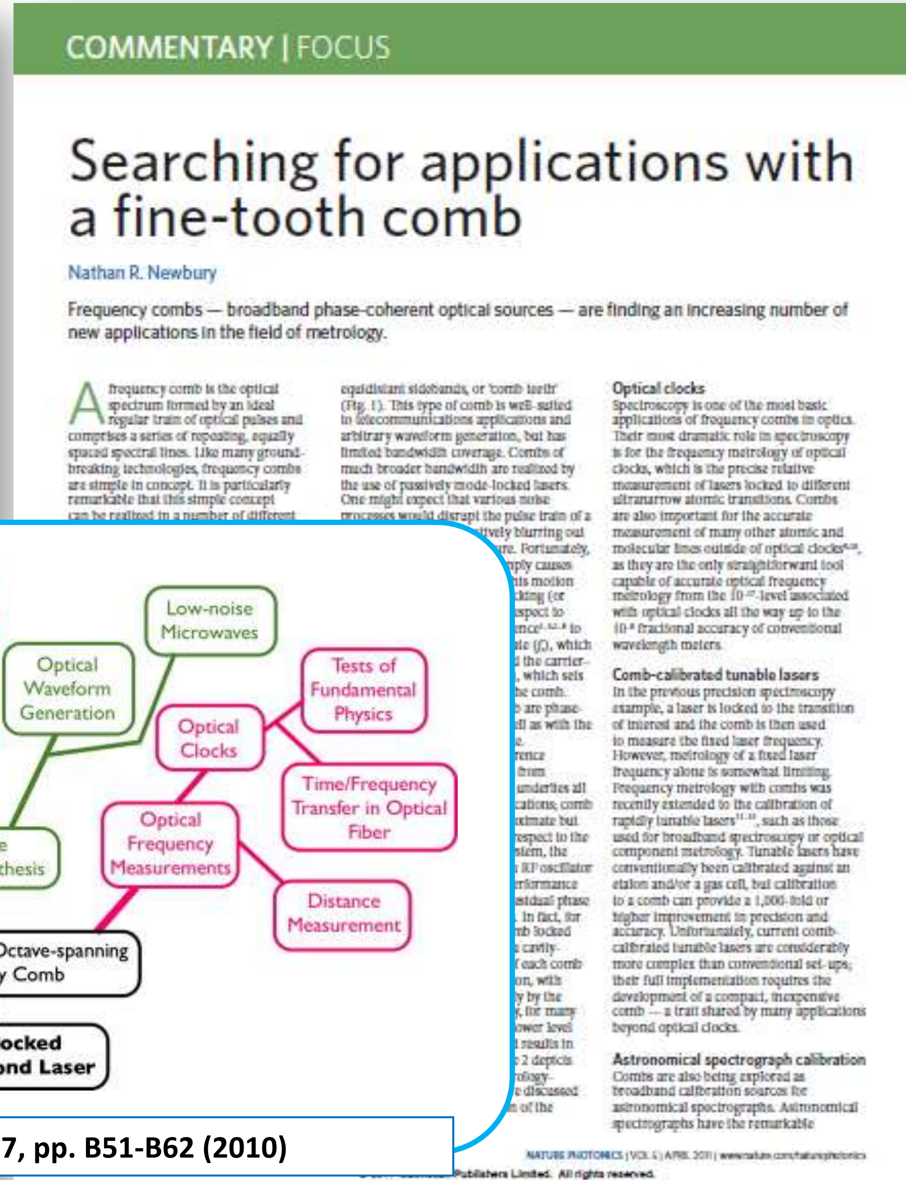
The ability to measure distances with high precision is of fundamental importance. Femtosecond optical frequency combs offer an intriguing solution to the problem and could prove invaluable in space satellite missions of the future.

Seung-Woo Kim

Length is a basic physical quantity and its precise measurement is of fundamental significance in science and technology. The ability to determine the absolute distance to an object — ranging — is important for applications such as large-scale manufacturing and future space satellite missions involving tight formation-flying, where fast, accurate measurements of distance are critical for maintaining the relative pointing and position of individual satellites. Reporting on page 351 of this issue[1], researchers at the National Institute of Standards and Technology in the United States describe a laser ranging system that offers a unique combination of length precision, recording speed and large measurement range.

Distance measurement has come on in leaps and bounds since Albert A. Michelson first proposed using the wavelength of light as a ruler in 1887. Today, optical interferometers are commonly used to measure distances with an accuracy better than an optical wavelength; indeed, in extreme cases, such as gravitational wave detection, which calls for ultra-sensitivity, the accuracy can be many orders of magnitude below the wavelength. Figure 1 summarizes key milestones in the development of optical interferometers. In 1983, the SI definition of a metre was redefined as the distance travelled by light in vacuum during 1/299,792,458th of a second, with the consequence that the wavelength of any optical radiation used in length metrology can be most precisely determined by calibrating its frequency with respect to the time standard. The current SI definition of time states that the second is 9,192,631,770 periods of the radiation emitted from the transition between the two hyperfine levels of the ground state of a caesium-133 atom. But because optical frequencies are several hundreds of terahertz, their calibration with reference to the microwave-frequency caesium clock has presented considerable challenges, until the recent advent of clockwork making use of the frequency comb of a mode-locked femtosecond laser.

S.-W. Kim, Nature Photonics, 3, pp. 313-314 (2009)



COMMENTARY | FOCUS

Searching for applications with a fine-tooth comb

Nathan R. Newbury

Frequency combs — broadband phase-coherent optical sources — are finding an increasing number of new applications in the field of metrology.

Optical clocks

Spectroscopy is one of the most basic applications of frequency combs in optics. Their most dramatic role in spectroscopy is for the frequency metrology of optical clocks, which is the precise relative measurement of lasers locked to different ultranarrow atomic transitions. Combs are also important for the accurate measurement of many other atomic and molecular lines outside of optical clocks, as they are the only straightforward tool capable of accurate optical frequency metrology from the 10^{-17}-level associated with optical clocks all the way up to the 10^{-8} fractional accuracy of conventional wavelength meters.

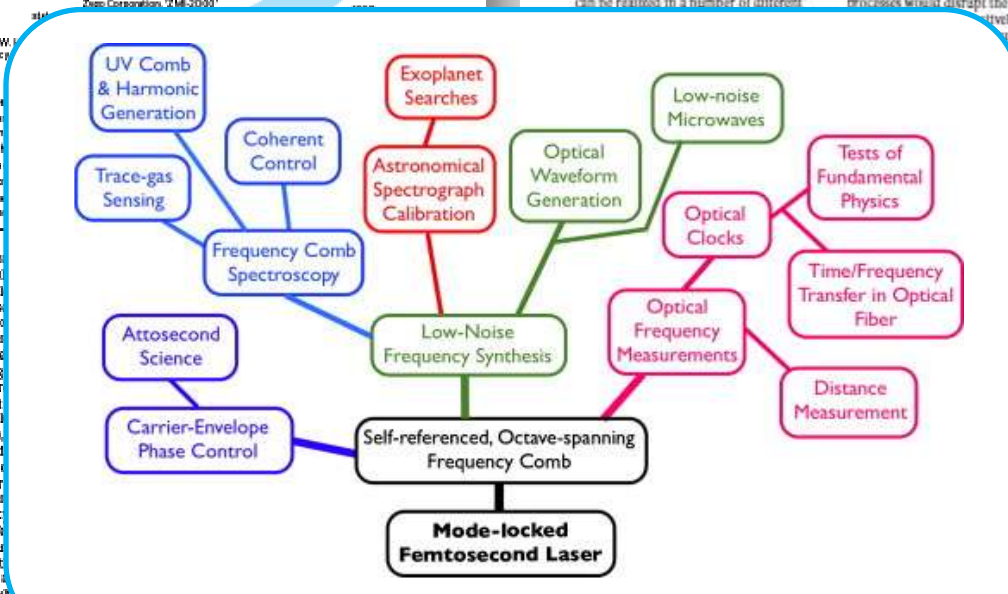
Comb-calibrated tunable lasers

In the previous precision spectroscopy example, a laser is locked to the transition of interest and the comb is then used to measure the fixed laser frequency. However, metrology of a fixed laser frequency alone is somewhat limiting. Frequency metrology with combs was recently extended to the calibration of rapidly tunable lasers, such as those used for broadband spectroscopy or optical component metrology. Tunable lasers have conventionally been calibrated against an etalon and/or a gas cell, but calibration to a comb can provide a 1,000-fold or higher improvement in precision and accuracy. Unfortunately, current comb-calibrated tunable lasers are considerably more complex than conventional set-ups; their full implementation requires the development of a compact, inexpensive comb — a trait shared by many applications beyond optical clocks.

Astronomical spectrograph calibration

Combs are also being explored as broadband calibration sources for astronomical spectrographs. Astronomical spectrographs have the remarkable

N. R. Newbury, Nature Photonics, 5, pp. 186-188 (2011)



S. Diddams, JOSA B, 27, pp. B51-B62 (2010)

Ultrafast Femtosecond Laser: Critical Advantages

Ultra-short Pulse Duration

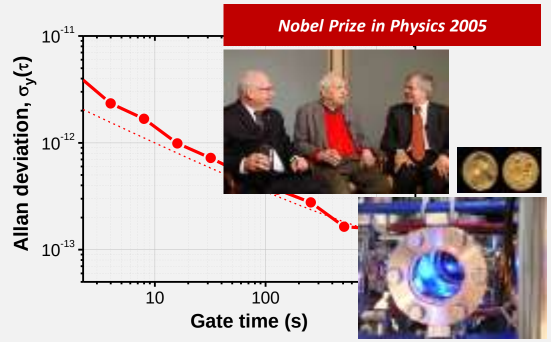
- Short pulse duration: several fs
  (1 fs=1/1,000,000,000,000,000 s)
  (1 fs=1/10^{-15})

→ Advantageous to
the precise timing and distance measurement in SPACE

- High peak power: upto several GW
  (1 GW=1,000,000,000)
  Stronger than light bulbs

→ Capable of initiating
Nonlinear optical phenomena with high efficiency in SPACE

High Frequency Stability



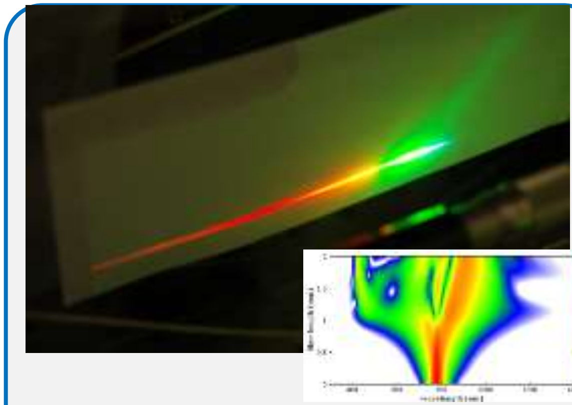
- Extreme frequency stability:
  upto 10^{-17}~10^{-18}

→ Advantageous to
precision time/frequency measurement and dissemination in SPACE

- Direct Linkage between the radio-wave and the optical light wave

→ Enhancing the performance of the base clock of the satellite
for GPS system in SPACE

Broad Spectral Range



- Broad spectral coverage:
  from Ultraviolet to Infra-Red

→ Advantageous to
broadband spectroscopy and DWDM communication in SPACE

- Conserving the original frequency comb structure

→ Dramatically enhancing the
calibration capability of SPACE spectrometers

Ultrafast femtosecond laser will be a key device enabling next generation metrological space missions

Ultrafast Optics for Ultra Precision
Fiber-based Ultrafast Femtosecond Laser
Precision Frequency Metrology
Absolute Distance Metrology
Ultrafast Plasmonics
Ultrafast Optics for Ultra Precision in SPACE
Space Qualified Ultrafast Femtosecond Fiber Laser
Absolute Distance Metrology
Ultra-high Density Space Optical Communication
Precision Spectroscopy in Space (LIDAR)
Atomic Clock in Space for Testing General Relativity
Precise Calibration of Space Spectrometers
Precision Time-Transfer for Testing General Relativity

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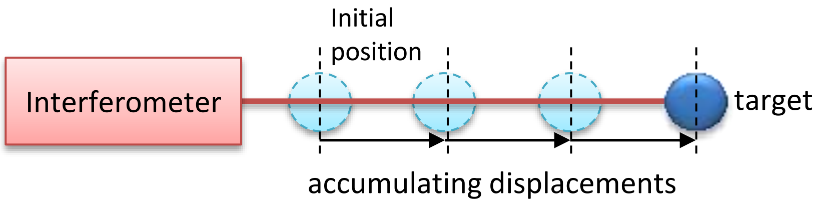
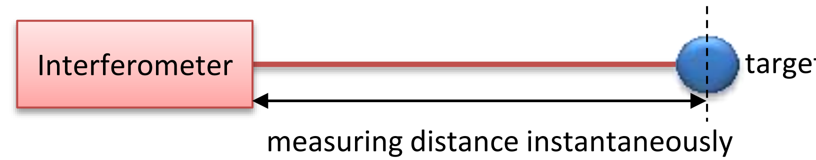
Absolute Distance Measurement (ADM)

