MSTAR: An absolute metrology sensor with sub-micron accuracy for space-based applications

Robert D. Peters

Oliver P. Lay

Serge Dubovitsky

Johan P. Burger

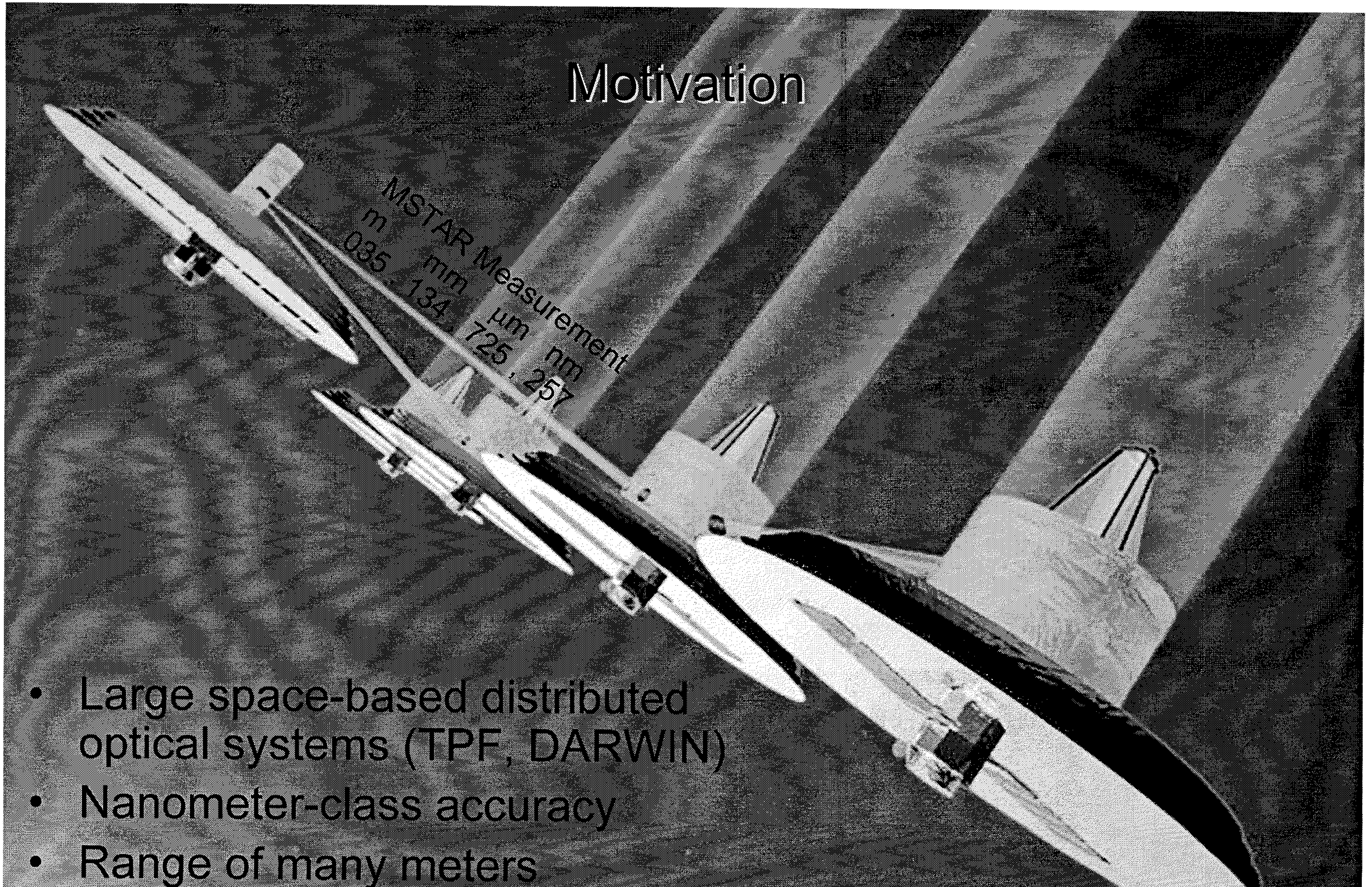
Muthu Jeganathan

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

Outline

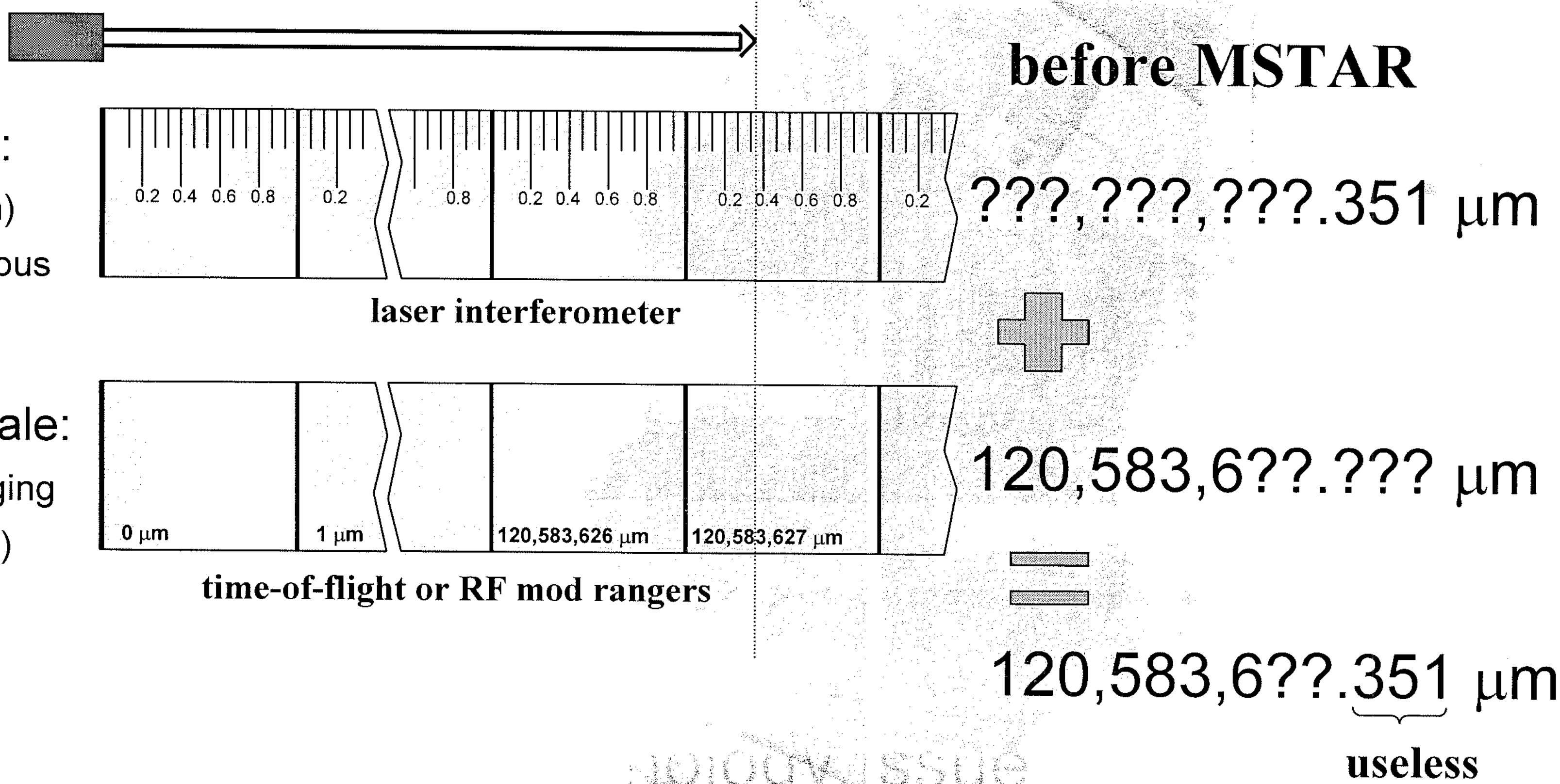
- Motivation and what MSTAR does.
  - Mission example and MSTAR's role
  - How MSTAR is different form state-of-the-art
- Details – How MSTAR works
- Verification – What we did to test MSTAR and how well it worked
  - Experiments
  - Results
- Improvements – Making MSTAR work in space
- Applications – distributed spacecraft, large optics, antennas
- 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*

