Metrology for space-based science missions

Oliver Lay, Serge Dubovitsky, Robert Peters

Jet Propulsion Laboratory

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Outline

- Survey of current and future science missions
- Design issues
- The Space Interferometry Mission
- Terrestrial Planet Finder mission
- The MSTAR absolute metrology system
Already launched

2000

Shuttle Radar Topography Mission

GRACE

‘Near’ future

2010

Space Interferometry Mission

James Webb Space Telescope
Further out

2015

LISA

Darwin

Terrestrial Planet Finder

2020

GAIA

Terrestrial Planet Finder

2025

MAXIM Pathfinder

Stellar Imager

SPECS
Trends

- Increasing sensitivity to faint objects
  - Push to larger collecting areas
  - Deployable optics
- Increasing angular resolution
  - Larger apertures and baselines
  - Formation flying
- Higher dynamic range for imaging
  - Better control of optical surfaces

Need for increasingly sophisticated metrology systems

Issues for metrology designers

- Operate without intervention for 5 - 10 years
- Mass, power, volume are valuable commodities
- Survive launch environment
- Resistant to radiation damage
- Materials must be carefully selected
- Long-term design process
Space Interferometry Mission (SIM)

- **Key science goals:**
  - Measure star positions to ~ 4 microarcseconds (20 prad)
  - Changes in position to ~ 1 μas
  - Detect terrestrial planets down to 3 Earth masses (wobble)
  - Distance measurements to X%
SIM Principle of Operation

\[
\sin \Delta \theta = \frac{D_2 - D_1}{B}
\]

1 μas uncert => \( \delta D \sim 50 \) pm

- Key parameters:
  - 9 m baseline
  - visible light
  - 2011 launch
  - Cost ~ $1 billion
  - 5 year mission
SIM design

- 11 metrology gauges
- 50 pm precision
- Metrology budget ~ $100M
- 5 – 10 year mission
- Performance demonstrated in series of testbeds
Terrestrial Planet Finder Interferometer

- Primary science goal: directly detect & characterize the spectrum of earth-like planets in the mid-infrared

- Challenges:
  - Sun-Earth @ 10 pc

  Subtended angle ~ 0.1 arcsec (0.5 µrad)

  Very faint signal

  Contrast ratio @ 10 µm ~ 10^7

 Formation-flying interferometry

Large collecting area
4 x 4 m diameter => ~ 1 photon / s

Nulling interferometry
Nulling interferometry

Challenge: variations in the path lengths lead to time-variable star leakage that swamps planet signal
- Must match and stabilize the paths to within ~ 1 nm
Matching the paths

- 1 nm path matching is the biggest challenge
- Combination of fringe tracking & laser metrology, with calibration
- Brief description of fringe tracking
- Planet Detection Testbed
MSTAR
Modulation Sideband Technology for Absolute Ranging

- A laser range sensor capable of nanometer accuracy over multi-km range
- Funded by Cross-Enterprise NRA to meet the future needs of large space-based distributed optical systems
- Key challenge: resolving the integer optical cycle ambiguity
Integer cycle ambiguity: unresolved

The few micron ranging accuracy of existing coarse scale sensors is not sufficient to resolve the ambiguity of optical phase measurements.
Integer cycle ambiguity: resolved

Key technical challenge

- The 0.1 μm MSTAR coarse stage ranging accuracy is sufficient to resolve the ambiguity of the fine scale gauge
- MSTAR integrates both fine and coarse sensors to enable nm accuracy
MSTAR concept

- Multi-color measurement scheme
- Colors generated by 40 GHz phase modulation of a single laser
- Synthetic wavelength 3.75 mm (first sidebands)
- Optical phase measurement accuracy of 0.3 mrad (1/20,000 cycle)
- Optical demodulation scheme allows use of slow detector and electronics (200 kHz)
- Switchable modulation frequency to extend unambiguous range of measurement to many meters
Lab set-up
Experimental Results

- Meets requirement for coarse scale
- Sufficient to resolve integer number of optical wavelengths

RMS Error 0.13 µm
Space Technology 9

- The NASA Space Technology series of missions are for demonstrating new technology
- Precision Formation Flying is being considered for Space Technology 9 (nominal launch 2010)
- MSTAR proposed to demonstrate laser ranging between spacecraft at up to 1 km separation

Other MSTAR applications

- Not just for space
- A tool for convenient measurement of length much more accurately than previously possible
- Seeking other uses
Summary

- Sensitivity & resolution => large, distributed optical systems
  - Formation flying
  - Deployable optics

- Laser metrology and active control will provide the extreme ‘stiffness’ and precision

- Metrology is central to the quest for finding earth-like planets

- Will be great demand for new metrology ideas

- Motivated MSTAR
Back up
Phase modulators

- 40 GHz modulators were not commercially available when we started
- Polymer-based modulators were designed for MSTAR, leveraging technology funded by DARPA and AFOSR at USC and UCLA

USC

- Commercial Lithium Niobate devices recently became available, and are implemented in the current set-up
MSTAR schematic

Laser
\[ \lambda = 1319 \text{ nm} \]

Modulation

Optics & target

Verification

Photodetectors

Acquisition & processing
Other Features

- **Longer synthetic wavelength**
  - Switch to much lower modulation frequency to extend ambiguity range
  - e.g. 30 MHz extends ambiguity range to 2.5 m

- **Longer range operation**
  - No major obstacles to ranging over hundreds of meters
  - Requires locking laser and modulation frequency to accurate standards
    - e.g. for 10 nm @ 100 m requires $\frac{\Delta \lambda}{\lambda} < 10^{-10}$ and $\frac{\Delta F_M}{F_M} < 10^{-9}$
    - Well within state-of-the-art

- **Miniaturization**
Optics schematic: data acquisition

- Sampled at 500 kHz
- Phase resolution of 0.3 milliradians achieved
- Other optical configurations possible

Nd:YAG laser

$\lambda = 1300 \text{ nm}$

$f_m = 40.090 \text{ MHz} \quad F_m = 40.000 \ 040 \text{ GHz}$

Frequency shifter

Phase Modulator

Measurement

Target retro-reflector

Reference mirror

Measurement beamsplitter

Local beamsplitter

Detector mirror

Target Photodetector

Computer

A/D
Iodine locking system

- Modulation transfer spectroscopy (MTS) method for Doppler free locking.
- Commercially available from Innolight with $10^{-13}$ fractional stability
Existing state of the art ~ 10 µm

- **2-color metrology, using two or more lasers**
  - Synthetic wavelength \( (\nu_1 - \nu_2) / c \)
  - Extends unambiguous range
  - Limited by laser frequency stability

- **RF modulation of an optical carrier**
  - Requires high frequency detection and processing

- **MSTAR** is a hybrid
  - Implements 2-color metrology with RF phase modulation of a single laser
MSTAR Sensor Concept

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

- *Electrical spectrum* is filtered to isolate beats resulting from desired *optical sidebands*
MSTAR Sensor Concept

- Lithium Niobate modulators @ 40 GHz
- Synthetic wavelength = 3.75 mm
- 0.1 µm accuracy requires phase accuracy of 0.3 milliradians (1/20,000 cycle)
- Need a very clean optical and signal processing system
- Do not require high-speed detectors and signal processing
To do

- Summary
- SIM distance precision