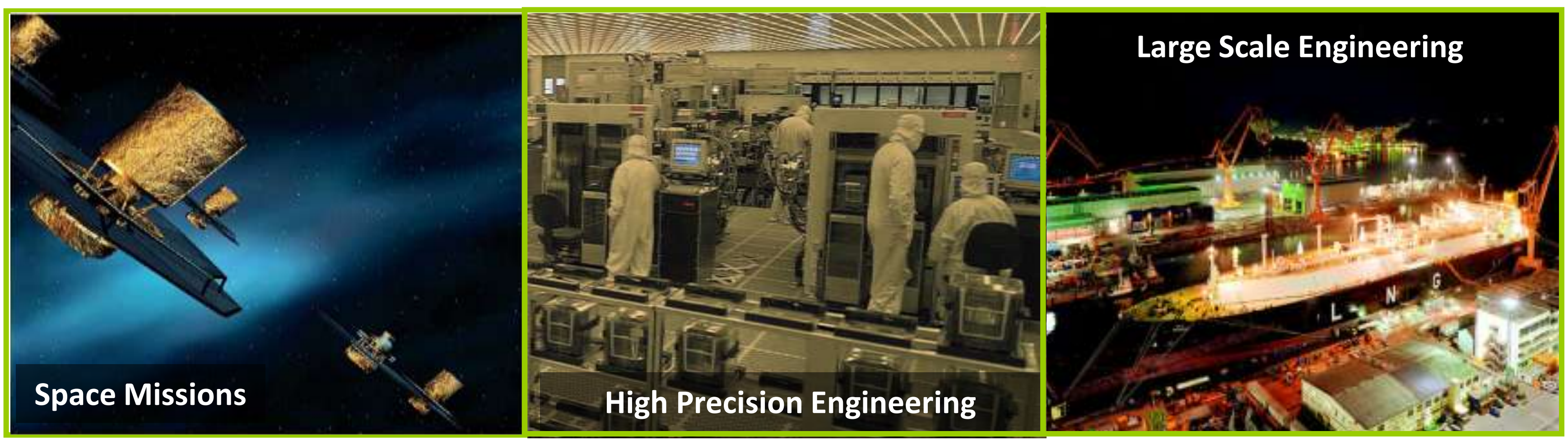
❖ *Conventional Laser Interferometer*



❖ *Absolute Distance Measurement*

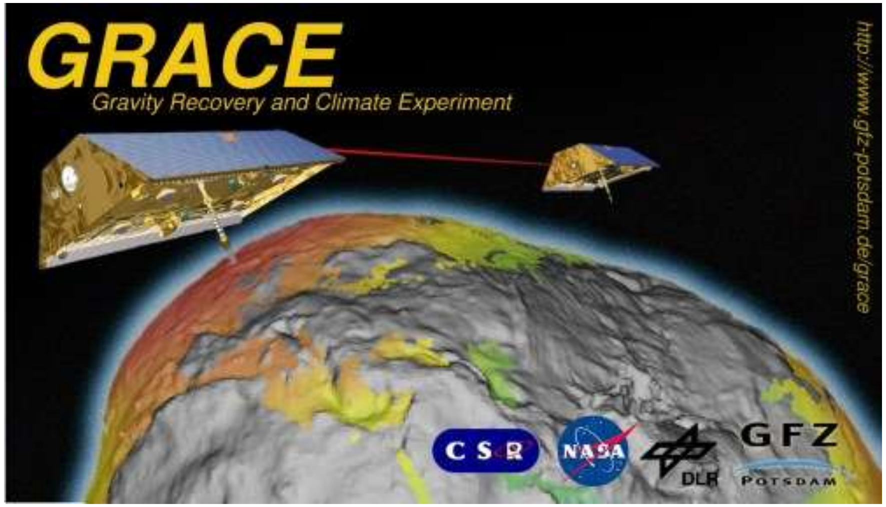


- ADM determines the distance between two objects instantaneously with a single operation without accumulation of incremented/decremented displacements.
- ADM does suffer no measurement error accumulation caused by the environmental parameters.
- ADM determines the distance between targets not feasible to move continuously.



S.-W. Kim, J. Jin, Y.-J. Kim, HAALDM Workshop 2007, by Menlo Systems GmbH and European Space Agency (ESA)

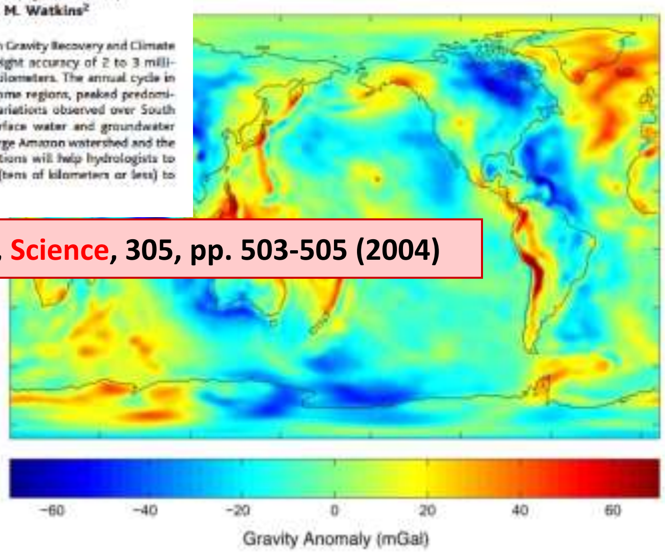
Formation Flying Space Missions: GRACE (RDM)



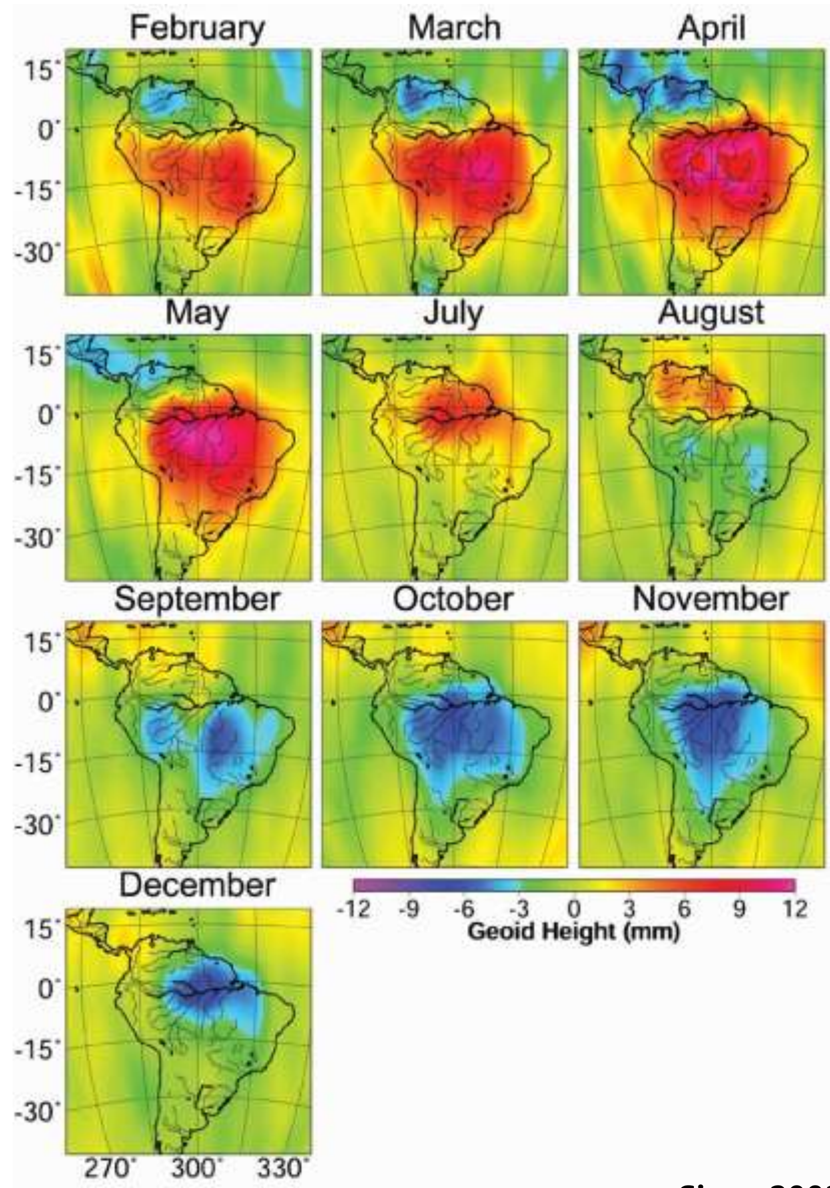
GRACE Measurements of Mass Variability in the Earth System

Byron D. Tapley,[1] Srinivas Bettadpur,[1] John C. Ries,[1*] Paul F. Thompson,[1] Michael M. Watkins[2]

Monthly gravity field estimates made by the twin Gravity Recovery and Climate Experiment (GRACE) satellites have a geoid height accuracy of 2 to 3 millimeters at a spatial resolution as small as 400 kilometers. The annual cycle in the geoid variations, up to 10 millimeters in some regions, peaked predominantly in the spring and fall seasons. Geoid variations observed over South America that can be largely attributed to surface water and groundwater changes show a clear separation between the large Amazon watershed and the smaller watersheds to the north. Such observations will help hydrologists to connect processes at traditional length scales (tens of kilometers or less) to those at regional and global scales.



B. D. Tapley et al., Science, 305, pp. 503-505 (2004)

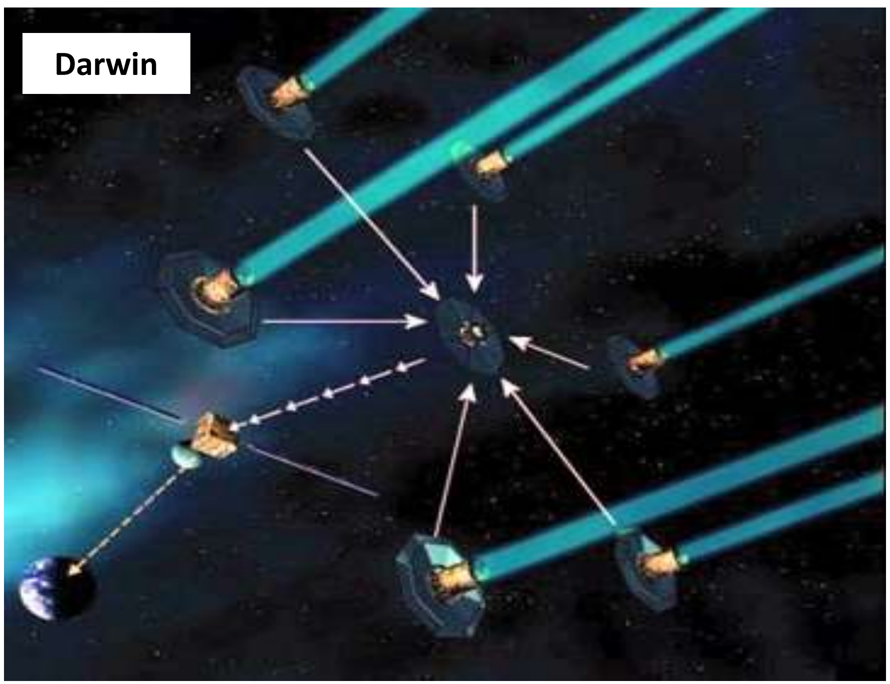


Since 2002

ADM for Formation Flying in SPACE

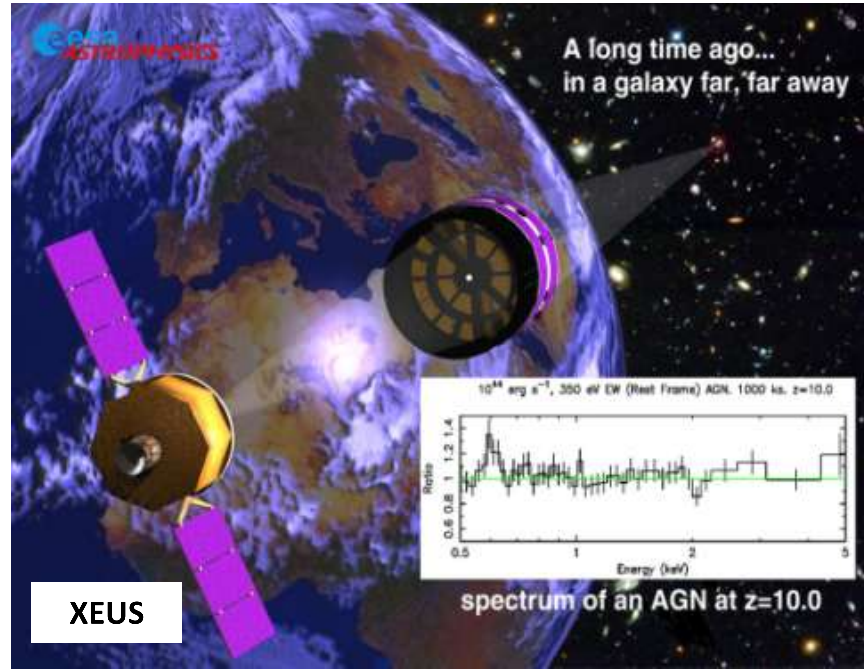
Precision Absolute Distance Metrology for Satellite Formation Flying

