Design considerations and validation of the MSTAR absolute metrology system

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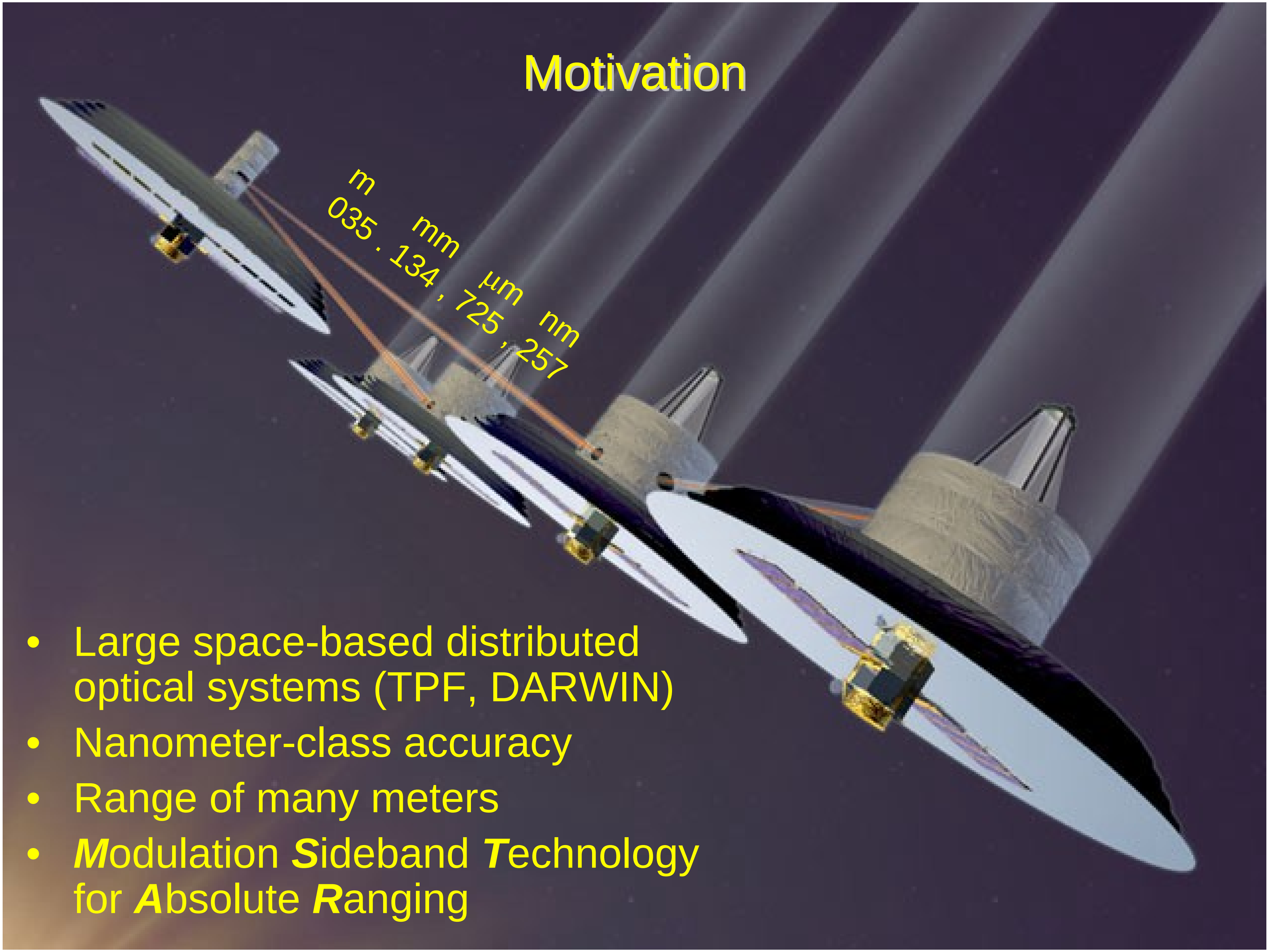
Sponsor: NASA Cross-Enterprise Technology Development Program - Distributed Spacecraft

Outline

- **Motivation**
- **Theory**
- **Validation**
- **Design considerations**
- **Summary**

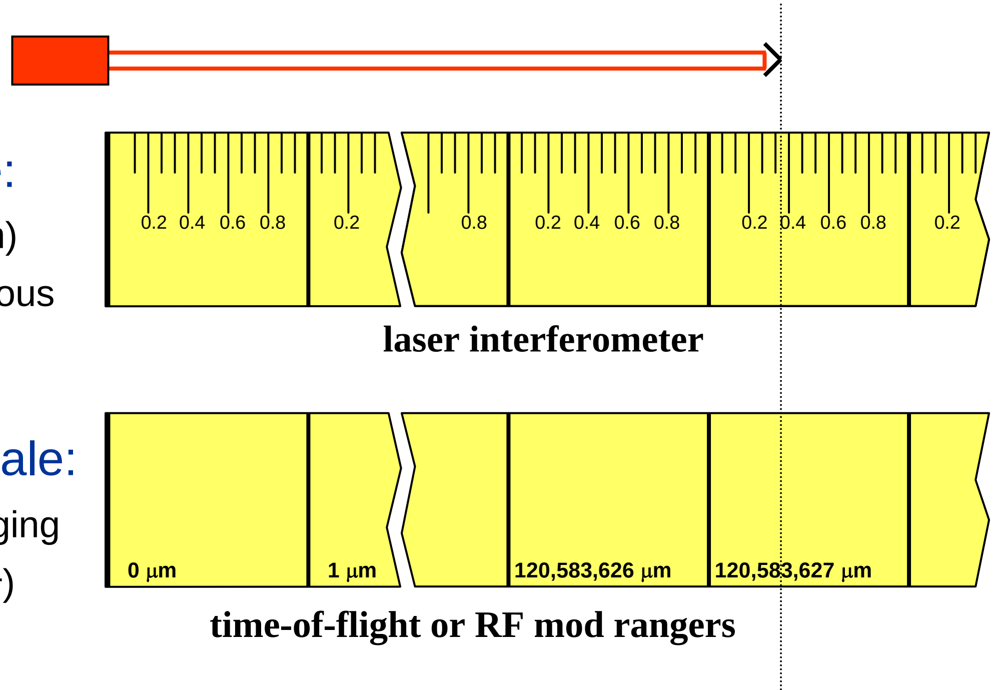
Motivation



- Large space-based distributed optical systems (TPF, DARWIN)
- Nanometer-class accuracy
- Range of many meters
- ***M***odulation ***S***ideband ***T***echnology for ***A***bsolute ***R***anging