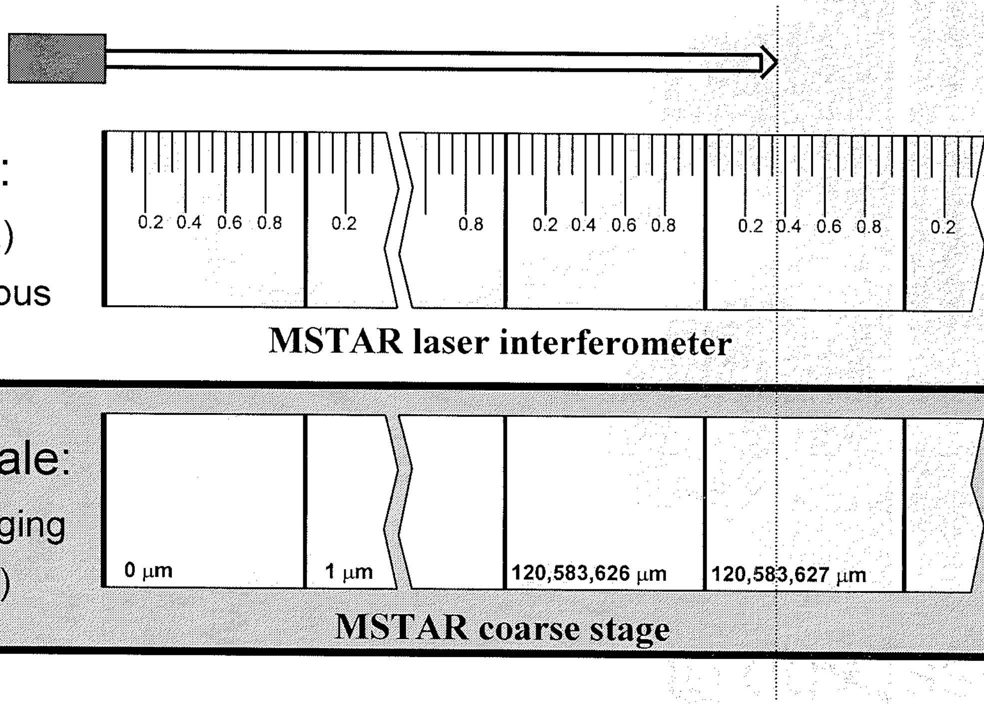
Main Technology Issue



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

- 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



with MSTAR

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

???,???,???.351 μm

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

120,583,627.3?? μm

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

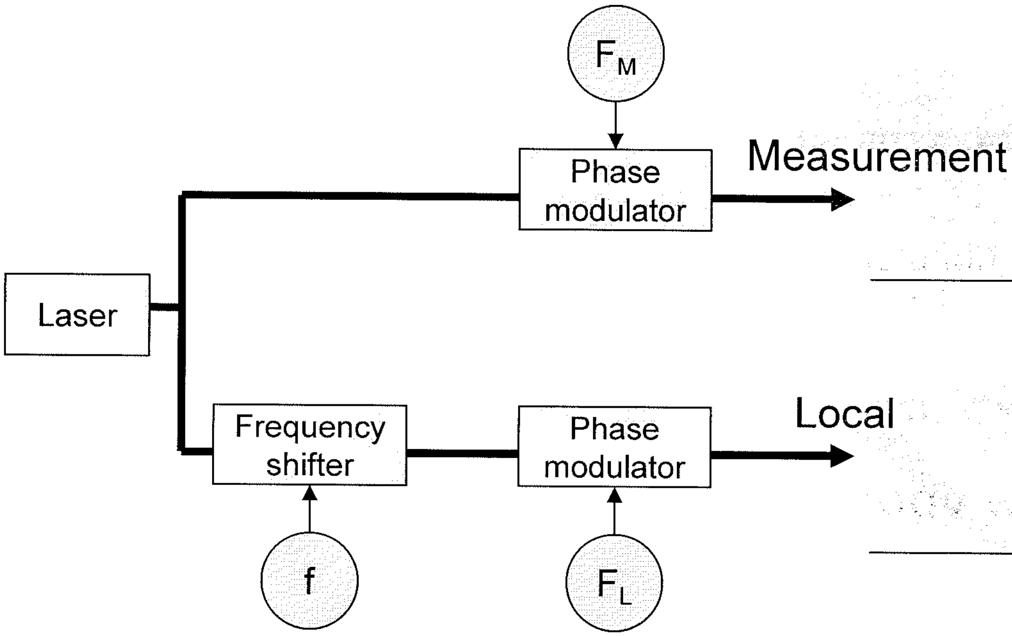
120,583,627.351 μm

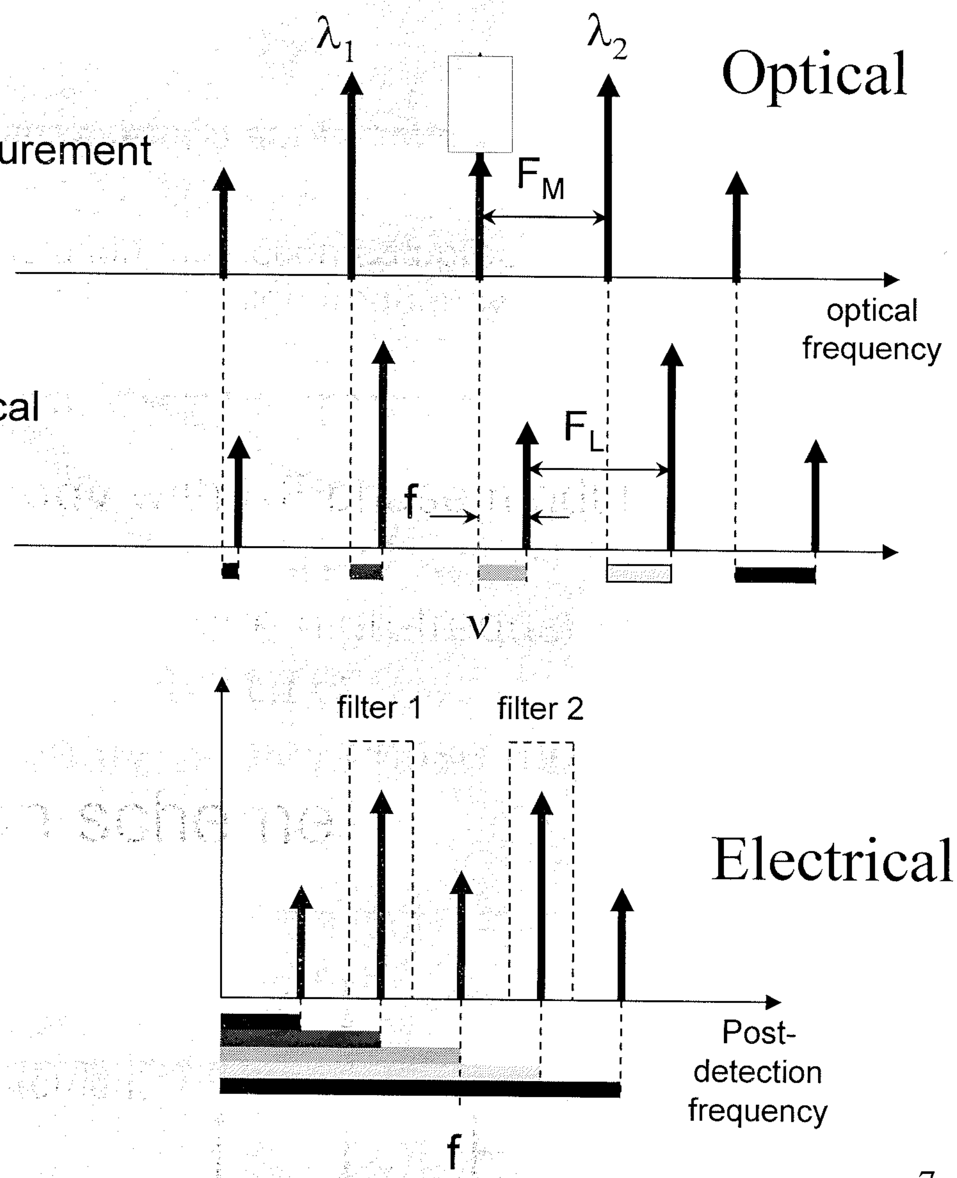
- The 0.1 μm MSTAR **coarse stage ranging accuracy** is sufficient to resolve the ambiguity of the built-in fine scale gauge

MSTAR architecture

- Existing techniques
  - 2-color metrology (e.g. SIM)
    - Using two or more lasers
    - Performance limited by laser frequency stability and tuning range
  - RF modulation (e.g. GEOSAR, LAMP)
    - 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 metrology** with RF phase modulation of a **single laser**
  - Heterodyne detection does not require high-frequency detectors and processing
  - Enabled by availability of high-frequency phase modulators