Roadmap by ESA/NASA



Extra-solar Planet Finder

- Configuring of synthetic aperture
- Searching for and investigation of earth-like planets



The X-ray Evolving Universe Spectroscopy

- X-ray observatory with two space crafts
- Investigation of clusters of galaxies, massive black holes, stellar matter

Mission Requirements

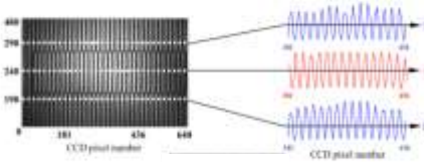
Item		XEUS	DARWIN
Number of satellites		2	8
Distance between satellites		35 m	250 m
Metrology requirement	Lateral	< 1000 ㎛	< ±32 ㎛
	Longitudinal	< 300 ㎛	< ±32 ㎛
	Angular	< 60 arcsec	< ±10 arcsec

Absolute Distance Measurement (ADM)

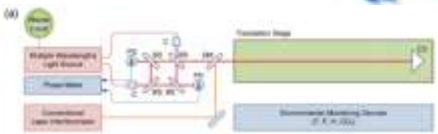
Absolute Distance Measurement using Femtosecond Laser Pulses

- **Synthetic Wavelength Interferometry**
  - K. Minoshima, H. Matsumoto, App. Opt. 39, 5512 (2000)
  - N. R. Doloca, K. Meiners-Hagen, M. Wedde, F. Pollinger, and A. Abou-Zeid, Measurement Science and Technology 21, 115302 (2010).

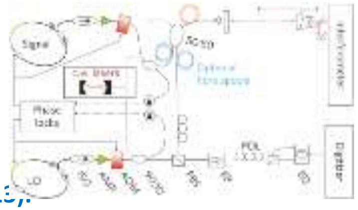
- **Multi-Wavelength Interferometry**
  - J. Jin, Y.-J. Kim, Y. Kim, S.-W. Kim, and C.-S. Kang, Optics Express 14, 5968 (2006).
  - N. Schuhler, Y. Salvade, S. Leveque, R. Dandliker, R. Holzwarth, Opt. Lett., 31, 3101-3103 (2006).
  - J. Jin, Y.-J. Kim, Y. Kim and S.-W. Kim, Int. J. Prec. Eng. Manuf., 8, 22-26 (2007).
  - Y. Salvade, N. Schuhler, S. Leveque, S. Le. Floch, App. Opt., 47, 2715-2720 (2008).
  - S. Hyun, Y.-J. Kim, Y. Kim, J. Jin, and S.-W. Kim, Meas. Sci. Technol., 095302 (2009).
  - S. Hyun, Y.-J. Kim, Y. Kim, and S.-W. Kim, CIRP Annals - Manufacturing Technology 59, 555–558 (2010).



- **Dispersive Interferometry**
  - K.N. Joo and S.-W. Kim, Opt. Express, 14, pp. 5954-5960 (2006).
  - K.N. Joo and S.-W. Kim, Opt. Lett., 32, pp. 647-649 (2007).
  - K.N. Joo, Y. Kim and S.-W. Kim, Opt. Express, 16, pp.19799-19806 (2008).
  - M. Cui, M. G. Zeitouny, N. Bhattacharya, S. A van den Berg, and H. P. Urbach, Optics Express 19, 6549 (2011).
  - P. Jian, O. Pinel. C. Fabre, B. Lamine and N. Treps, Opt. Express 20, 27133-27146 (2012).
  - O. Pinel, P. Jian, R. M. de Araujo, J. Feng, B. Chalopin, C. Fabre, and N. Treps, Phy. Rev. Lett., 108, 083601 (2012).
  - S.A. van den Berg, S.T. Persijn, G.J.P. Kok, M.G. Zeitouny, and N. Bhattacharya Phys. Rev. Lett. 108, 183901 (2012).

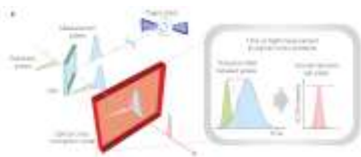


- **Dual-comb Interferometry**
  - I. Coddington, W.C. Swann, L. Nenadovic and N.R. Newbury, Nature Photonics, 3, 351–356 (2009).
  - S. Yokoyama, T. Yokoyama, Y. Hagihara, T. Araki, and T. Yasui, Opt. Express, 17, 9300–9313 (2009).
  - M. Godbout, J. D. Deschênes, and J. Genest, Opt. Express, 18, pp.15981-15989 (2010).
  - T. A. Liu, N. R. Newbury and I. Coddington, Opt. Express, 9, pp. 18501–18509 (2011).
  - J. Lee, S. Han, K. Lee, E. Bae, S. Kim, S. Lee, S.-W. Kim and Y.-J. Kim, Meas. Sci. Technol., 24, 045201 (2013).



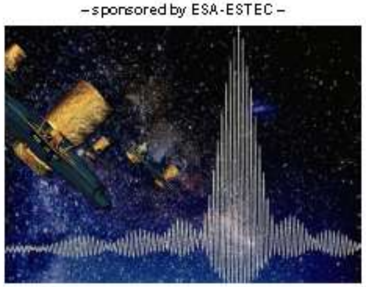
- **Interferometric cross-correlation**
  - J. Ye, Opt. Lett, 29, 1153 (2004).
  - M. Cui, M.G. Zeitouny, N. Bhattacharya, S.A. van den Berg, H.P. Urbach, and J.J.M. Bratt, Opt. Lett., 34, 1982 (2009).
  - P. Balling, P. Kren, P. Masika, S.A. van den Berg., Opt. Express, 25, 9300 (2009).

- **Time-of-flight measurement using balanced optical cross-correlation**
  - J. Lee, Y.-J. Kim, K. Lee, S. Lee, and S.-W. Kim, Nature Photonics 4, 716–720 (2010).
  - J. Lee. G. Lee, S. Lee, S.-W. Kim, and Y.-J. Kim, Meas. Sci. Technol, 23, 065203 (2012).



HAALDM Project (High Accuracy Absolute Long-Distance Measurement) by ESA (European Space Agency) since 2007

DOC.NO.	:	HALLDM-Final Report
VOL	:	1
ISSUE	:	1
DATE	:	December 10,2008
PAGE	:	1 of 182
DRL.NO.	:	APPE-RAP-2008-03629