Main Technology Issue

- Fine scale:
  - precise (nm)
  - but ambiguous
- Coarse scale:
  - 10 μm ranging accuracy (1 σ)



before MSTAR

???,???,???.351 μm

+

120,583,6??.??? μm

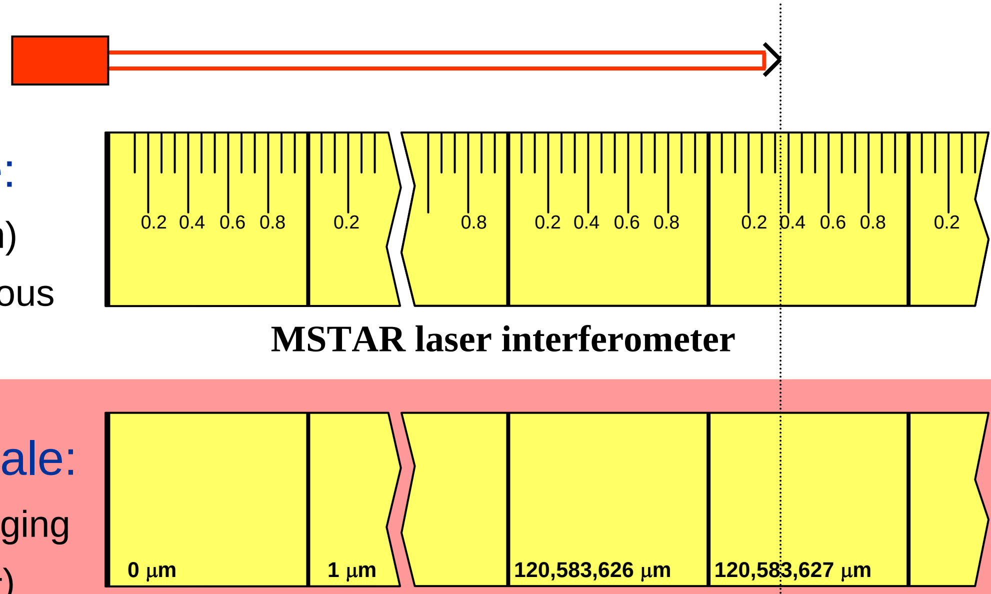
=

120,583,6??.351 μm

useless

- The 10 μm ranging accuracy of the existing coarse scale gauges is not sufficient to resolve the ambiguity of the existing fine scale gauges

Main Technology Issue



MSTAR laser interferometer

MSTAR coarse stage

with MSTAR

- Fine scale:
  - precise (nm)
  - but ambiguous

???,???,???.351 µm

+

- Coarse scale:
  - 0.1 µm ranging accuracy (1 σ)

120,583,627.3?? µm

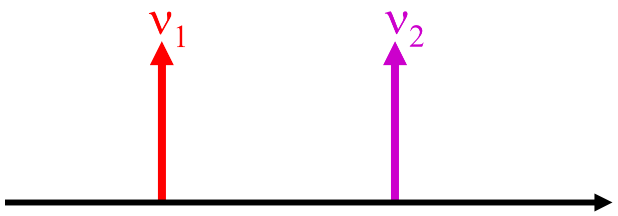
=

120,583,627.351 µm

- MSTAR: -integrated sensor, -nm accuracy, -no ambiguity

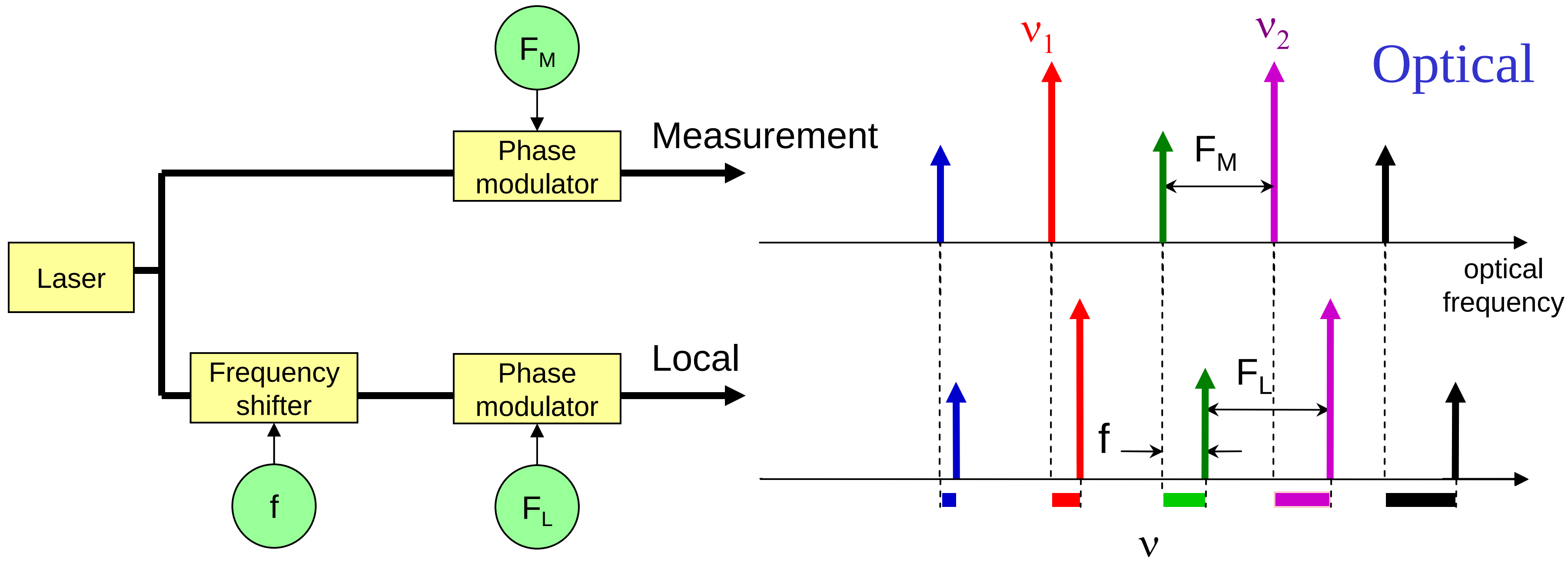
- The 0.1 µm MSTAR **coarse stage ranging accuracy** is sufficient to resolve the ambiguity of the built-in fine scale gauge

MSTAR architecture



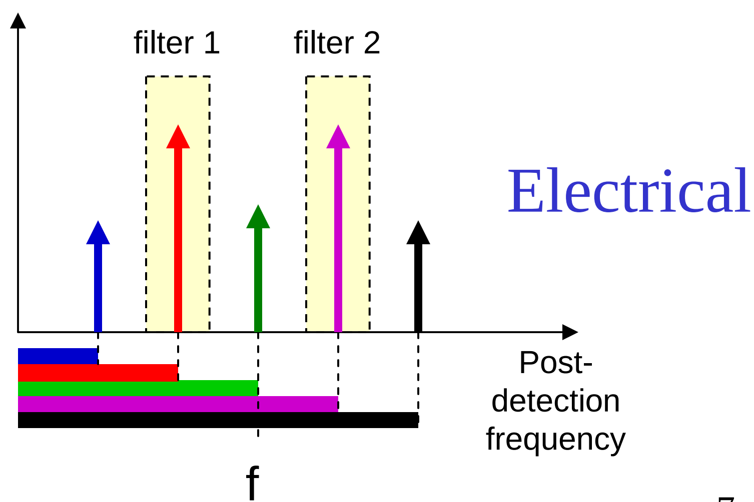
- Existing techniques
  - 2-color Interferometry (e.g. SIM)
    - Using two or more lasers
    - Performance limited by laser frequency stability and tuning range
  - RF modulation (e.g. GEOSAR)
    - Requires high-frequency modulation, detection and processing
    - Performance limited by low sensitivity of high frequency detectors and electronics
- *MSTAR* is a hybrid
  - Implements **2-color interferometry** with RF phase modulation of a **single laser**
  - Heterodyne detection does not require high-frequency detectors and processing
  - Enabled our novel architecture and by availability of high-frequency phase modulators