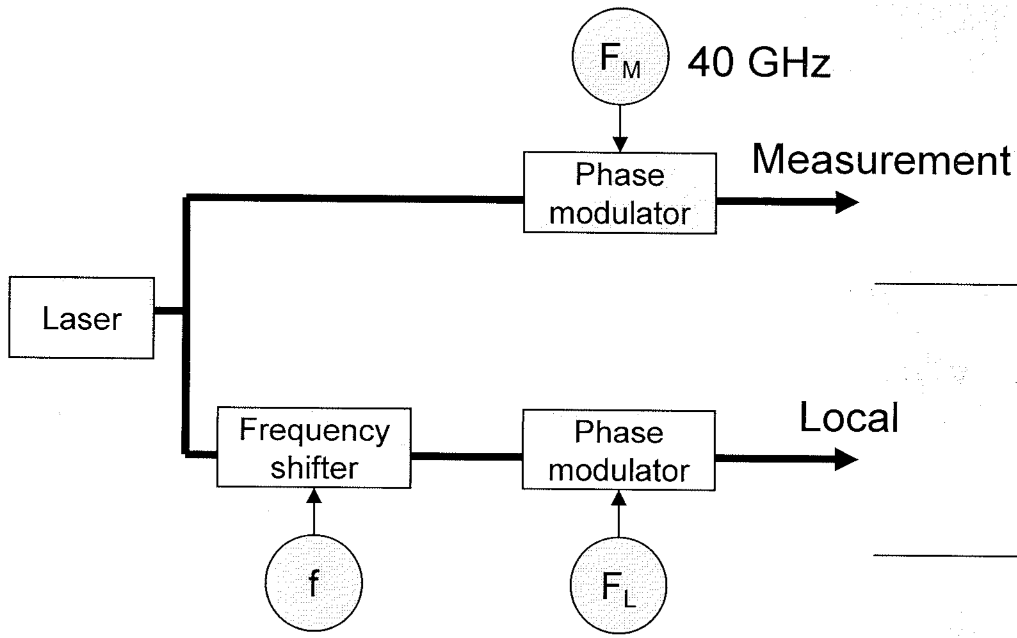
Modulation scheme

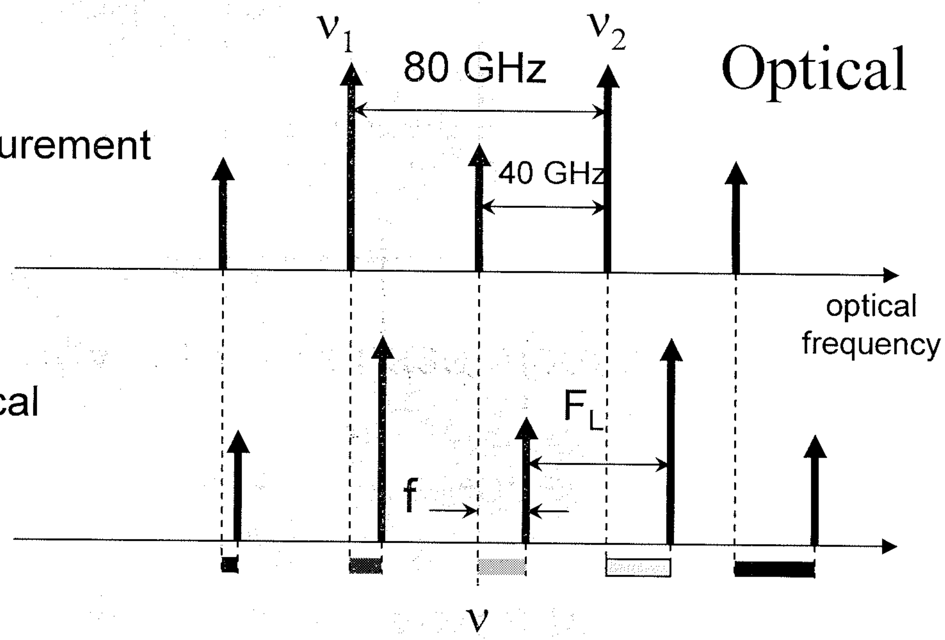


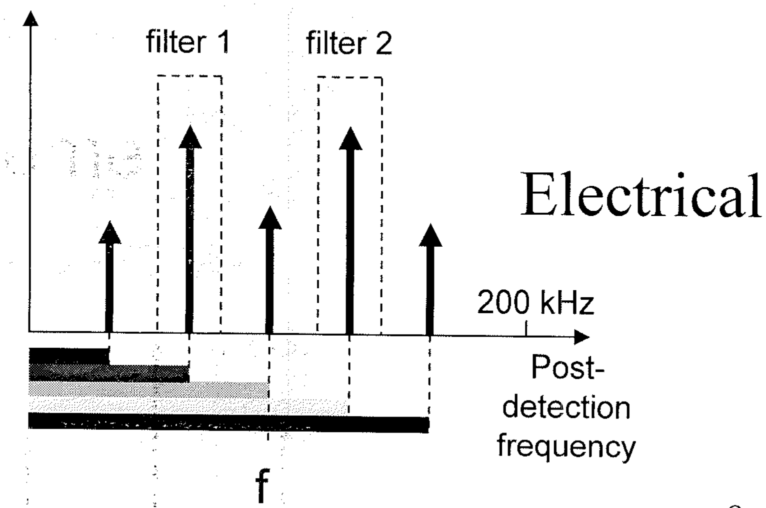


- Measurement and Local beams mix to produce a unique beat frequency for each sideband
- Electrical Spectrum is filtered to isolate beats resulting from desired optical sidebands