Technology overview workshop

on

High Accuracy

Absolute Long-Distance Measurement

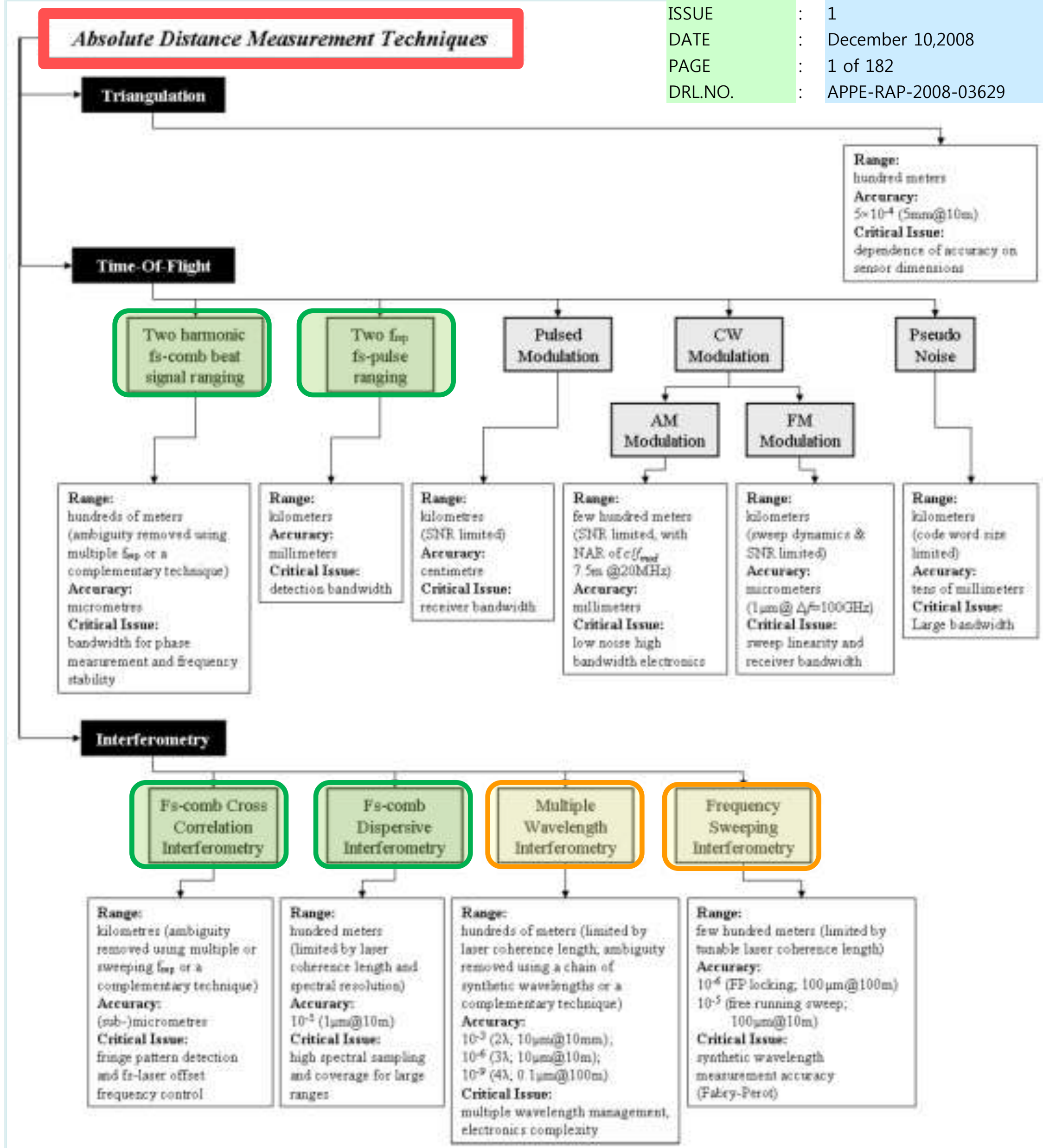
HAALDM 2007

Munich, 26. – 27. February 2007

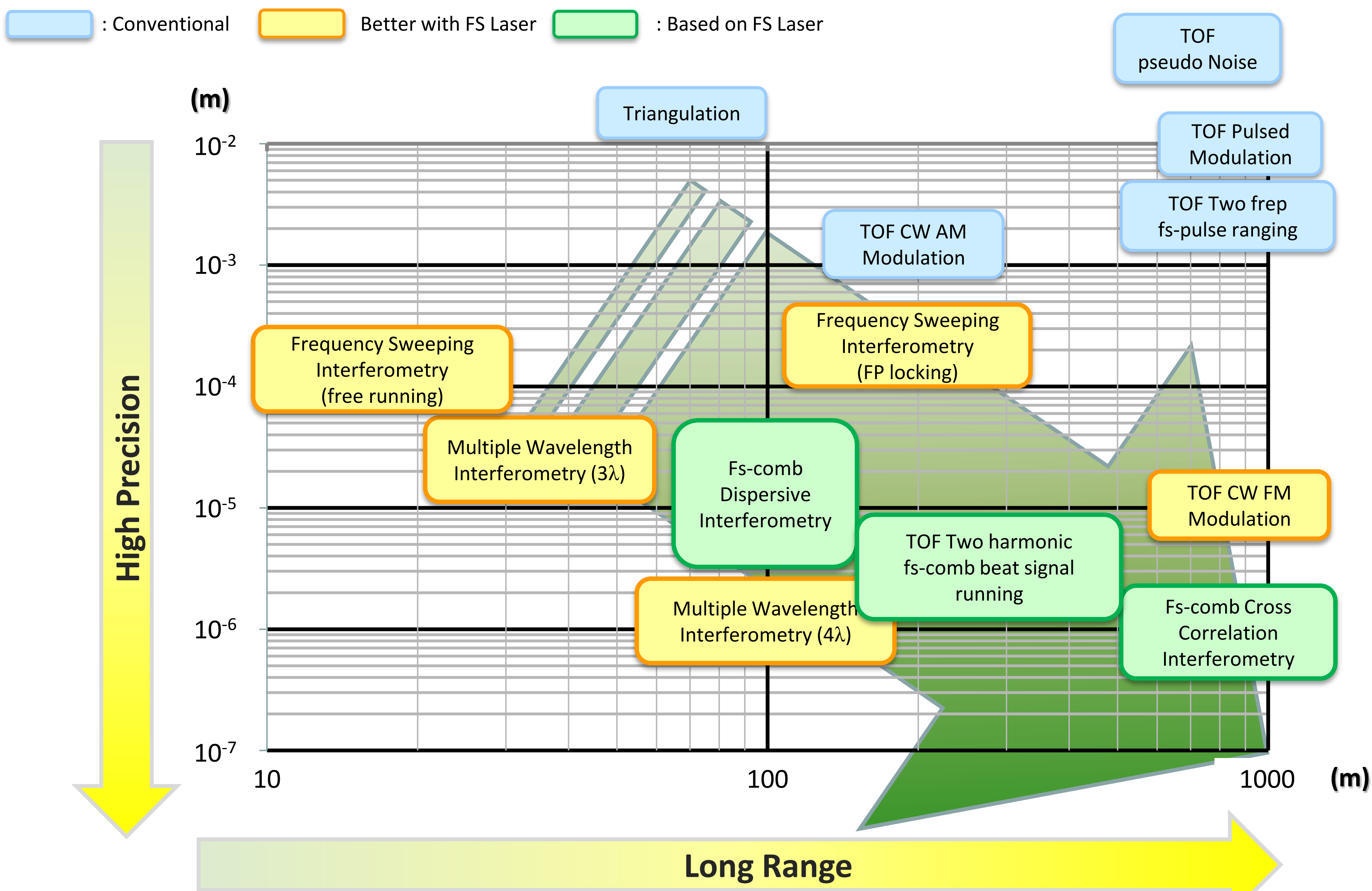
– sponsored by ESA-ESTEC –

Contact: Dr. Andreas Sizmann / Dr. Ronald Holzwarth
Menlo Systems GmbH (MS)
Am Klopferspitz 19,
D-82152 Martinsried, Germany
Tel +49 89 189 166 – 0
Fax +49 89 189 166 – 11
a.sizmann@menlosystems.com
r.holzwarth@menlosystems.com
www.menlosystems.com

This workshop is part of the ESA study 20184/06/NL/HE on Absolute Long Distance Measurement with (sub-)micrometer Accuracy for Formation Flight Applications



Absolute Distance Measurements



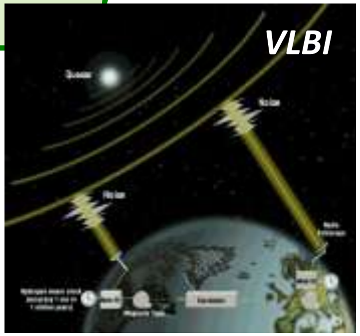
* BUPE: Billionth Uncertainty Precision Engineering

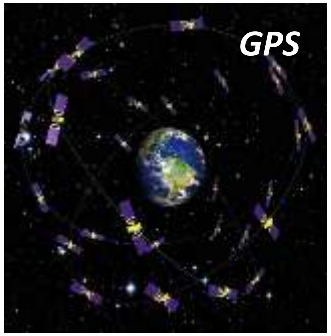
Definition of the 'Meter': Time-of-flight

The meter was redefined in 1983 in 17th CGPM.

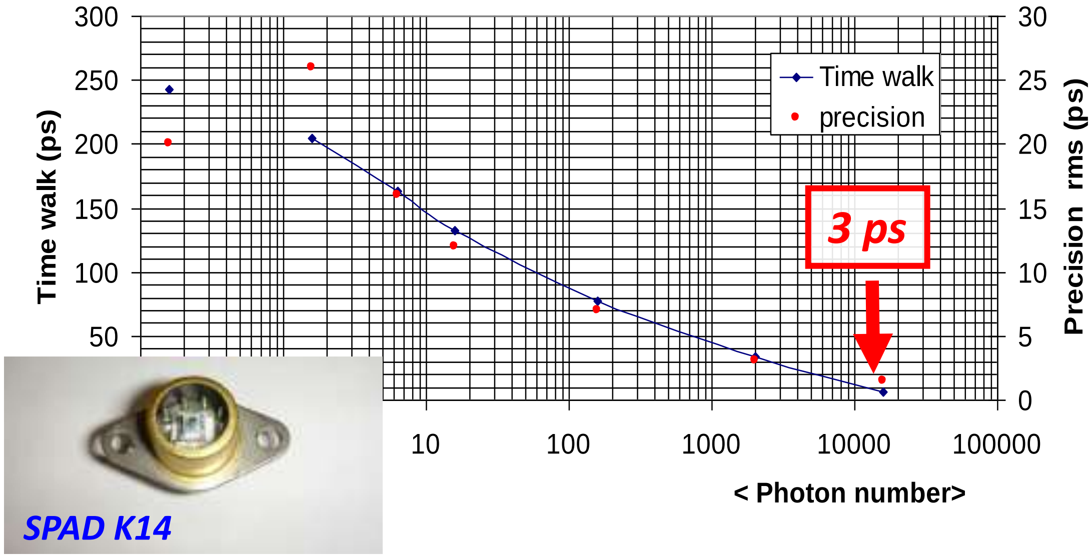
*"**the meter** is the length of the path traveled by light in vacuum during a **time interval** of 1/299,792,458 of a second."*

- *The speed of light is c=299,792,458 m/s (constant in vacuum).*





E. Samain et al, CERGA, Grasse, 2002



Technique	Précision sur les positions	Précision sur les vitesses
VLBI	2 mm	1 mm/an
LLR	50 mm	5 mm/an
SLR	2 mm	1 mm/an
GPS	2 mm	1 mm/an
DORIS	25 mm	4 mm/an

- Time walk compensated using the analog signal monitor
- Precision: 15 / 3 ps over the dynamic range 10 - 10ooo Ph.
- Time stability better than 1 ps over 1000 s
- Insensitive to the laser pulse width (20 - 200 ps)

Resolution/Precision : 3 ps, 1 mm !!

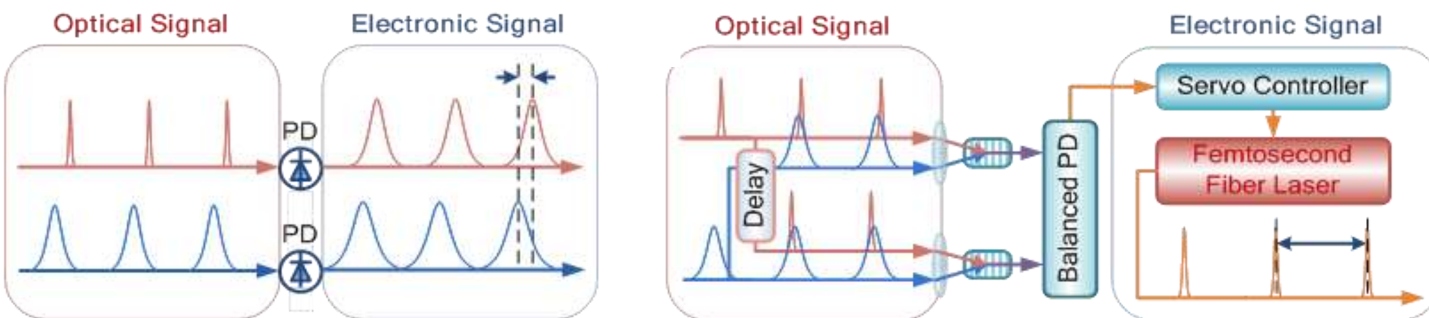
However, the precision was limited to the level of several millimeters

ADM using Time-of-flight (TOF) of Femtosecond Pulses

Scope

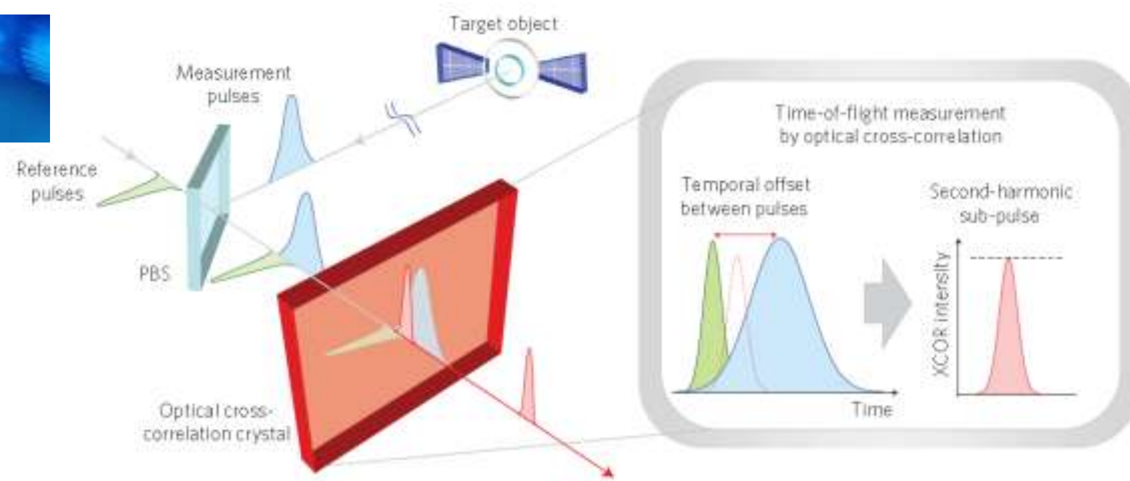
- High-resolution time-of-flight measurement using femtosecond pulses
- Applications for high precision ranging for next-generation space missions

Conventional TOF Measurement | **TOF Measurement using Balanced Optical Cross-Correlation**