Modulation scheme

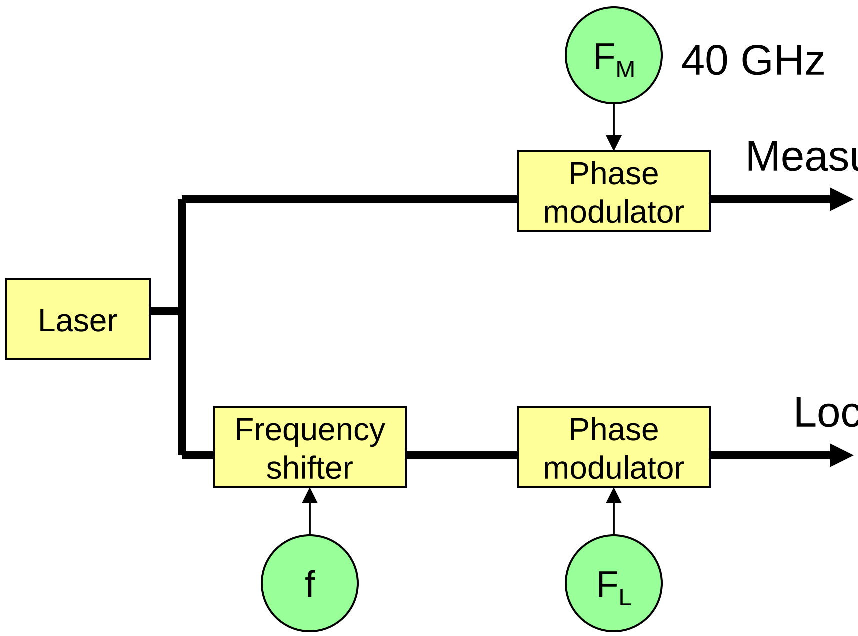


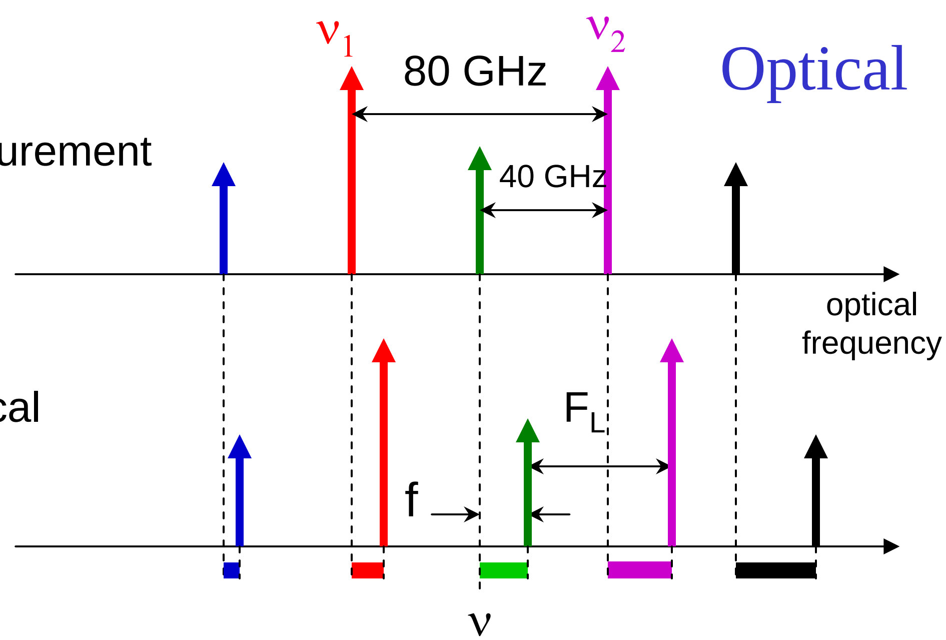
- Measurement and Local beams mix to produce a unique beat frequency for each sideband

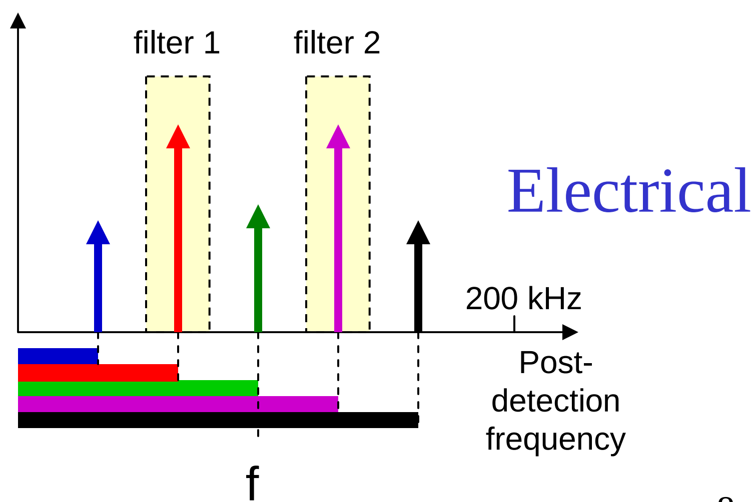
- Electrical Spectrum is filtered to isolate beats resulting from desired optical sidebands