Modulation scheme

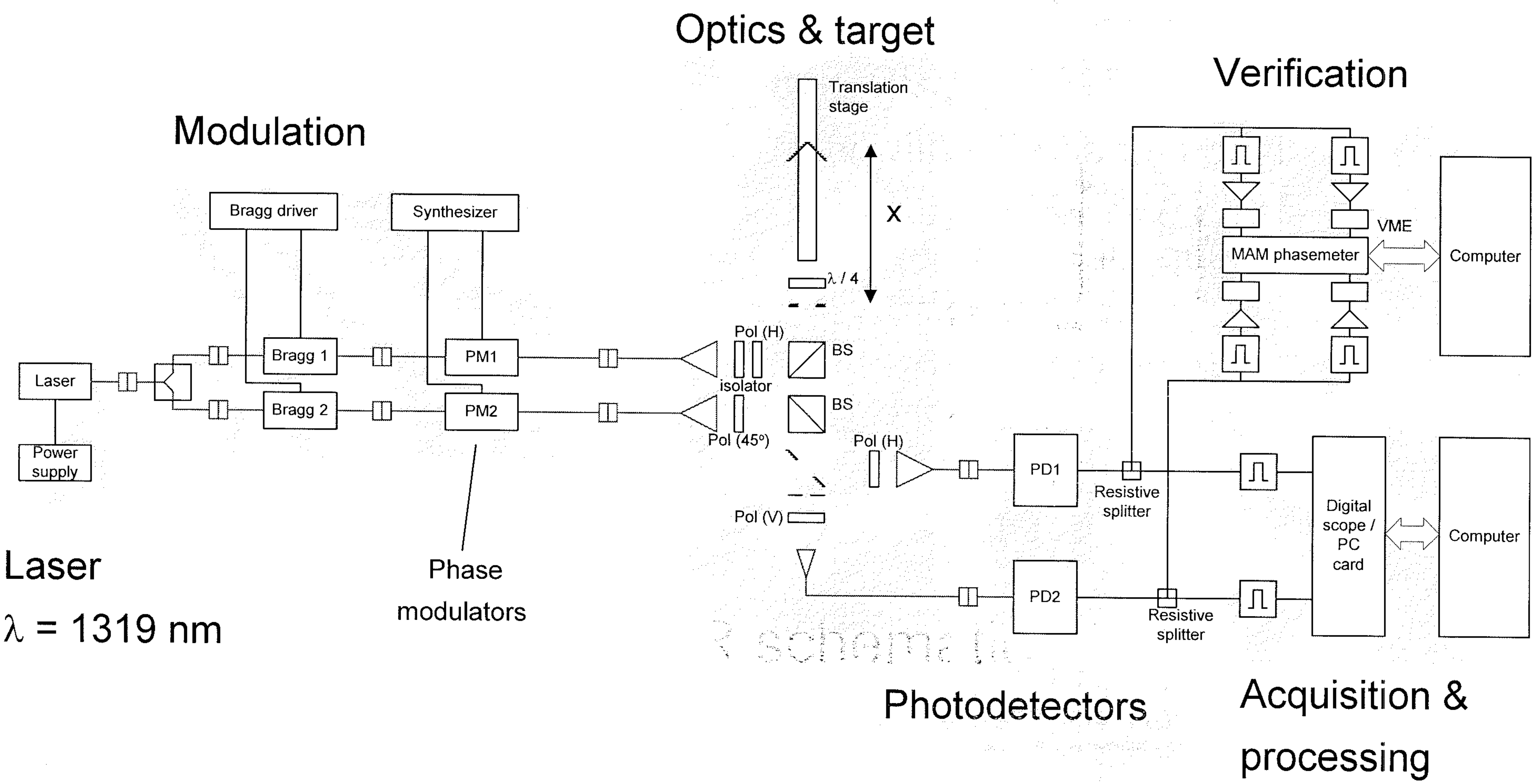




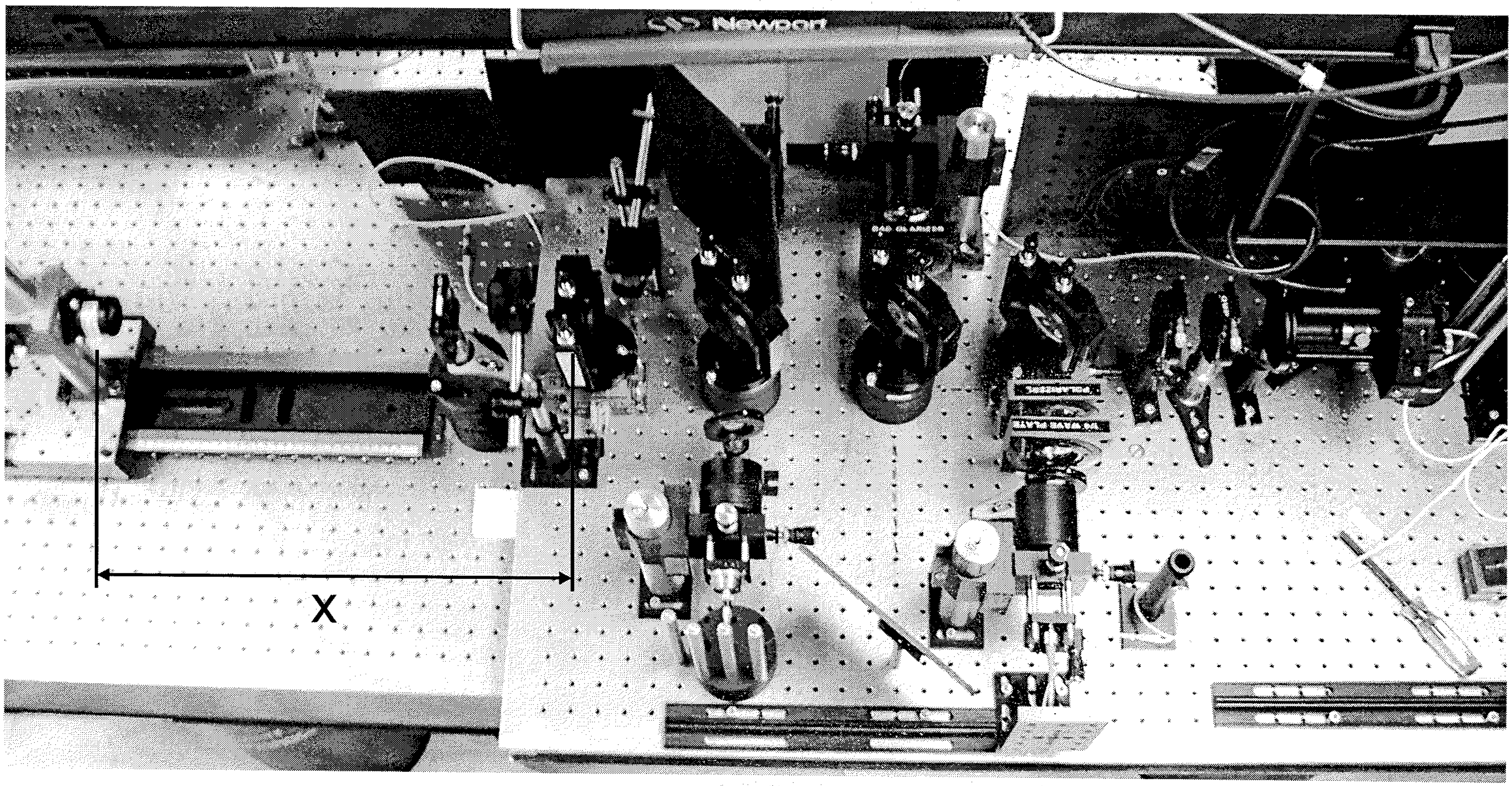


- Synthetic wavelength = 3.75 mm
- 0.1 μm accuracy requires phase accuracy of 3 milliradians
- Need a very clean optical and signal processing system
- Can use higher sidebands

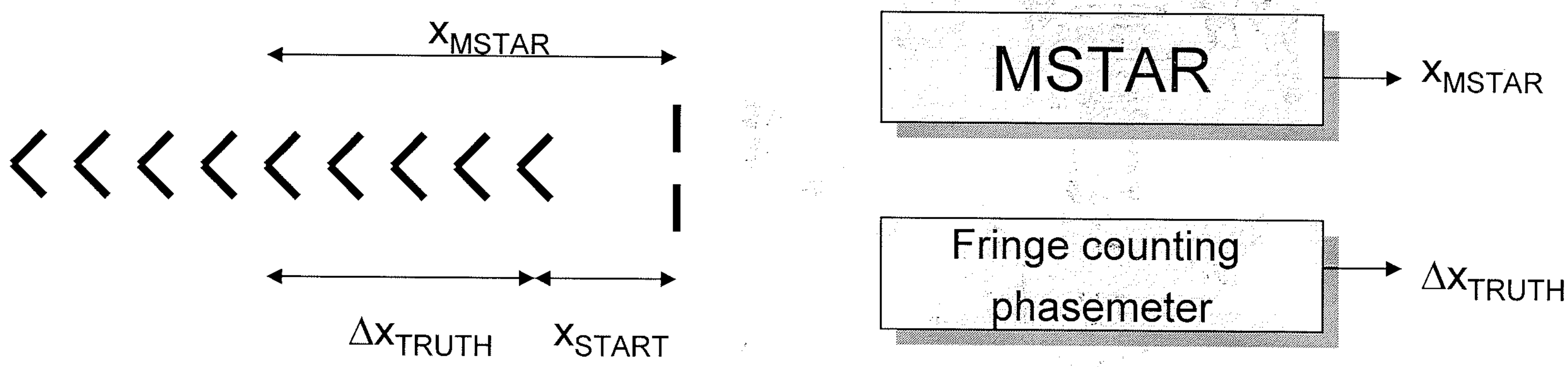