mm Precision → ***nm Precision***

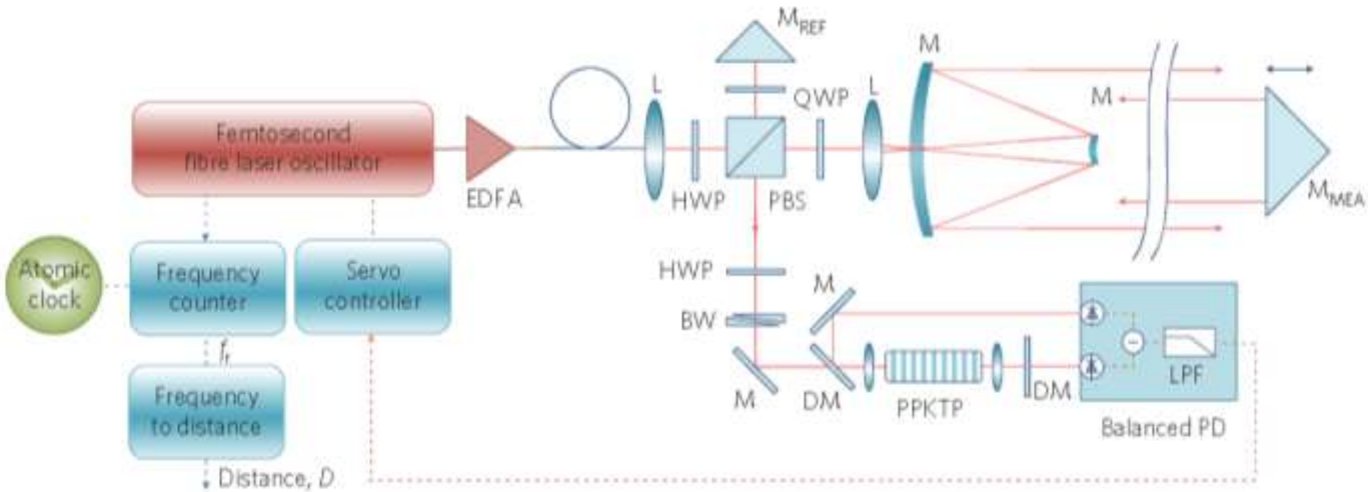
nature photonics



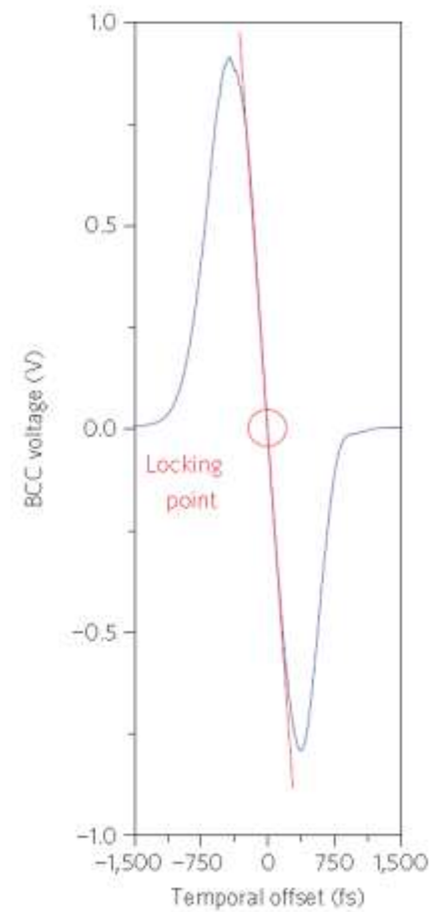
J. Lee, Y.-J. Kim, K. Lee, S. Lee, and S.-W. Kim, Nature Photonics 4, 716–720 (2010)
J. Lee. G. Lee, S. Lee, S.-W. Kim, and Y.-J. Kim, Meas. Sci. Technol, 23, 065203 (2012)

ADM using TOF of Femtosecond Pulses

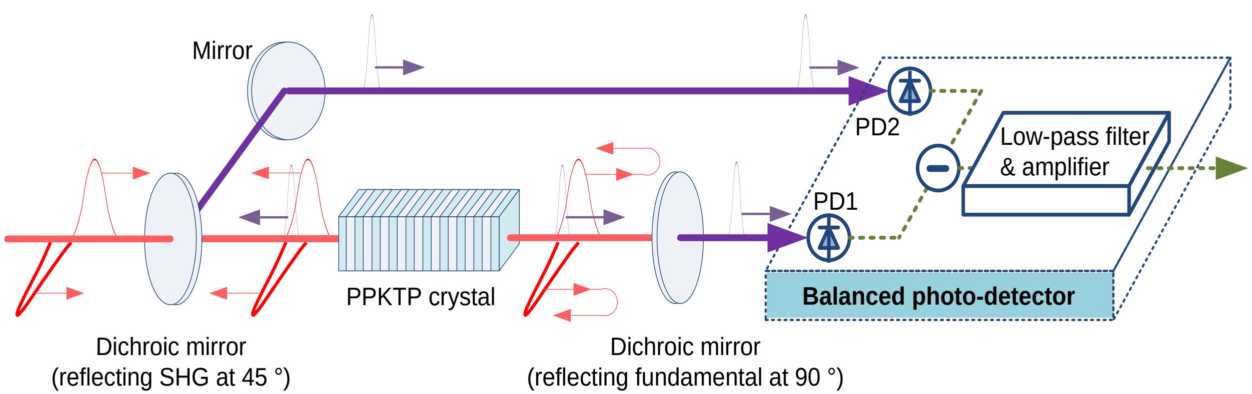
High Precision Absolute Ranging LIDAR: Optical Configuration



BXCOR Signal



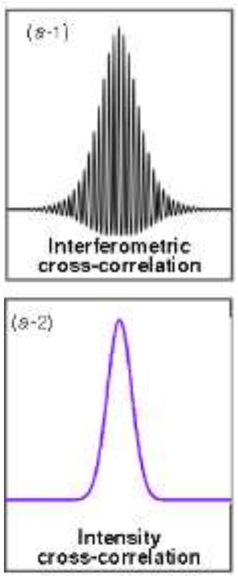
Balanced Optical Cross-correlation: Detailed Description

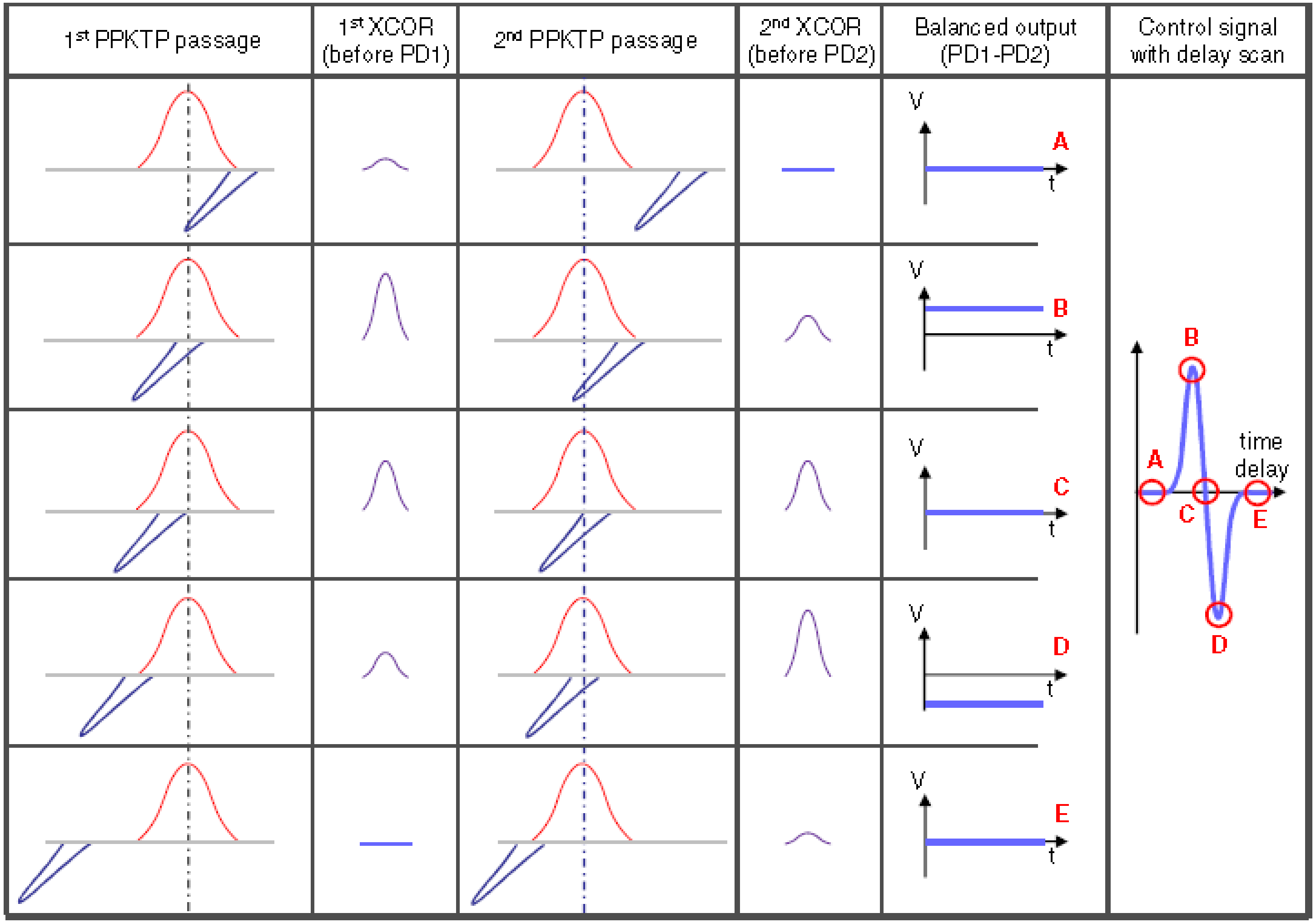


J. Lee, Y.-J. Kim, K. Lee, S. Lee, and S.-W. Kim, Nature Photonics 4, 716–720 (2010)

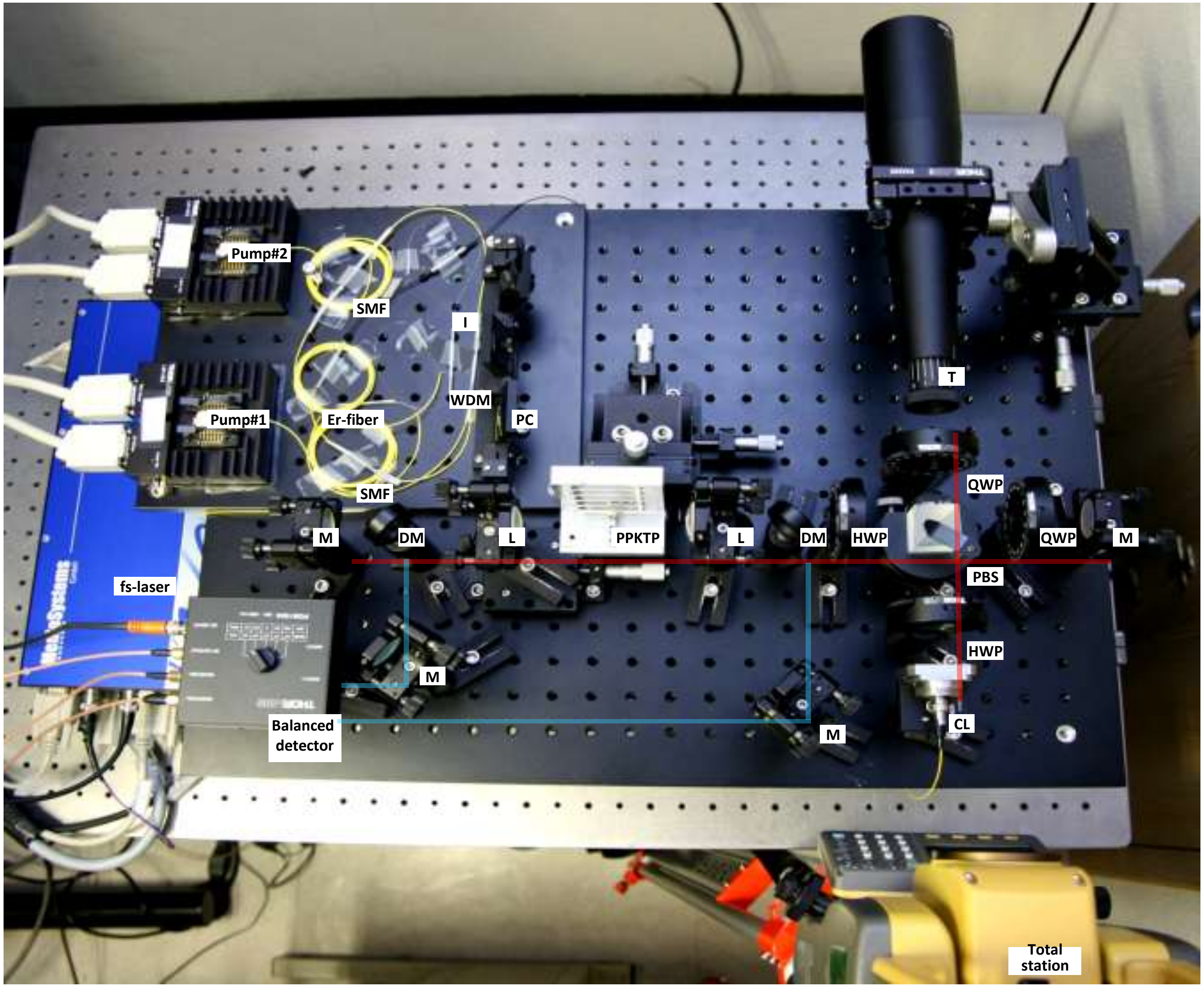
J. Lee. G. Lee, S. Lee, S.-W. Kim, and Y.-J. Kim, Meas. Sci. Technol, 23, 065203 (2012)