Modulation scheme

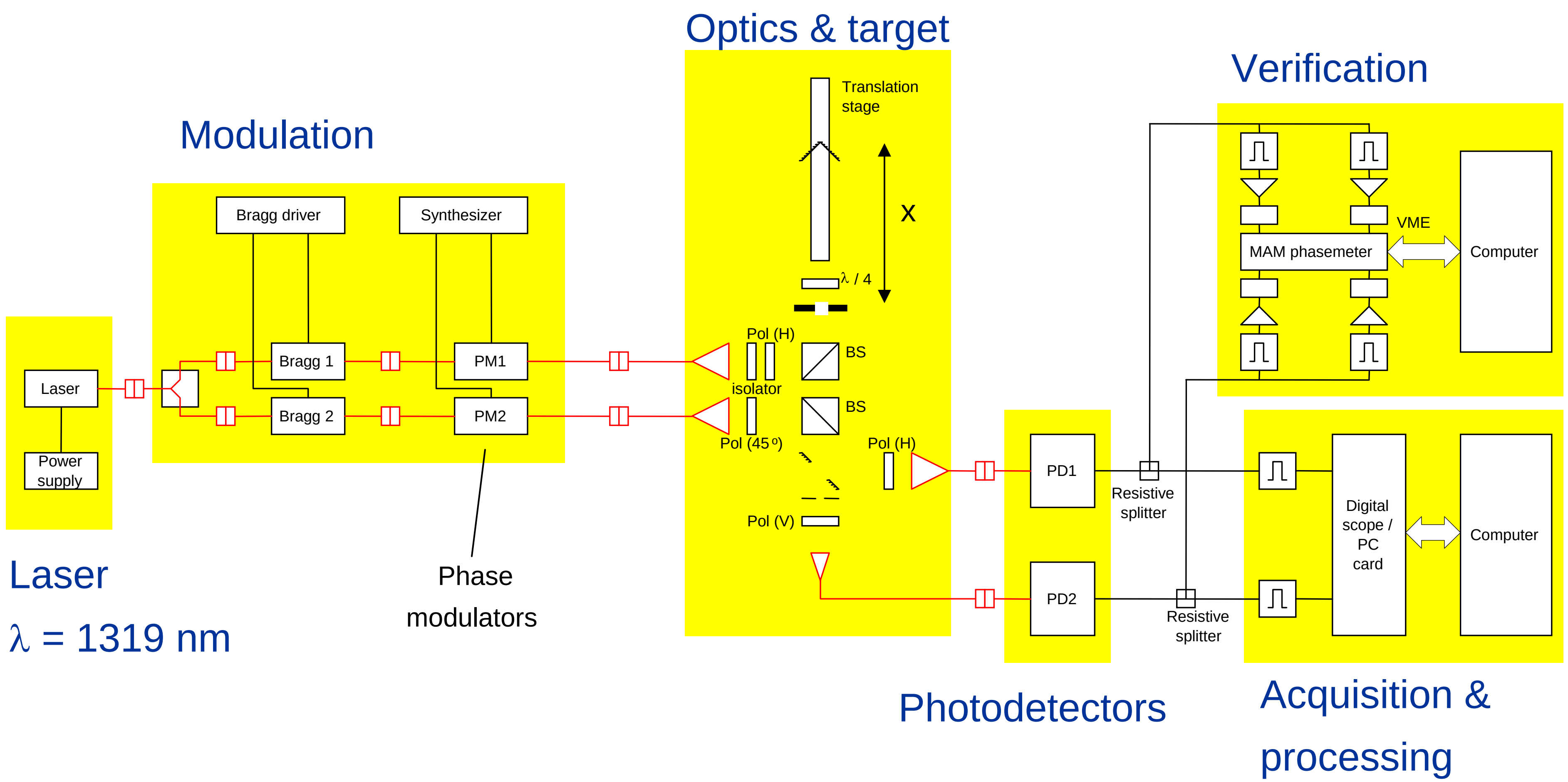






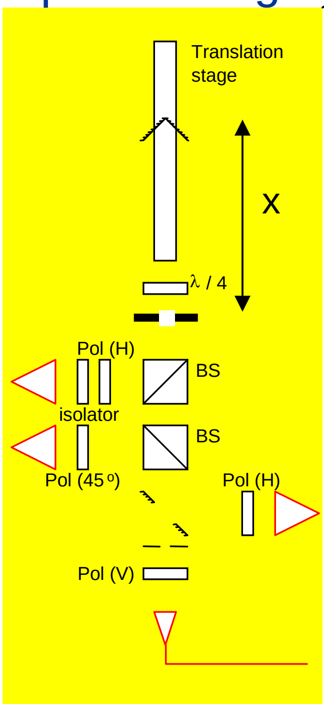
- Synthetic wavelength = 3.75 mm
- 0.1 µm accuracy requires phase accuracy of 3 milliradians
- Need a very clean optical and signal processing system
- Can use higher sidebands