MSTAR schematic



Lab set-up

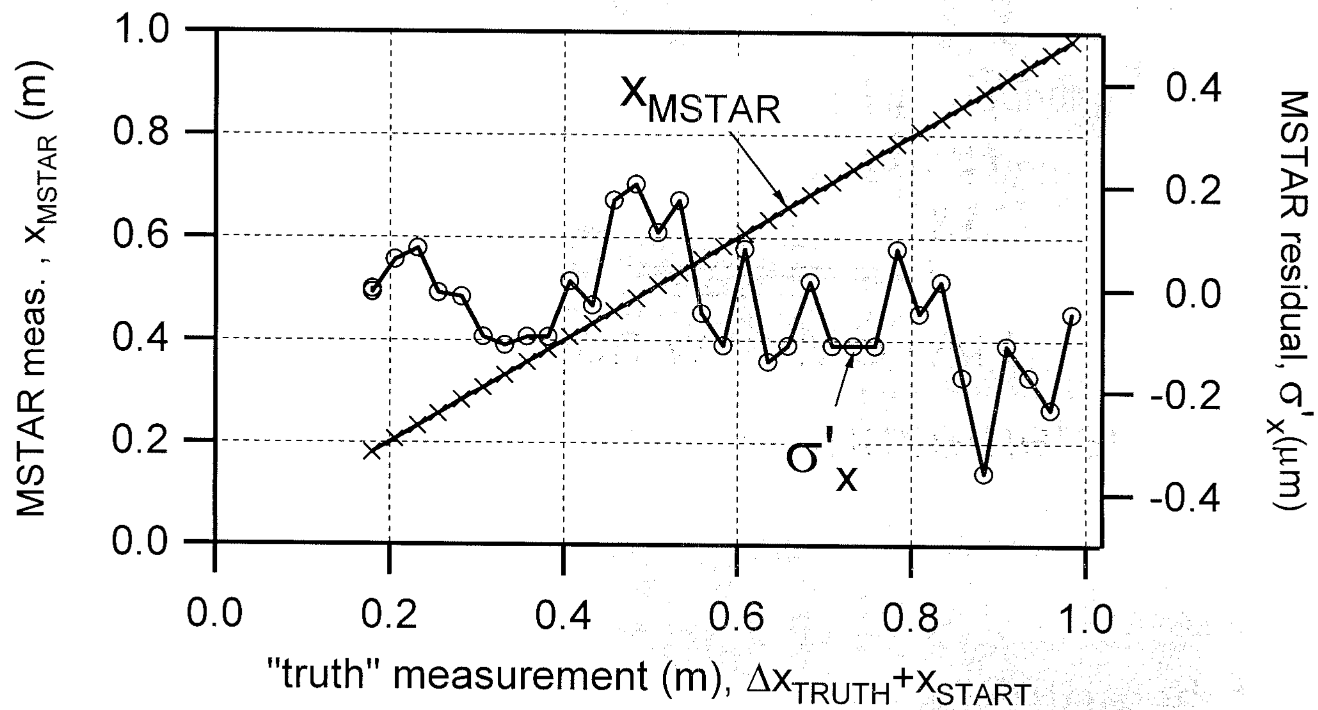


Displacement Test



- Measure absolute position with MSTAR
- Move target while tracking with phasemeter to measure displacement.
- Repeat many times.
- Plot MSTAR vs. phasemeter and calculate residual.
- Range tested from 0.2 m to 1 m.