Balanced Optical Cross-correlation: BXCOR



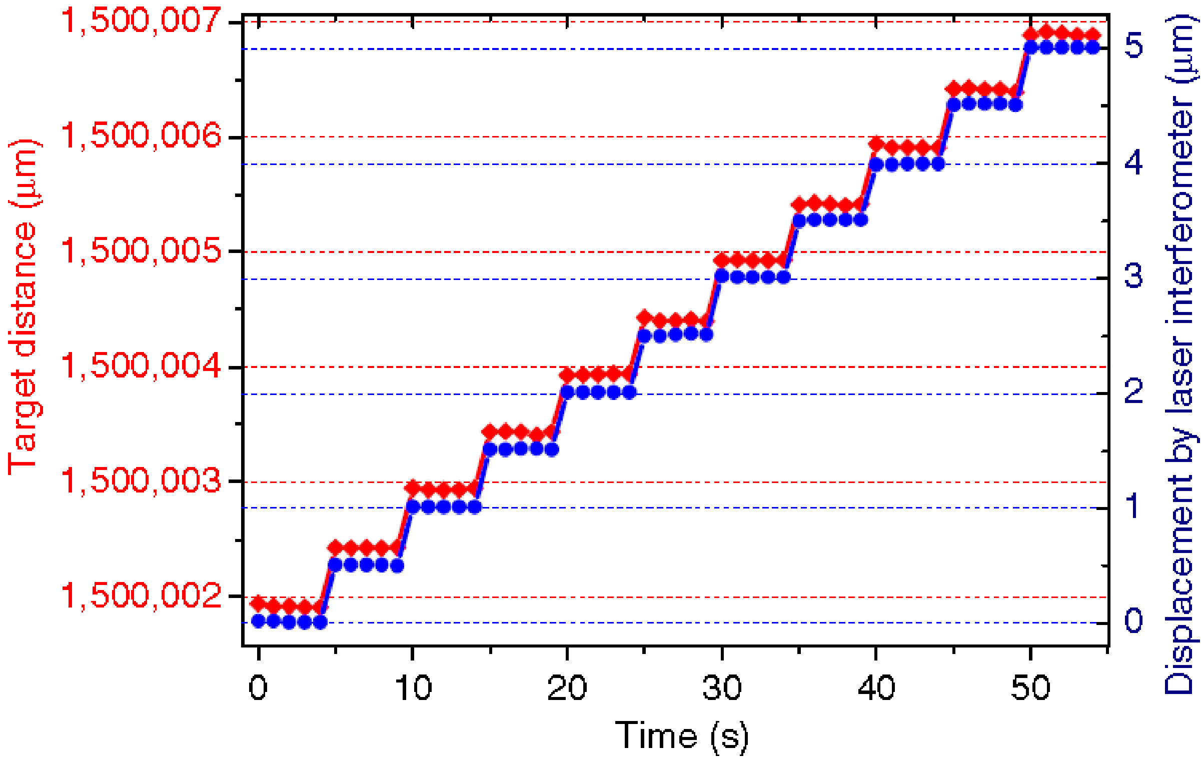


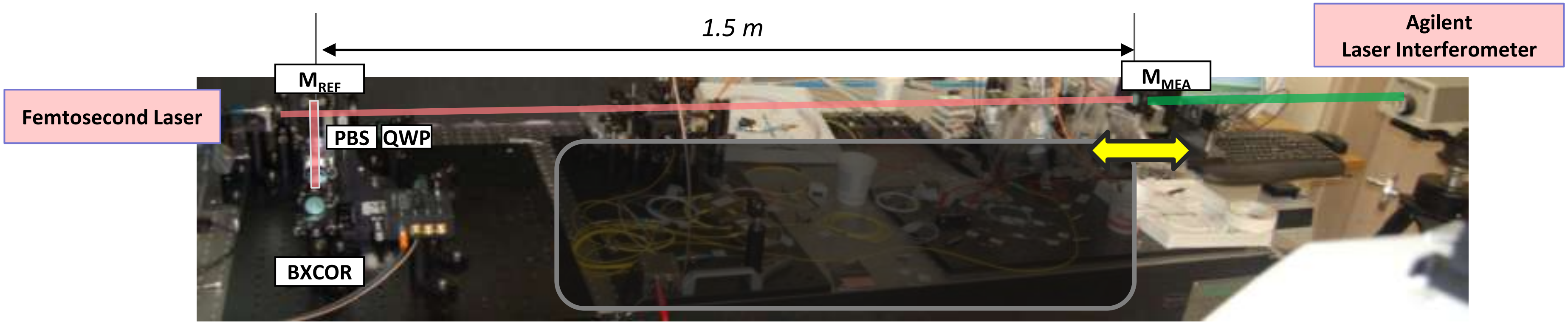
Experimental Configuration



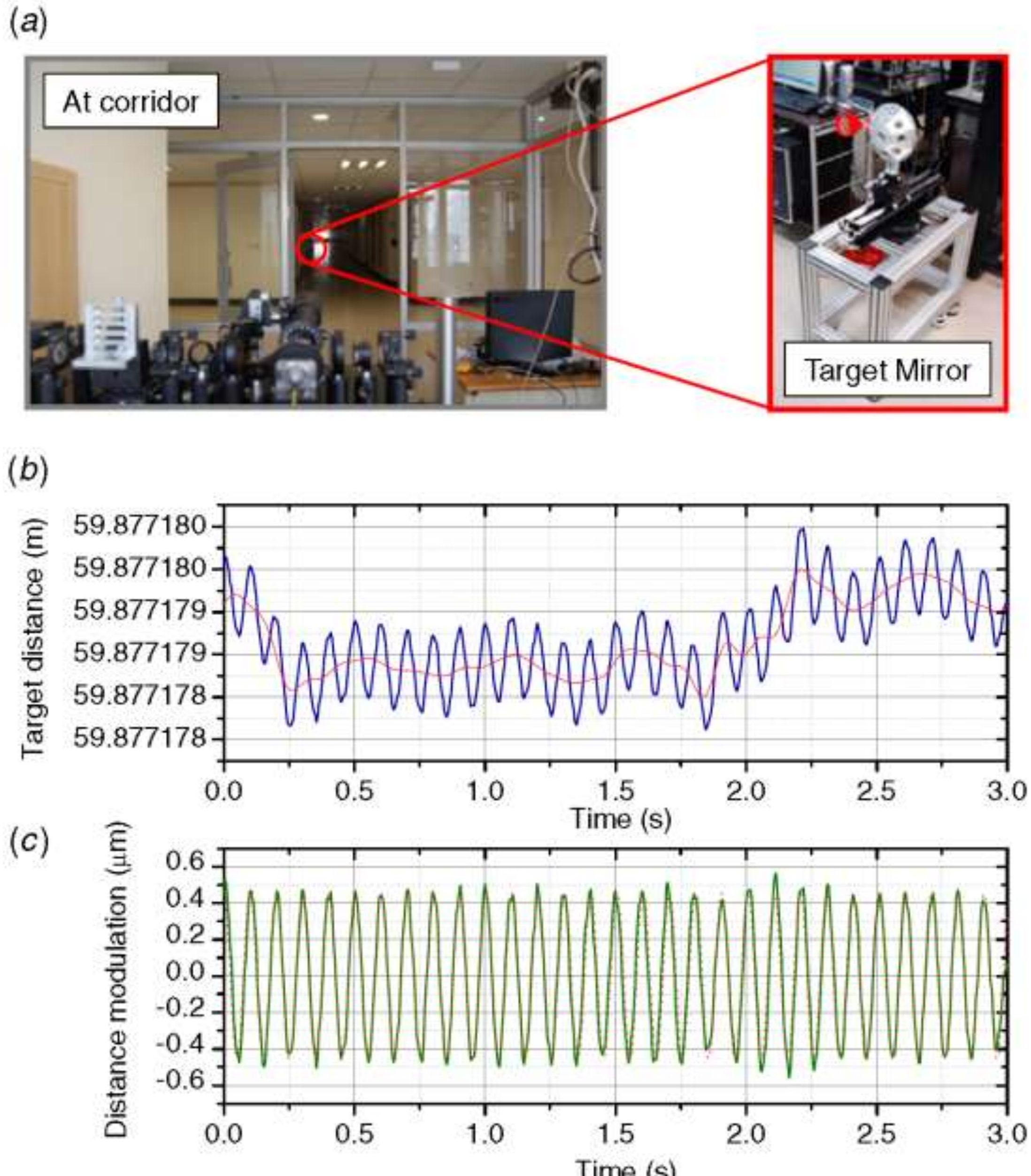
J. Lee, Y.-J. Kim, K. Lee, S. Lee, and S.-W. Kim, Nature Photonics 4, 716–720 (2010)
J. Lee. G. Lee, S. Lee, S.-W. Kim, and Y.-J. Kim, Meas. Sci. Technol, 23, 065203 (2012)