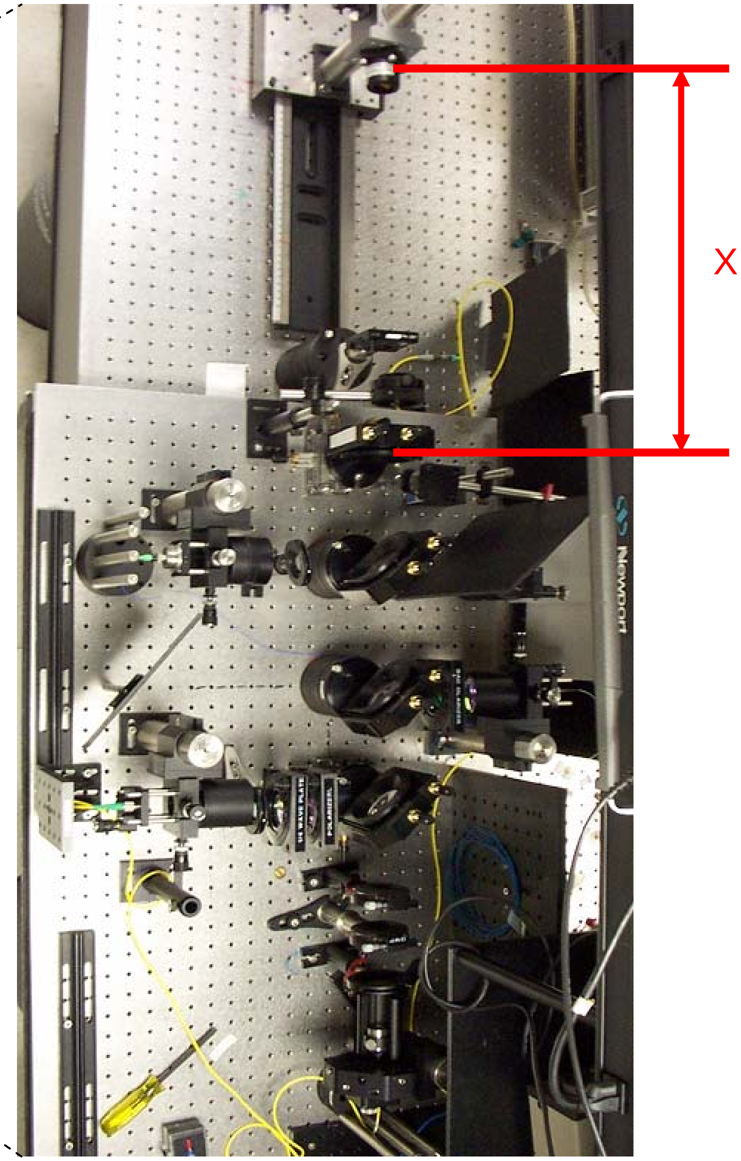
MSTAR schematic



Lab set-up

Optics & target





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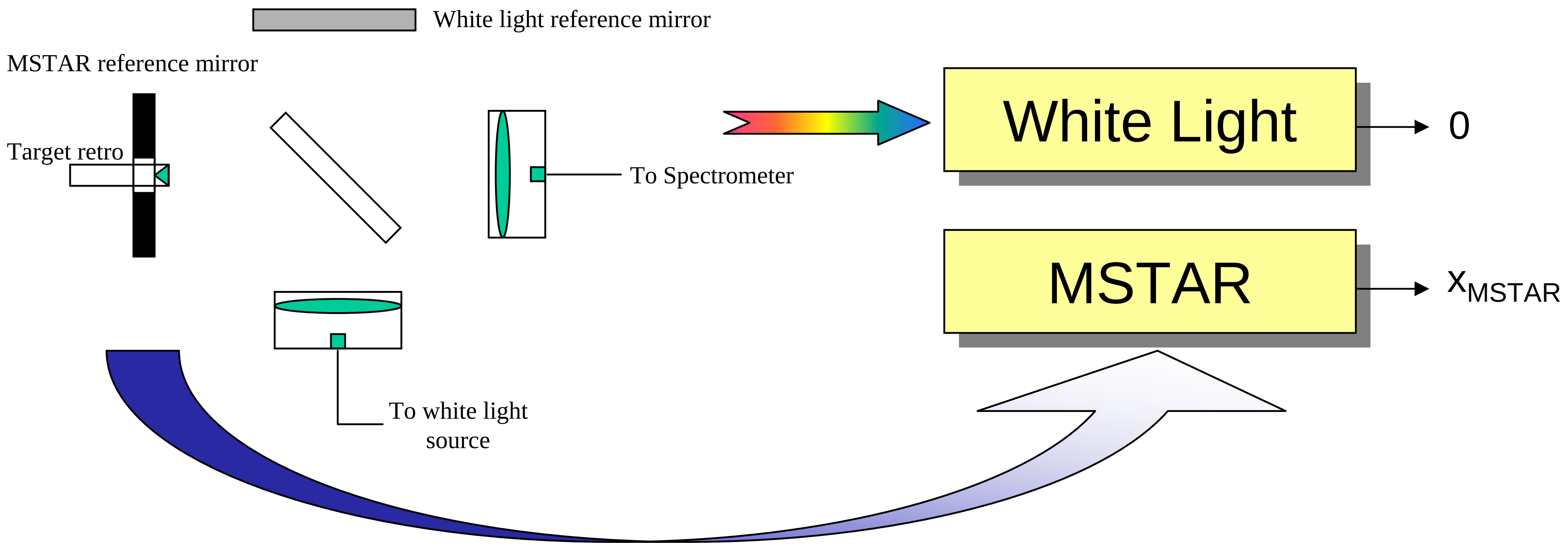
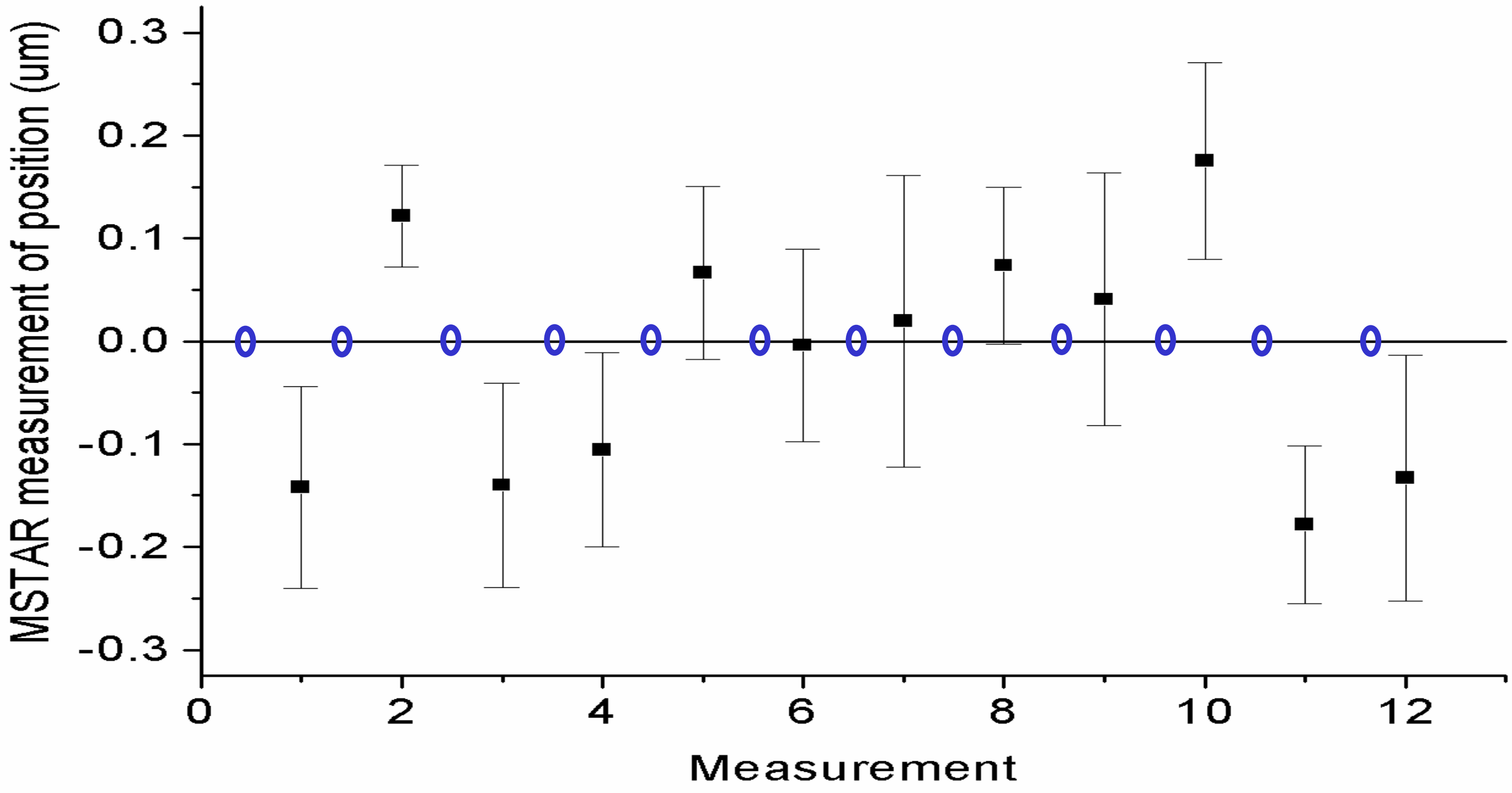
Setting the zero point



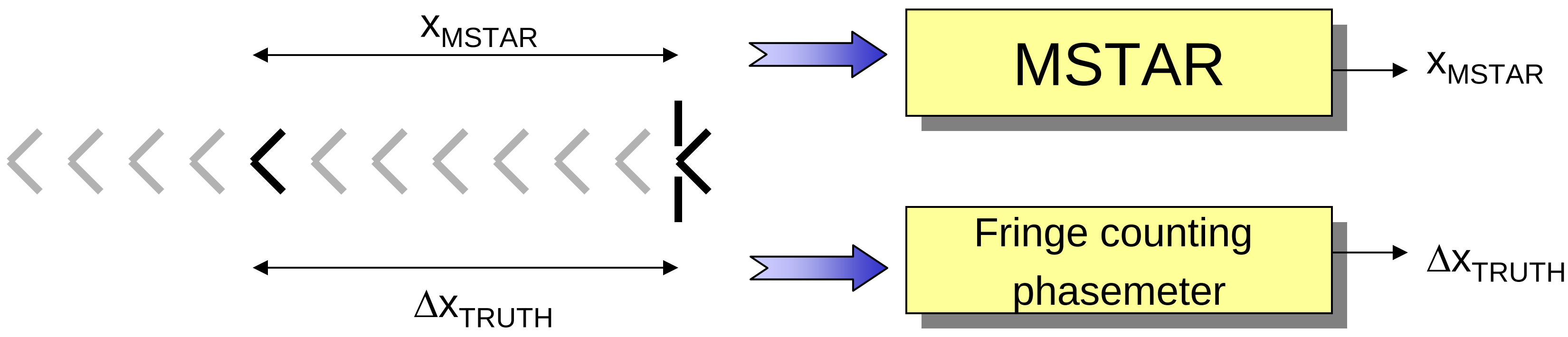
- Use white light Michelson interferometer to set zero point.
  - Match fringe pattern from target retro to MSTAR reference mirror
- Make measurement with MSTAR
- Repeat many times.