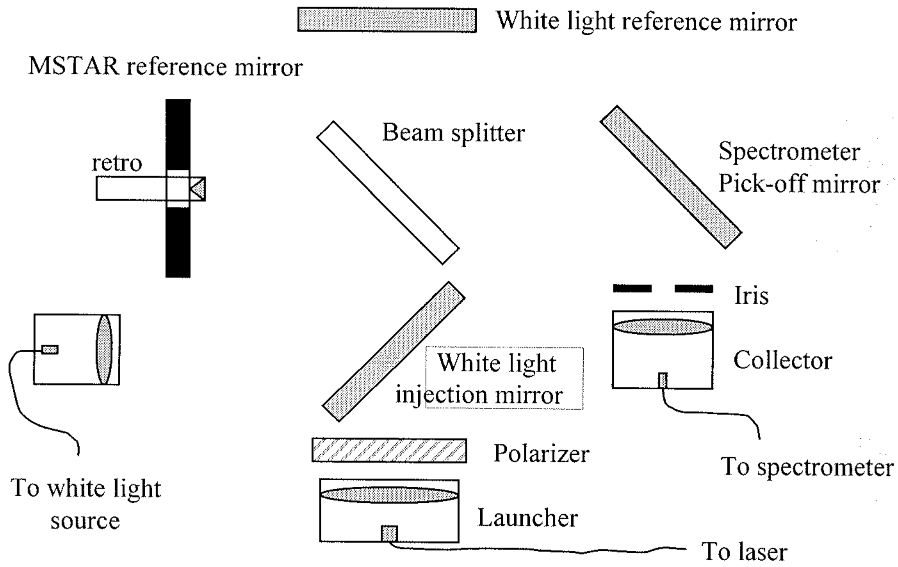
Displacement Results

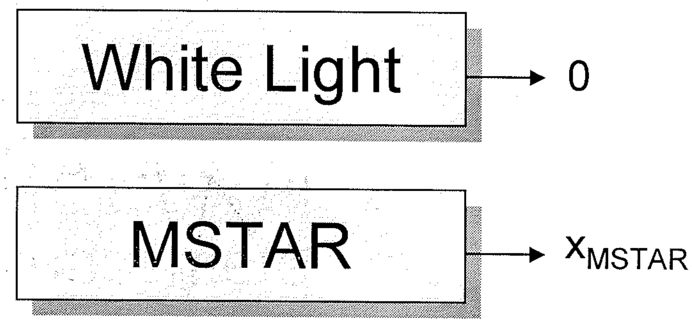


- Residual rms = 0.12 μm

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

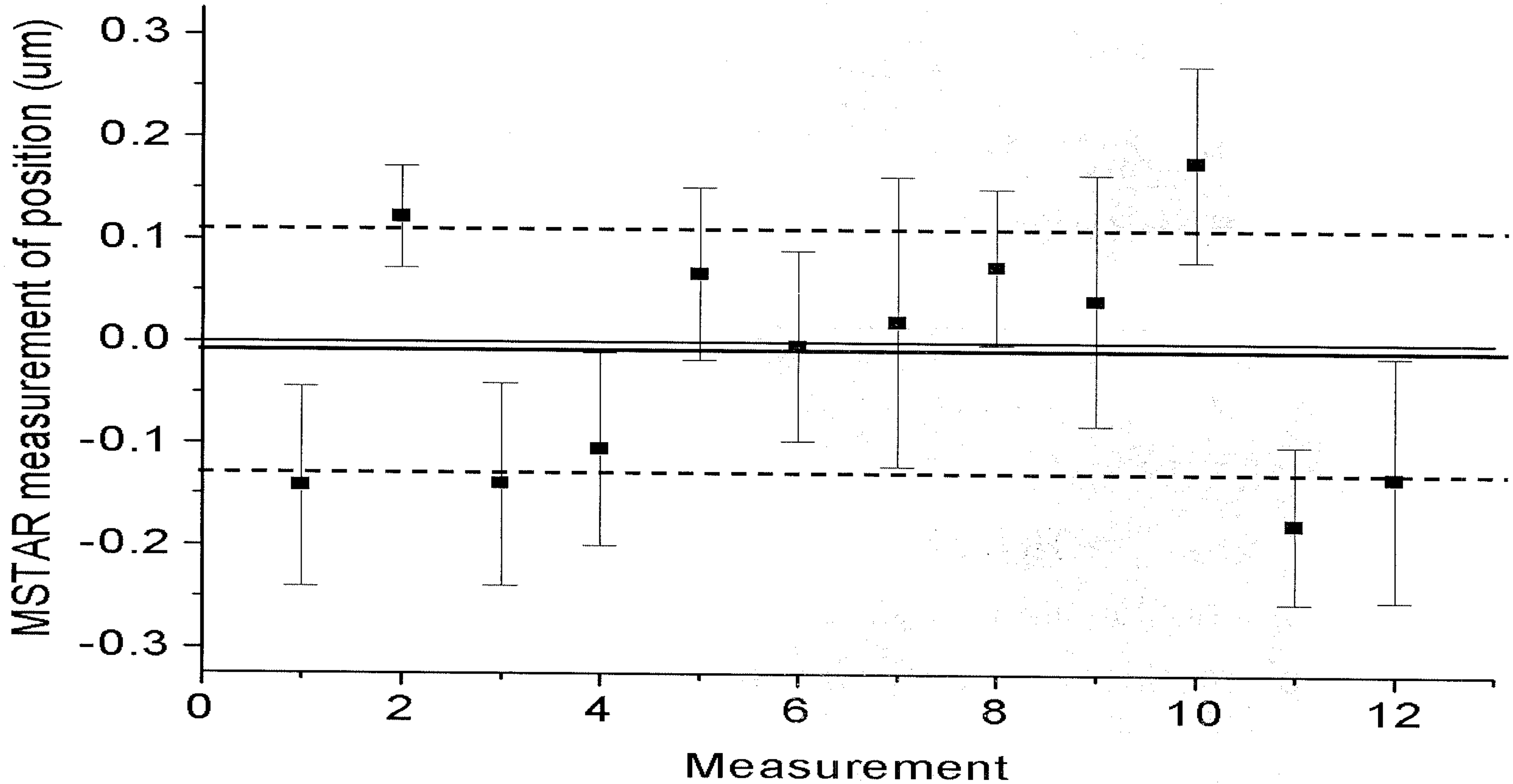
Zero Test





- Inject white light into last beam splitter of MSTAR
- Unblock white light reference mirror to make a Michelson interferometer.
- Adjust target retro to match the uncompensated spectrum from the MSTAR reference mirror
- Block or remove optics blocking MSTAR (in gray) and measure position
- Repeat many times.