Comparison with a Laser interferometer at ~1.5 m

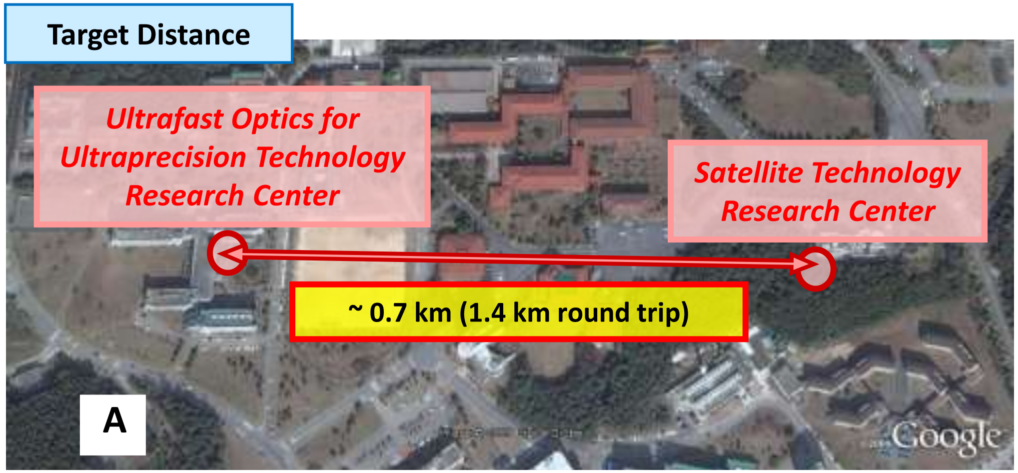


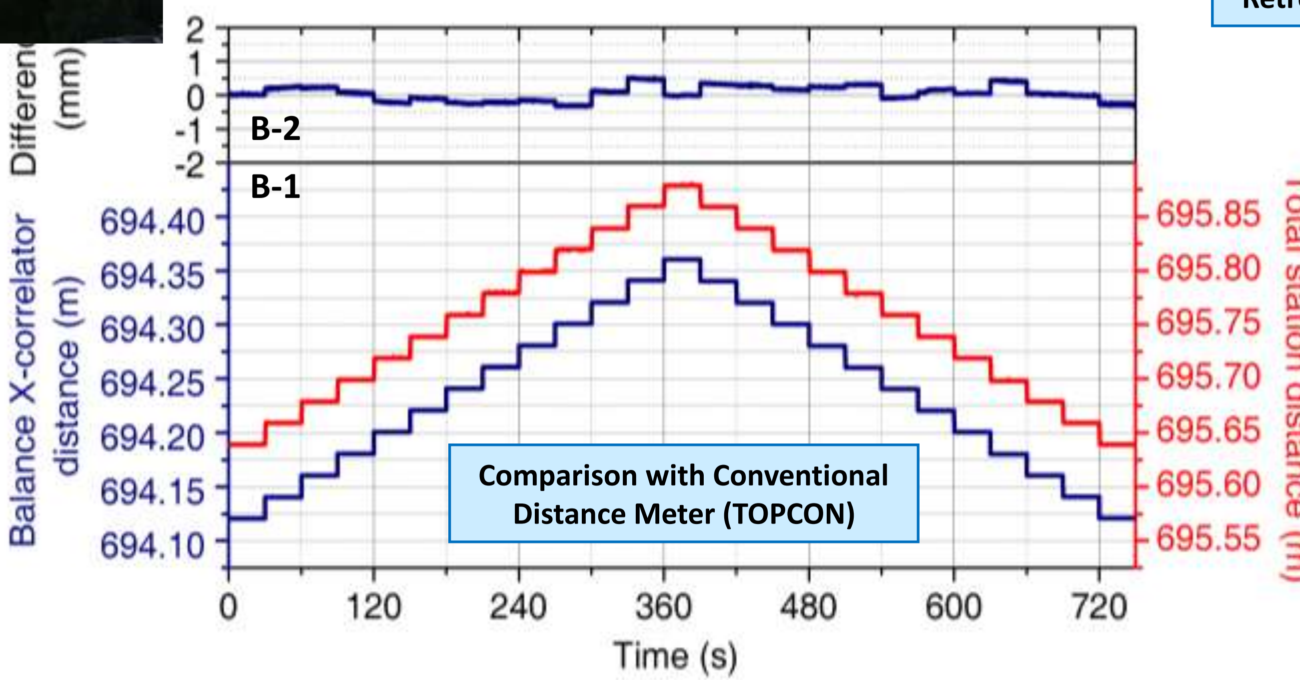


ADM using TOF of Femtosecond Pulses: at ~60 m

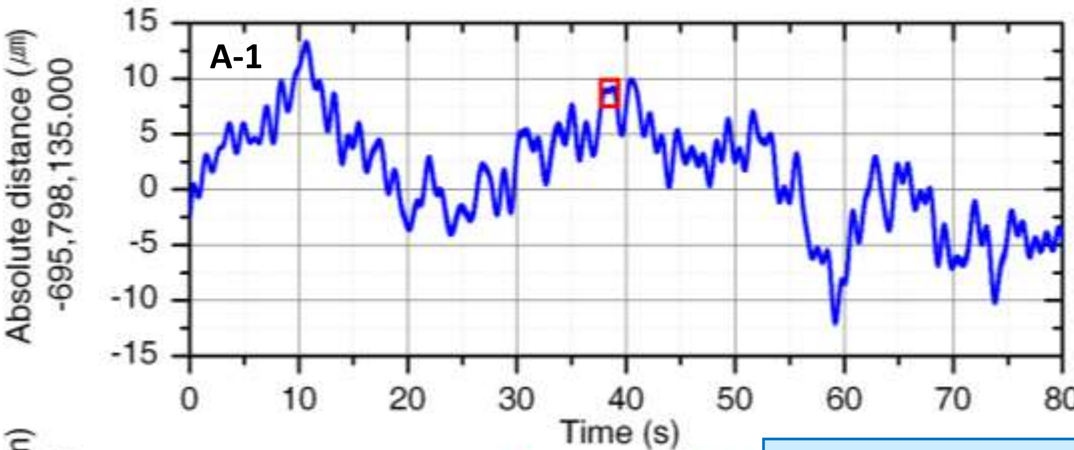


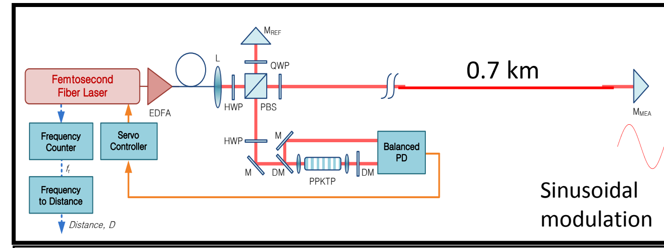
ADM using TOF of Femtosecond Pulses: at ~700 m



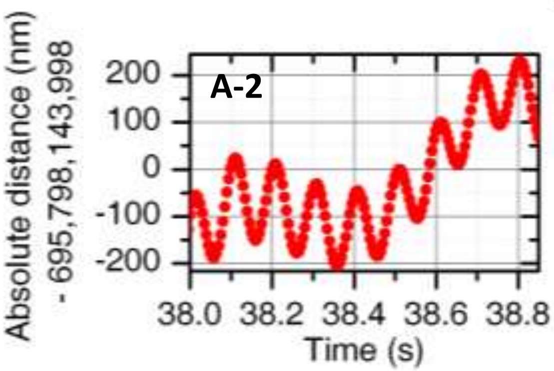


ADM using TOF of Femtosecond Pulses: at ~700 m

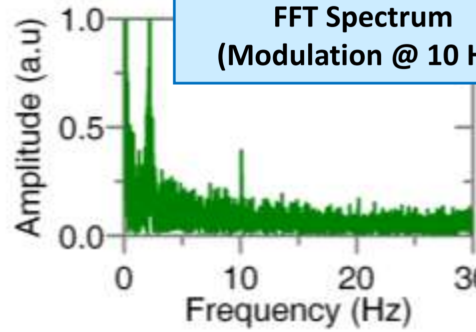




- *Measurement range : ~ 0.7 km*
- *150 nm, 10 Hz dithering on mirror array (using PZT)*

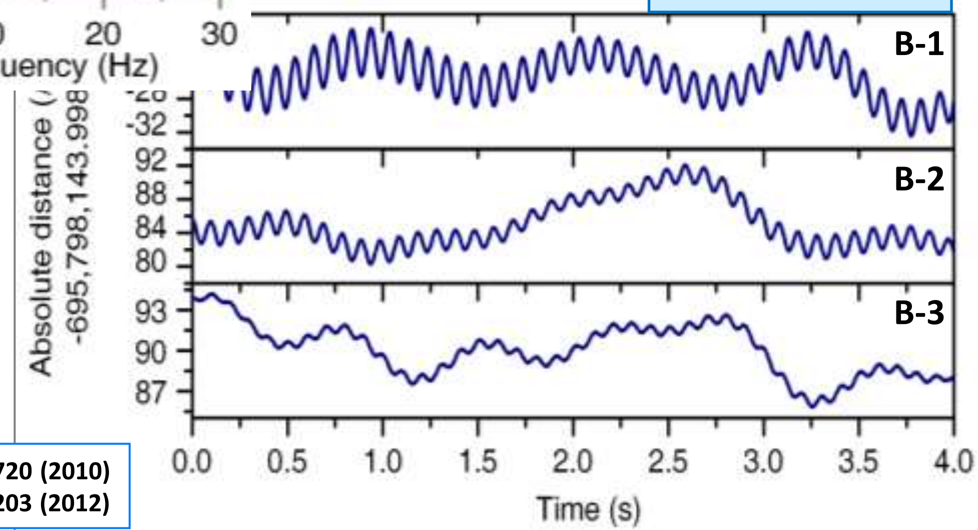


Modulation Depth: 130 nm



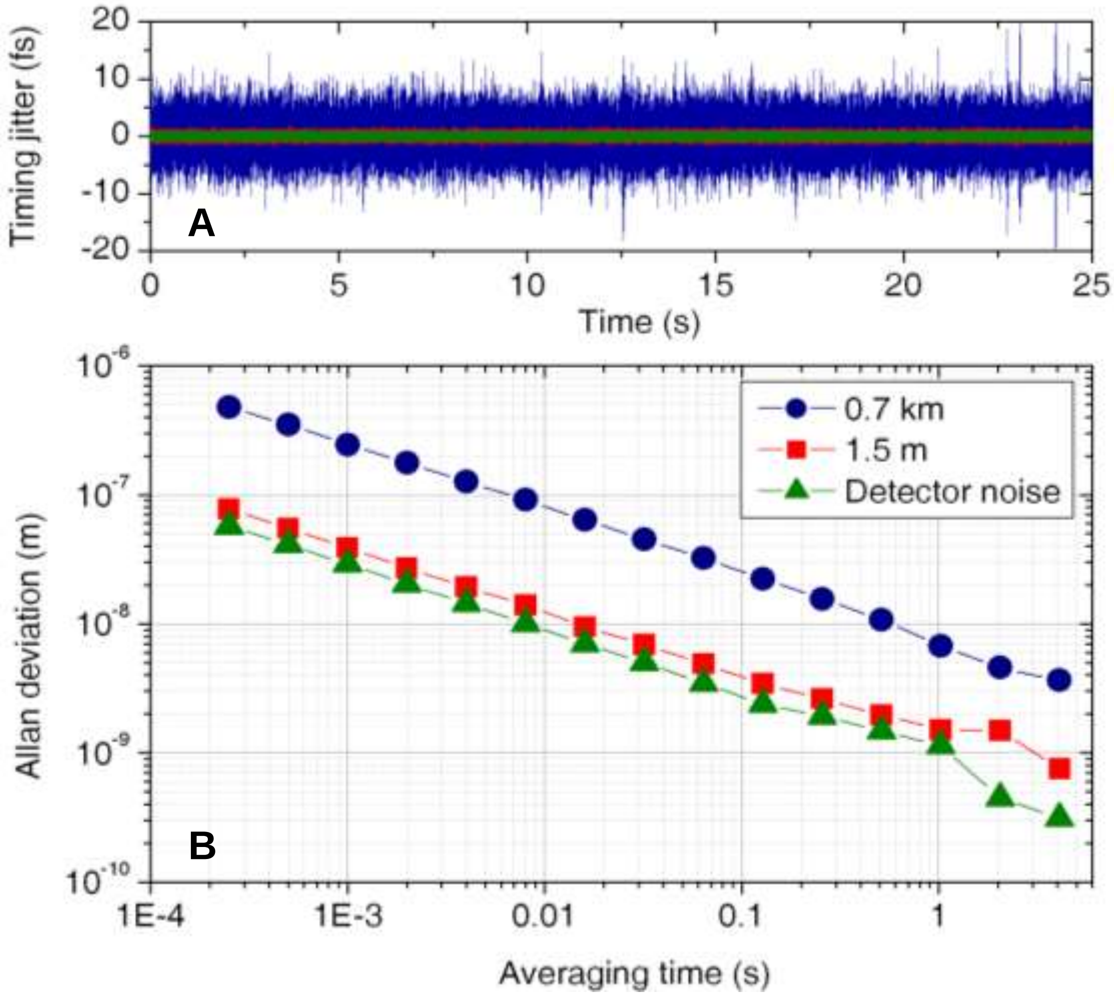
FFT Spectrum (Modulation @ 10 Hz)

Modulation Depth:
B-1) 5,000 nm
B-2) 2,000 nm
B-3) 700 nm



J. Lee, Y.-J. Kim, K. Lee, S. Lee, and S.-W. Kim, Nature Photonics 4, 716–720 (2010)
J. Lee. G. Lee, S. Lee, S.-W. Kim, and Y.-J. Kim, Meas. Sci. Technol, 23, 065203 (2012)

ADM using TOF of Femtosecond Pulses: Ultimate Precision



Measurement Precisions:

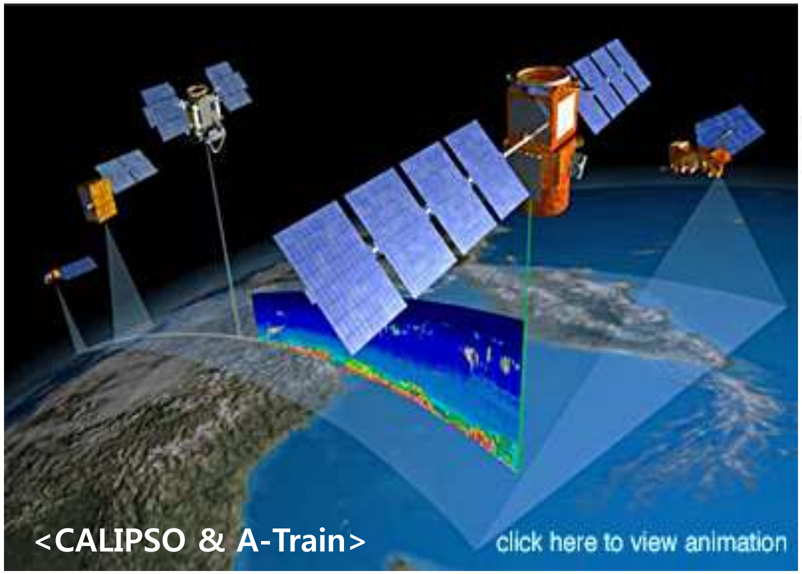
- *8.7 nm @ 10 ms*
- *2.7 nm @ 100 ms*
- *1.1 nm @ 1 s*

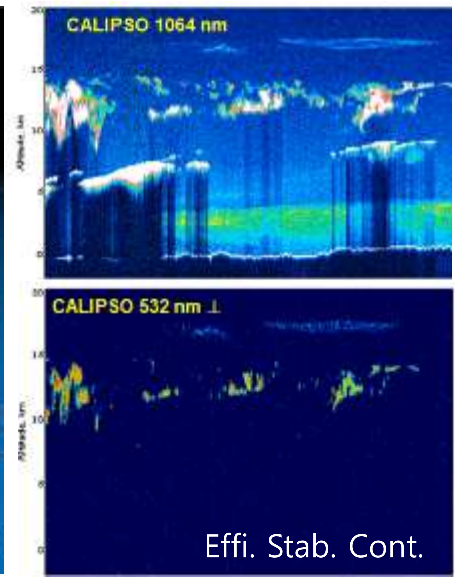
J. Lee, Y.-J. Kim, K. Lee, S. Lee, and S.-W. Kim, Nature Photonics 4, 716–720 (2010)
J. Lee. G. Lee, S. Lee, S.-W. Kim, and Y.-J. Kim, Meas. Sci. Technol, 23, 065203 (2012)