Zero Results



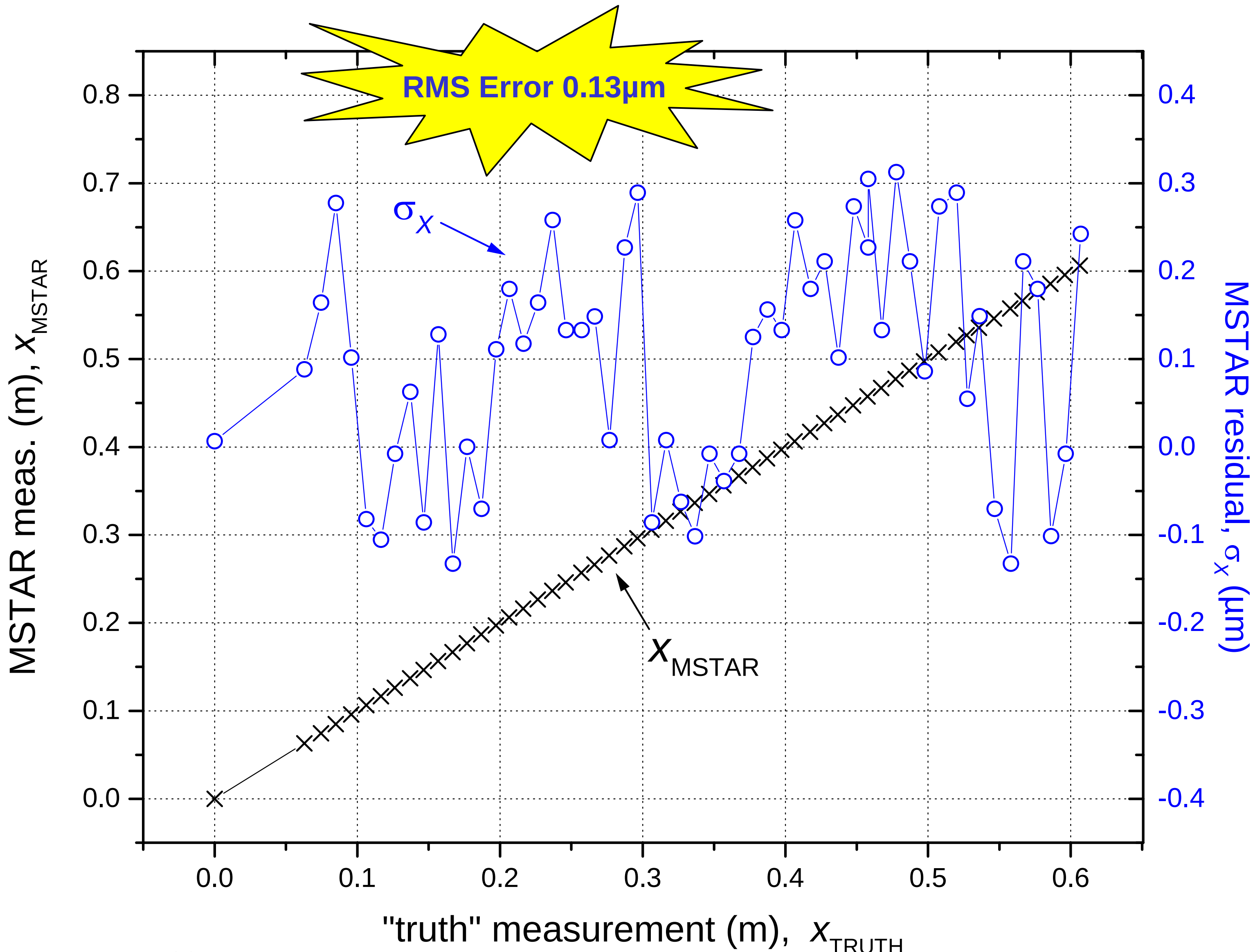
- Zero set with white light between each point.
- Average error 0.12 µm

Displacement Test



- Start with target at zero.
- Measure absolute position with MSTAR
- Move target while tracking with phasemeter to measure displacement.
- Repeat many times.
- Plot MSTAR vs. phasemeter and calculate residual.

Displacement Results



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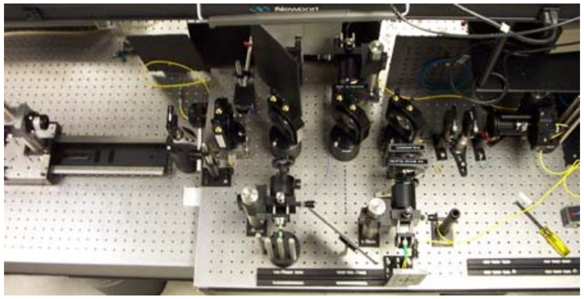
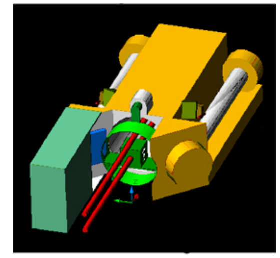
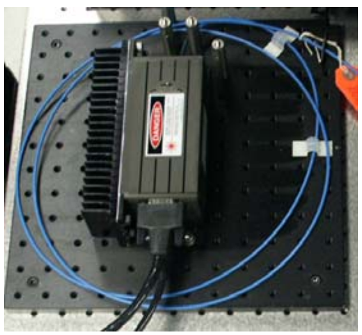
Miniaturization



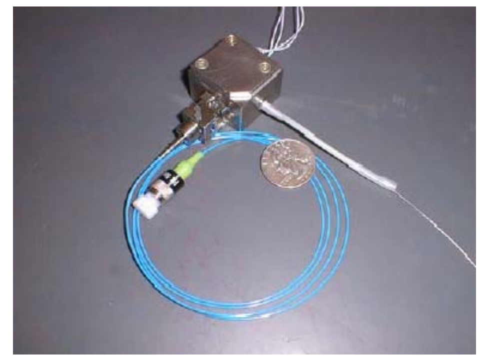
Lab breadboard to Space Interferometry Mission (SIM) type beam launcher



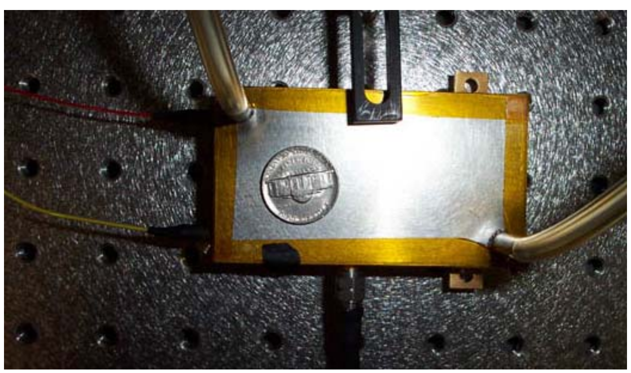
Size ~ 25x15x5 cm



Commercial Nd:YAG laser to SIM/StarLight developed laser



Brassboard exists



Experimental polymer 40GHz modulator to commercial telecom 40GHz modulator

Done

Frequency Stability

- Stability requirement given by σ_x/x
- Coarse (absolute) stage (required σ_x= 0.1 um)
  - Based on the RF modulation frequency
  - For 100m separation, fractional uncertainty is 10^{-9}
  - Easily met by commercially available for RF references.
- Fine stage (e.g. σ_x=30 nm)
  - Based on the laser frequency
  - For 100m requires a fractional uncertainty $3x10^{-10}$ (72kHz with a 1319 nm laser)
  - Laser locking systems have been developed which can meet this requirement

Moving Targets

- Use Carrier-Aided Smoothing
  - First developed for Global Positioning System
  - Allows for coherent averaging in the presence of moving targets
- Lab setup should track velocities up to 10 mm / s

