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

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Outline

- Motivation and what MSTAR does.
  - Mission example and MSTAR's role
  - How MSTAR is different from 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
• Large space-based distributed optical systems (TPF, DARWIN)
• Nanometer-class accuracy
• Range of many meters
• *Modulation Sideband Technology* for *Absolute Ranging*
Main Technology Issue

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

- Coarse scale:
  - 10 \( \mu m \) ranging accuracy (1 \( \sigma \))

before MSTAR

\[ \ldots, \ldots, \ldots, 351 \, \mu m \]

\[ + \]

\[ 120,583,6\ldots\ldots \, \mu m \]

\[ = \]

\[ 120,583,6\ldots\ldots 351 \, \mu m \] useless

- The 10 \( \mu m \) ranging accuracy of the existing coarse scale gauges is not sufficient to resolve the ambiguity of the existing fine scale gauges.
• Fine scale:
  • precise (nm)
  • but ambiguous

MSTAR laser interferometer

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

MSTAR coarse stage

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

120,583,627.3?? μm

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

120,583,627.351 μm
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.
- 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

Modulation

Laser
\( \lambda = 1319 \text{ nm} \)

Phase modulators

Optics & target

Verification

Photodetectors

Acquisition & processing

MSTAR ICSO 04
Lab set-up
- 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!*

MSTAR ICSO 04
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 $-0.01\ \text{um} \pm 0.12\ \text{um}$
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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 $\sigma_x/x$
- Coarse (absolute) stage (e.g. $\sigma_x = 0.1$ 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 ($\sigma_x = 30$ nm)
  - 30nm resolution over 100m requires a fractional uncertainty $3 \times 10^{-10}$ (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: **Modulation Sideband Technology for Absolute Ranging**
- 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

Spacecraft 1

Laser source (2 \( \mu \)m)

Spacecraft 2

Target retro-reflector

\[ \Delta \phi \]

\[ \frac{\lambda}{2} \]

MSTAR ICSO 04
Carrier-Aided Smoothing


- Down-converted Doppler shifted frequency, \( f = \frac{2 \cdot v}{\lambda} \) where \( v \) = target velocity and \( \lambda \) = laser frequency.

- Limiting factor is bandwidth of filters around down-converted sidebands. (e.g. 15kHz of Doppler shift with \( \lambda = 1319 \) nm => \( v = 1.3 \) mm/s)
S. Dubovitsky and Oliver P. Lay, “MSTAR: A high precision laser range sensor,” NASA patent pending