Zero Results



- Zero set with white light between each point.
- Each point average of 5 measurements with standard deviation
- Mean value –0.01 um +/- 0.12 um

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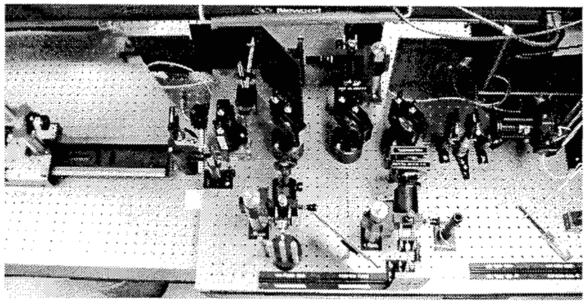
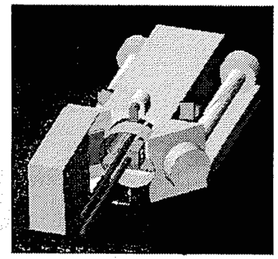
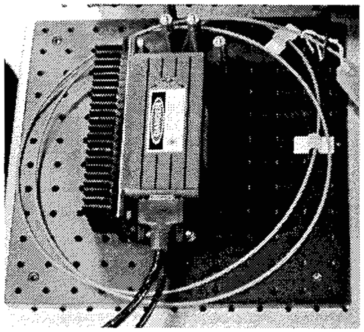
Miniaturization

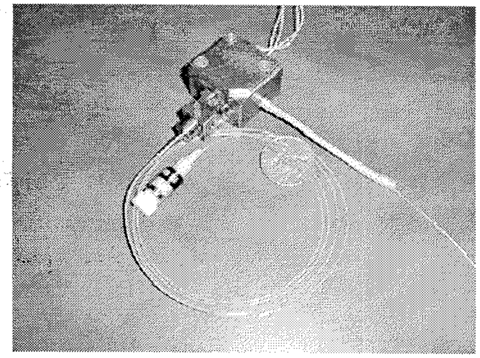


Lab breadboard to Space Interferometry Mission (SIM) type beam launcher

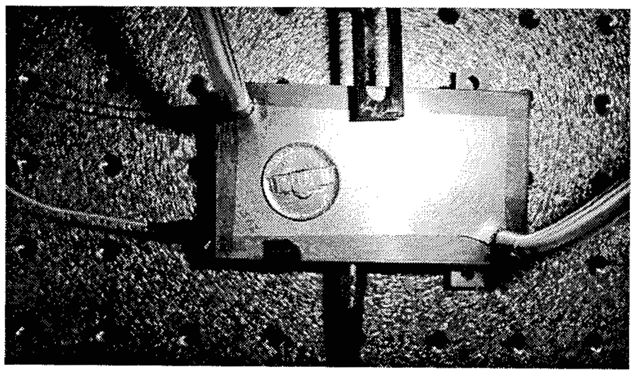




Commercial Nd:YAG laser to SIM/StarLight developed laser



Brassboard exists

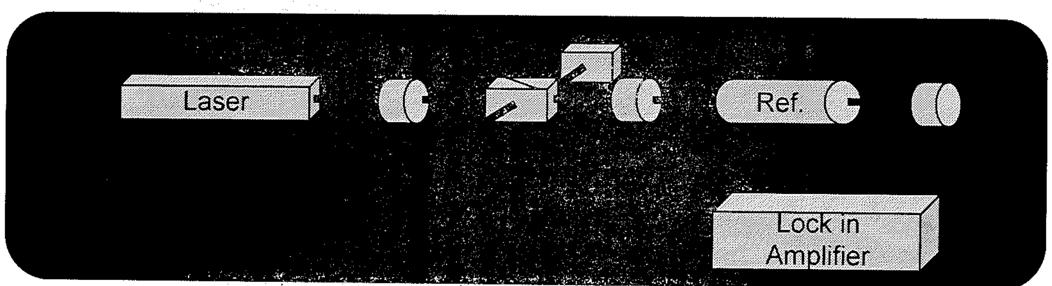


Experimental polymer 40GHz modulator to commercial telecom 40GHz modulator

Done

Frequency Stability

- Stability requirement given by σ_x/x
- Coarse (absolute) stage (e.g. σ_x= 0.1 um)
  - RF must be stable to resolve 100nm on course stage.
  - For 100m separation, fractional uncertainty is 10^{-9} (40Hz with 40GHz phase modulation)
  - Compact space-qualified rubidium and cesium references are commercially available for RF stabilization.
- Fine stage (σ_x=30 nm)
  - 30nm resolution over 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

- Can use Carrier-Aided Smoothing
  - First developed for Global Positioning Systems applications
- Carrier phase tracks the change in position over the measurement time relative to the start
- Carrier range vs. time is subtracted from sideband range
- Allows for longer integration time in the presence of moving targets
- Lab setup can track velocities up to 10 mm / s

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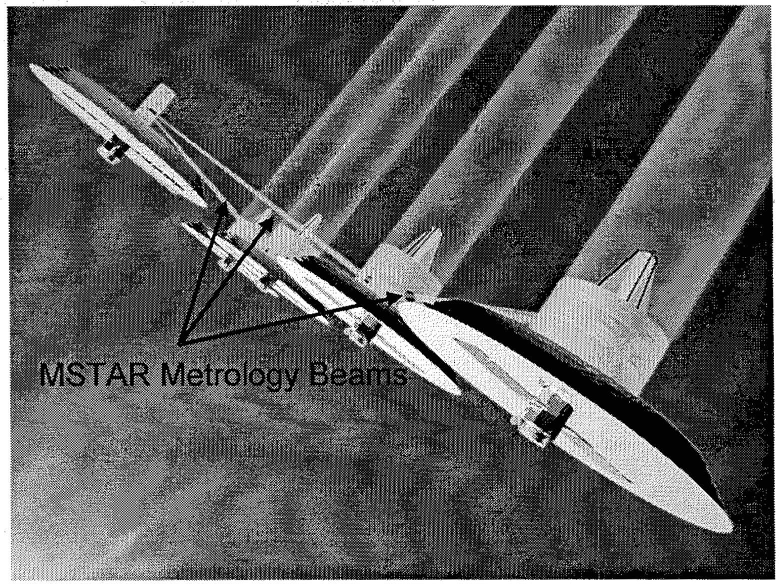
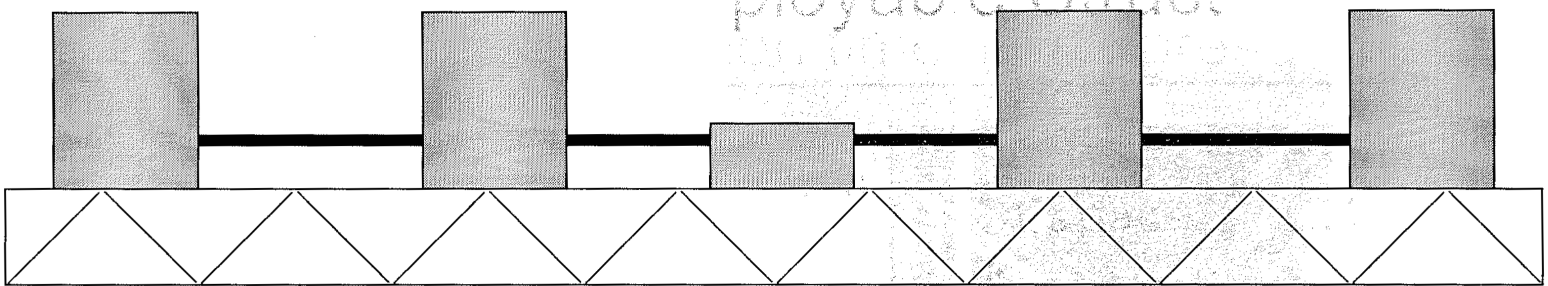
Distributed and Deployable Structures