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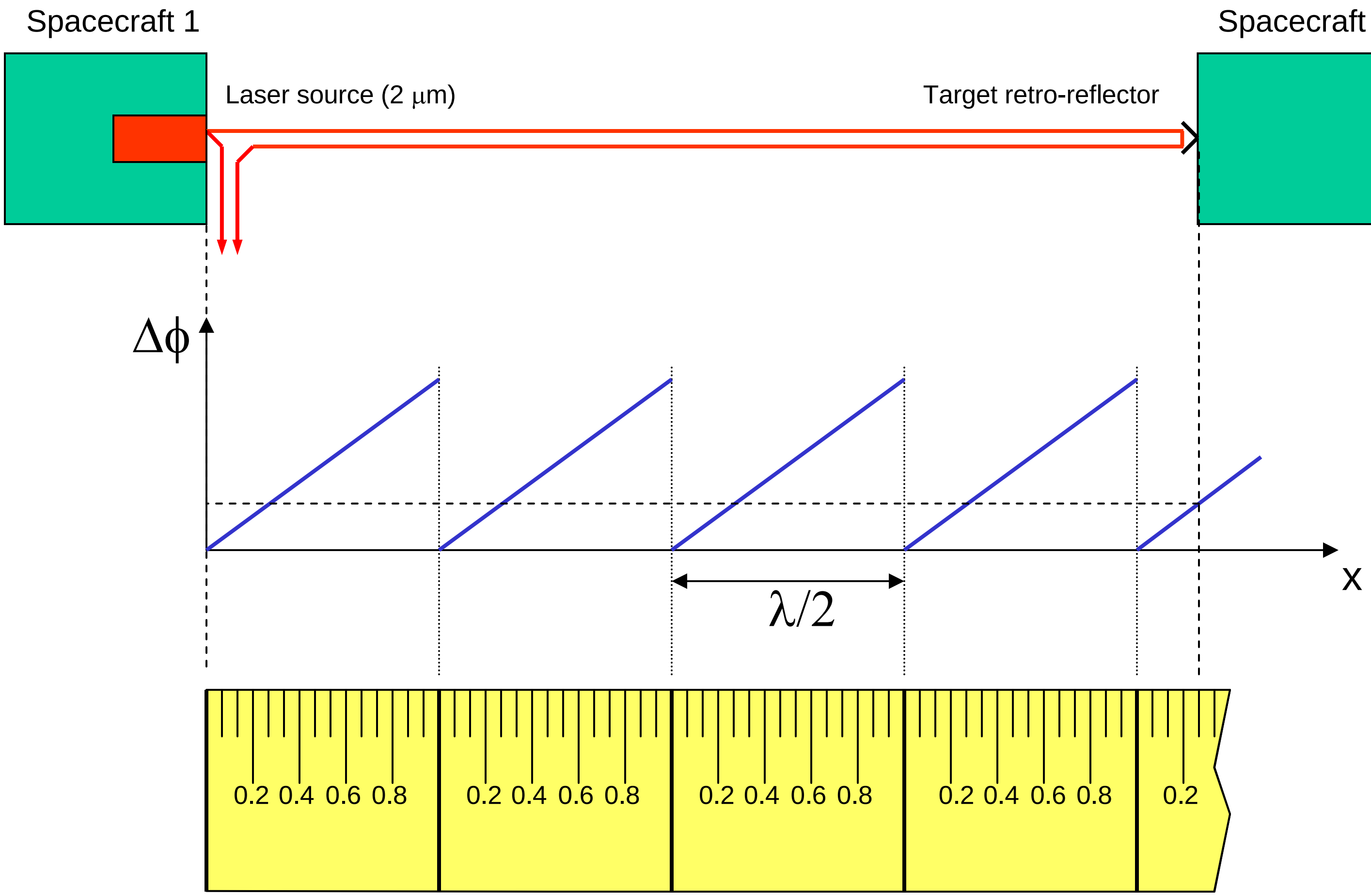
Summary

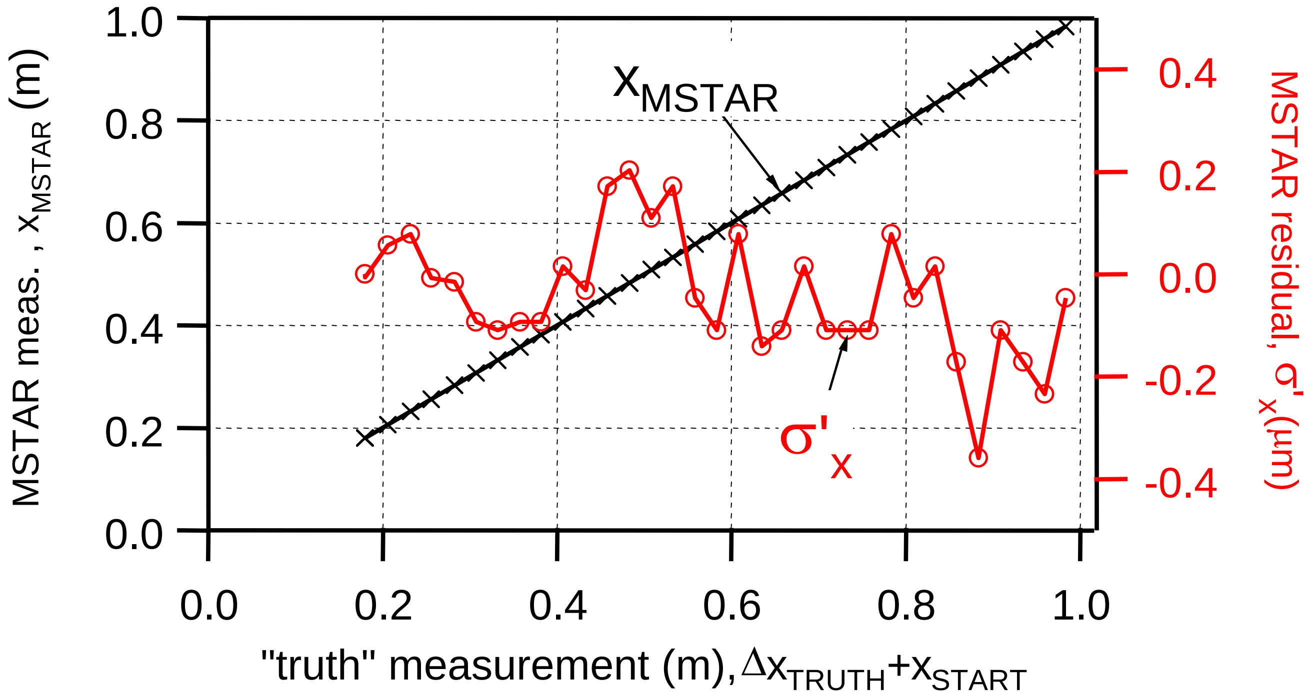
- ***M**odulation **S**ideband **T**echnology for **A**bsolute **R**anging*
- 0.1µm accuracy demonstrated over 1 meter.
- Resolves integer-cycle ambiguity: enables nm accuracy
- Standard heterodyne metrology gauge with 40 GHz phase modulation.
- Verified experimentally over 1 m
- Scaleable to large distance (~100 m) and moving targets (~10 mm/s)

Backup Slides

Laser Interferometer



First Displacement Results

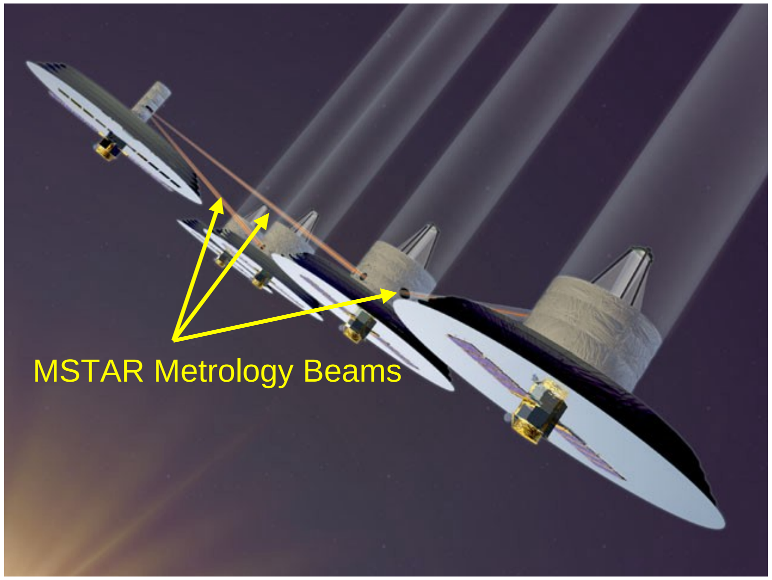


- Residual rms = 0.12 μm

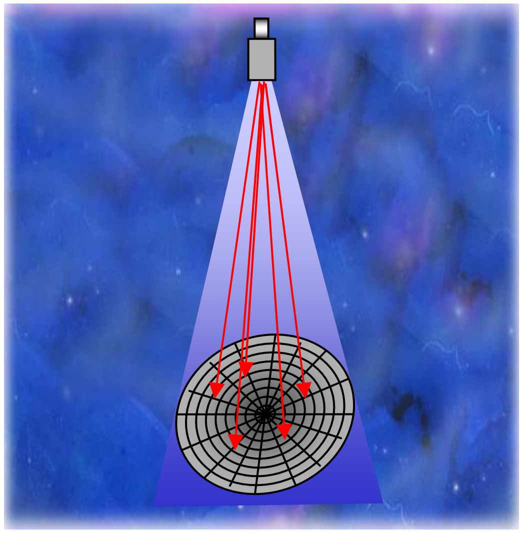
1st demonstration to resolve integer-wavelength ambiguity with this range in a practical sensor!