Contents

High-resolution Satellite LIDAR: Laser System

CALIOP (CALIPSO mission by NASA, 2006)

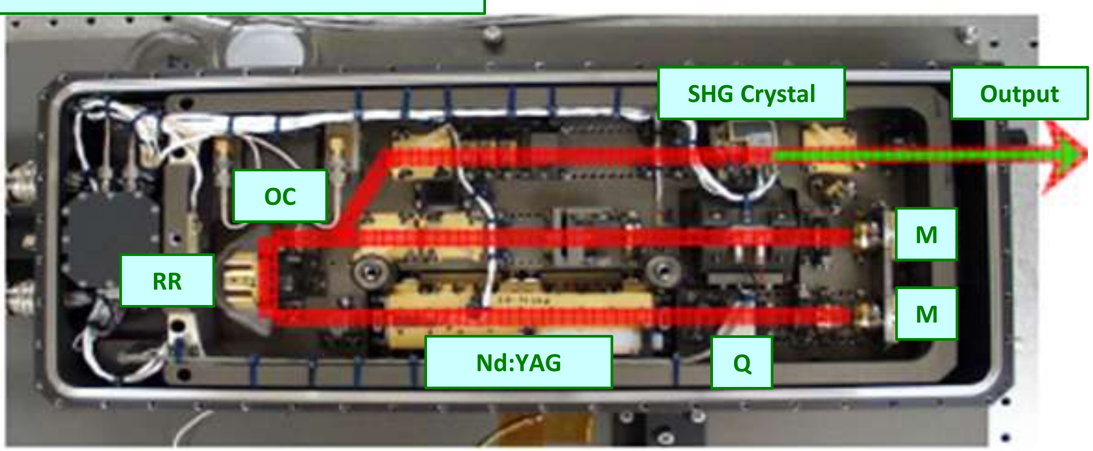


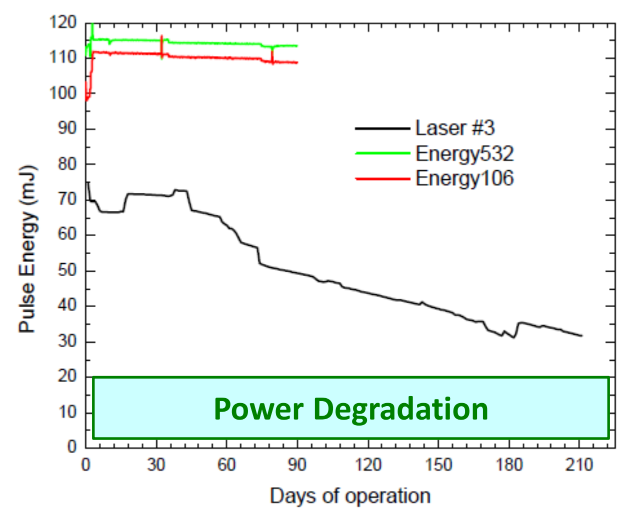


- Diode-pumped Nd:YAG slab
- Passively cooled
- Sealed canister, 1 atm dry air

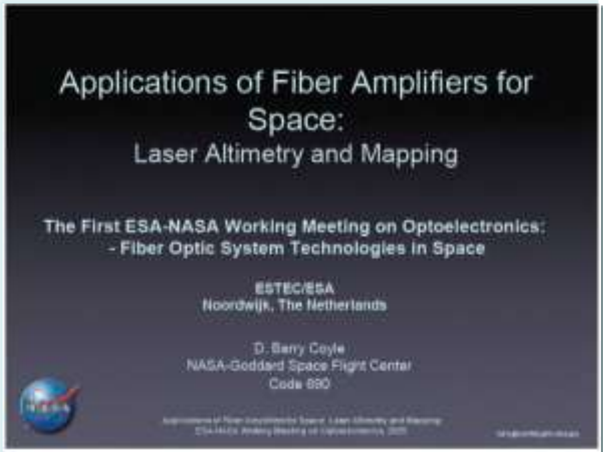
Laser in CALIOP

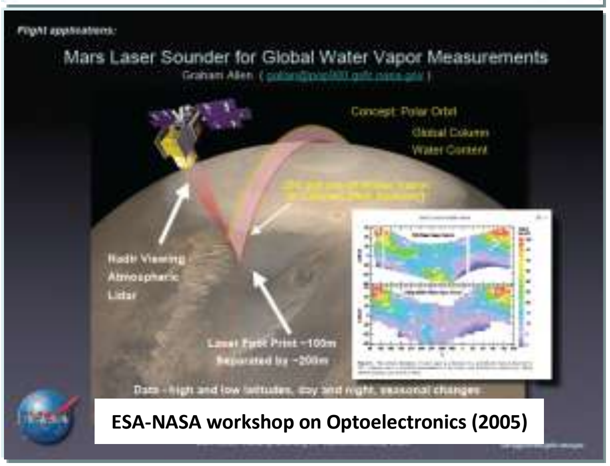
Laser in CALIOP





Fiber Laser vs. Crystal Laser in SPACE





ESA-NASA workshop on Optoelectronics (2005)

Cavity vs Fiber Lasers

Advantages in Capabilities

Laser Pulse Source	PRF	Pulse E	Pulsewidth	Polarization	Beam Quality
Cavity	√	√	√	√	
Fiber	√		√		√

Laser Pulse Source	Efficiency	Alignment Stability	Lifetime	Contamination	Cost
Cavity					
Fiber	√ √ !	√ √ !	√	√ √ !	√

Summary: Fiber-based laser sources have critical advantages that warrant immediate study and flight development investments.

Applications of Fiber Amplifiers for Space: Laser Altimetry and Mapping
ESA-NASA Working Meeting on Optoelectronics, 2005

barry@comlet.gsfc.nasa.gov

- Compact (Smaller than Lap-top)
- Alignment-free (All optical path in optical fiber)
- Vibration insensitive (All optical path in optical fiber)
- High efficiency (Pump to signal conversion more than 70 %)
- High-level power stability (Less than 1 %)
- Long-lifetime (More than 30 years)

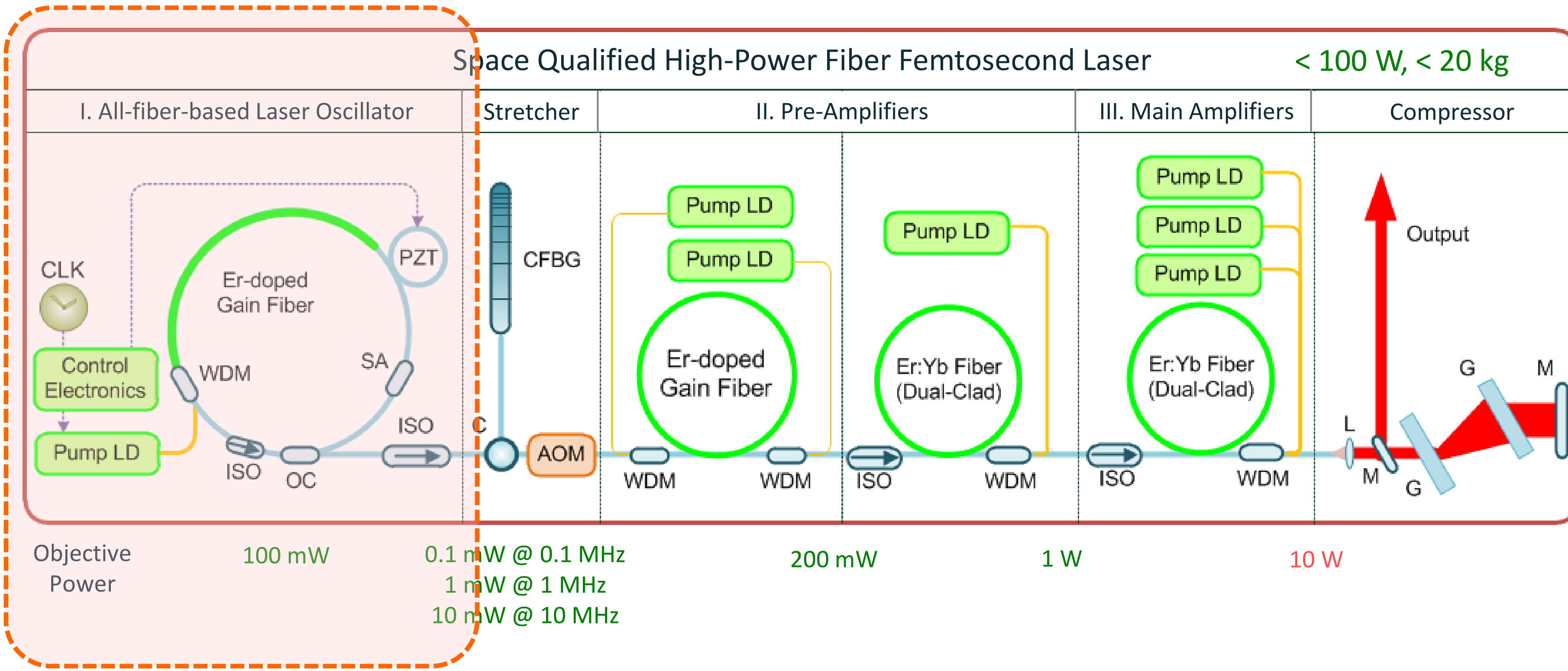
Current fiber-based NASA Projects

- CO_2 LIDAR (Er, Yb, Er+SHG)
- O_2 LIDAR (CW Er+SHG)
- Spectral Ratio Biospheric (Er+SHG)
- Mars Laser Sounder (Yb)

Fiber-based Femtosecond Laser in SPACE

Design Concept

- Fiber based laser design (Gain material: Er-doped fiber)
- MOPA(Master Oscillator Power Amplifier) based design
- Master Oscillator: Actively cooled
- Power Amplifiers: Passively cooled



Master oscillator determines [1]pulse duration, [2]repetition rate, [3]spectral bandwidth, [4]power stability and so on

Femtosecond Laser: Satellite Payload (FSO)

National Space Lab NSL

Scope

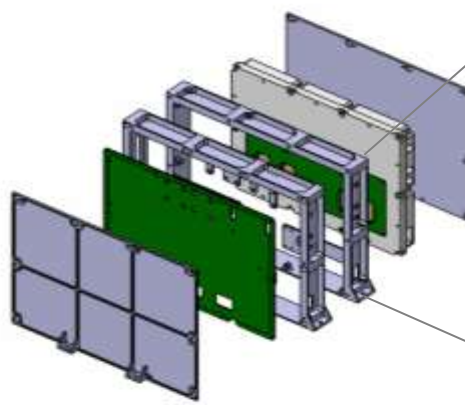
- Payload development for 3rd launching vehicle, NARO-ho (KSLV-1)
- Space Qualification of the Fiber-based Ultrafast Femtosecond Laser

NARO-ho (KSLV-1)

launched in Jan. 2013

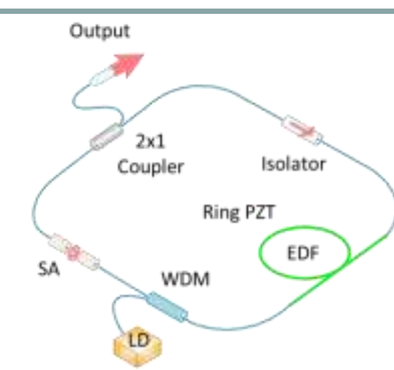
Naro Science Satellite (STSAT-2C)

(femtosecond oscillator, FSO)



< Satellite Specification >

ITEM	Specification
Design Life Time	1 year
Mass	< 100 kg
Power	100 W
Attitude control	Pointing accuracy +/- 20 degree
Payloads	3 payloads LP, IRS, FSO
Orbit	Perigee: 300 km Apogee 1500 km



All-fiber-based SA soliton fiber femtosecond oscillator

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Absolute Distance Metrology
Ultra-high Density Space Optical Communication
Precision Spectroscopy in Space (LIDAR)
Atomic Clock in Space for Testing General Relativity
Precise Calibration of Space Spectrometers
Precision Time-Transfer for Testing General Relativity
clock #1
clock #2

Ultrafast Optics for Ultra Precision Research Group

- School of Mechanical Engineering, KAIST
- Members (As of Feb. 2013)
  - Prof. Seung-Woo Kim
  - 3 Post-doctoral researcher
  - 10 Doctoral course students
  - 4 Master course students
  - 3 Technical Staffs
  - 1 Office Staff

-Thank you-

Young-Jin Kim, Ph. D (yj.kim@kaist.ac.kr)

Department of Mechanical Engineering,
Korea Advanced Institute of Science and Technology (KAIST)