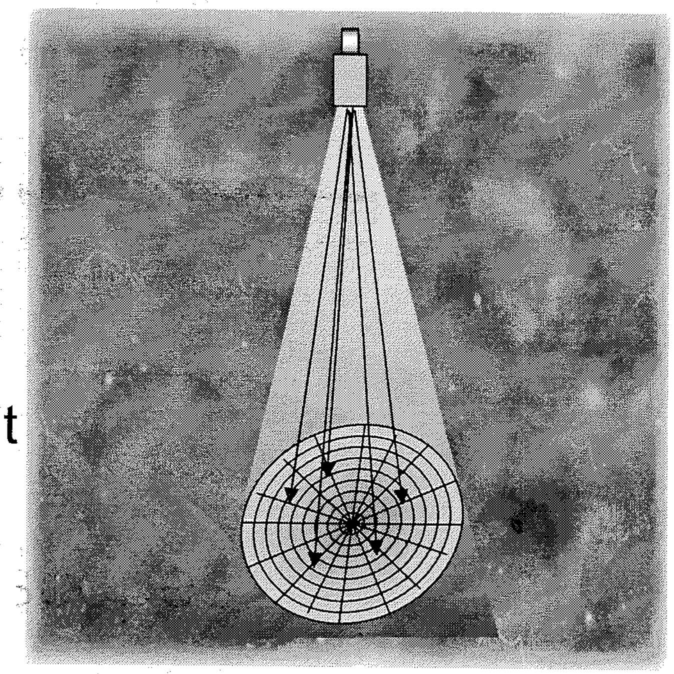
- Distributed Spacecraft Control
  - Track multiple targets with independent MSTAR sensors
  - Single MSTAR sensor may be switched to measure multiple targets.
- Optical Path Length Control
  - Does not need to be "homed"
  - Not affected by momentary beam interruptions





Large Aperture Telescopes

- Figuring large telescopes or antennas.
  - Accurate measurement of surface figure in flight
- One MSTAR sensor may be scanned to key locations
  - Periodic checking and adjustment
- Multiple MSTAR sensors may be used to monitor the figure
  - Real-time monitoring and adjustment

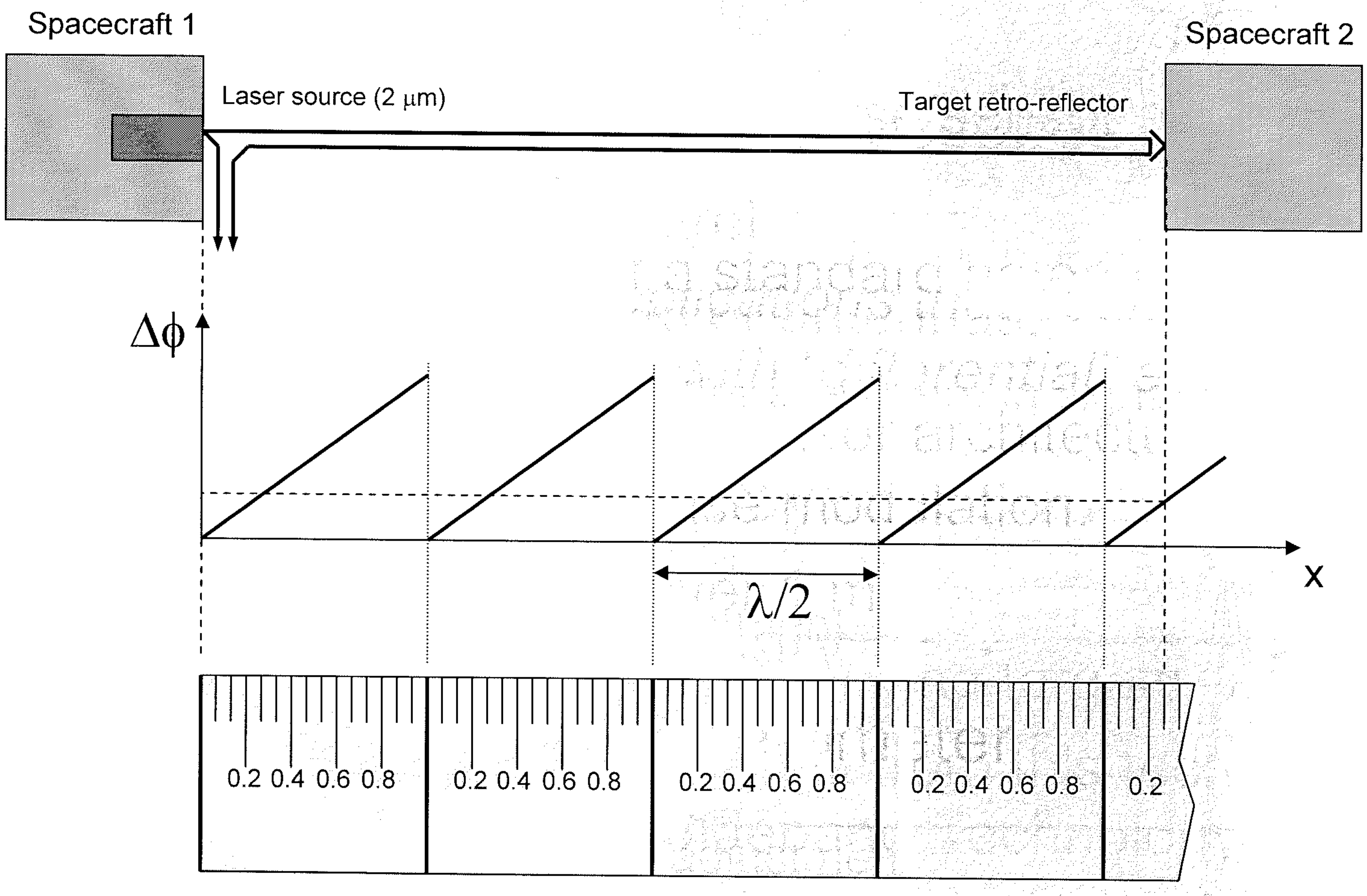


...And many more applications that could benefit from absolute metrology with "differential" accuracy...

Summary

- Our sensor: ***M**odulation **S**ideband **T**echnology for **A**bsolute **R**anging*
- Absolute range 100 nm on course sensor resolves fine sensor ambiguity
- Course gauge is part of a standard heterodyne metrology gauge
- Made possible by a novel sensor architecture and the availability of 40 GHz phase modulation.
- Verified experimentally over 1 m
- Scaleable to large distance / moving targets
- Many applications could benefit from this technology.

Laser Interferometer



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)
- 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).

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

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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