Applications in Space

- Distributed Spacecraft Control
  - Single MSTAR sensor may be switched to measure multiple targets.
  - Not affected by momentary beam interruptions



- Large Single Aperture Telescopes
  - In flight surface figure checking
  - Scan single sensor to many targets on the surface
  - Multiple sensors to monitor a few key targets.



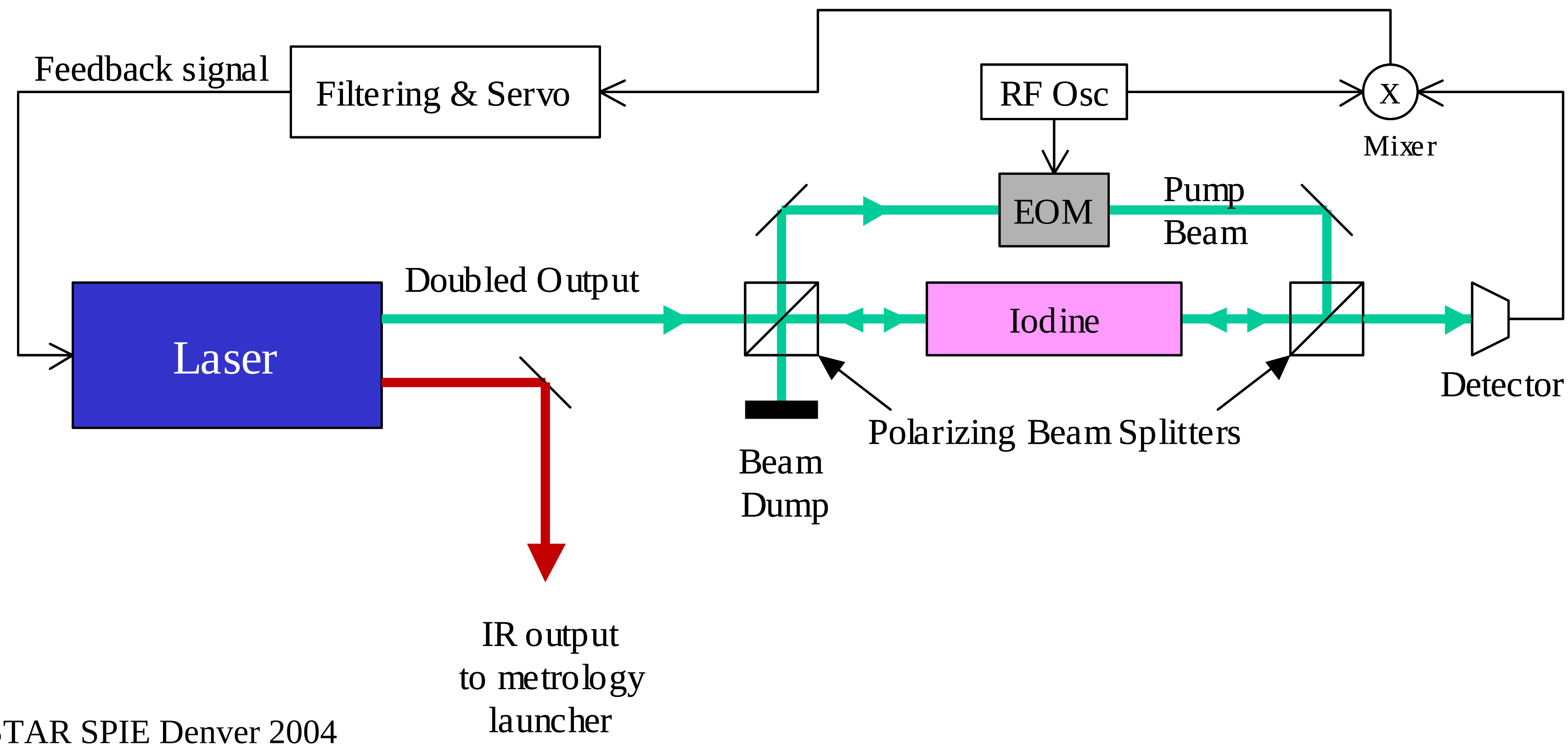
- And possibly many more…

Carrier-Aided Smoothing

- Reference: R. Hatch, *The Synergism of GPS Code and Carrier Measurements*, Proceedings of 3rd International Geodetic Symposium on Satellite Doppler Positioning, DMA/NGS, pp. 1213-1232, Washington, D.C. (1982)
- Carrier phase is tracked from the start of the sideband-phase measurement.
- Carrier phase subtracted from the sideband-phase time series.
- Down-converted Doppler shifted frequency, $f = 2*v/\lambda$ where v = target velocity and λ = laser frequency.
- Limiting factor is bandwidth of filters around down-converted sidebands. (e.g. 15kHz of Doppler shift with λ=1319 nm => v = 1.3 mm/s).

Iodine locking system

- Modulation transfer spectroscopy (MTS) method for Doppler free locking.
- Commercially available from Innolight with 10^{-13} fractional stability



Publications and Patents

S. Dubovitsky and Oliver P. Lay, “MSTAR: A high precision laser range sensor,” NASA Tech Briefs and New Technology Disclosure, NPO-30304, 2001

S. Dubovitsky and Oliver P. Lay, “MSTAR: A high precision laser range sensor,” NASA patent pending

O. P. Lay, S. Dubovitsky, R. D. Peters, J. P. Burger, S.-W. Ahn, W. H. Steier, H. R. Fetterman, Y. Chang, “ MSTAR:a submicrometer absolute metrology system”, Opt. Lett., vol 28, no 11, June 2003, pp. 890-892.

Seh-Won Ahn, Min-Cheol Oh, William H. Steier, Yin-Hao Kuo, Hyung-Jong Lee, Cheng Zhang, and Harrold R. Fetterman, "Integration of electro-optic polymer modulators with low-loss Fluorinated polymer waveguides" Opt. Lett.27, 2109, December 2002

O. P. Lay, Serge Dubovitsky , Robert D. Peters , Johan Burger , Seh-Won Ahn , William H. Steier , Harrold R. Fetterman , Yian Chang , “Absolute distance measurement with the MSTAR sensor”, SPIE International Symposium on Optical Science and Technology, SPIE's 48th Annual Meeting, August 2003, San Diego, California USA

S. Dubovitsky ,Oliver P. Lay, Robert D. Peters, Johan P. Burger, “MSTAR: A sub-micron absolute metrology sensor for space-based applications”, accepted for presentation at ICSO 2004, 5th International Conference on Space Optics, March 2004