National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Metrology for space-based science missions

Oliver Lay, Serge Dubovitsky, Robert Peters

Jet Propulsion Laboratory

ASPE Summer Topical Meeting
7/20/2005

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

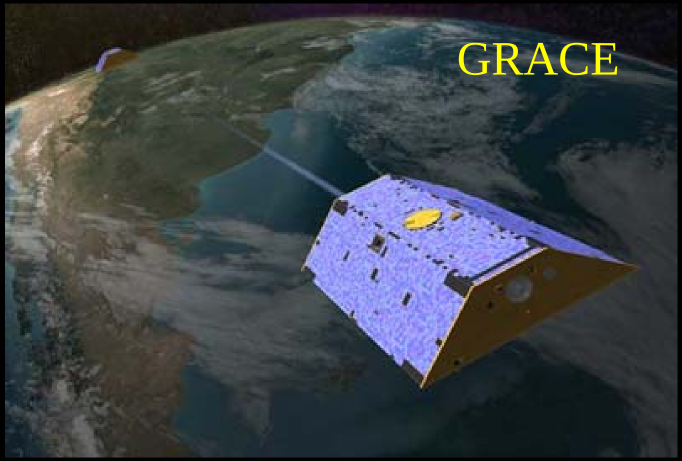
‘Near’ future

2000

2010

Shuttle Radar Topography Mission

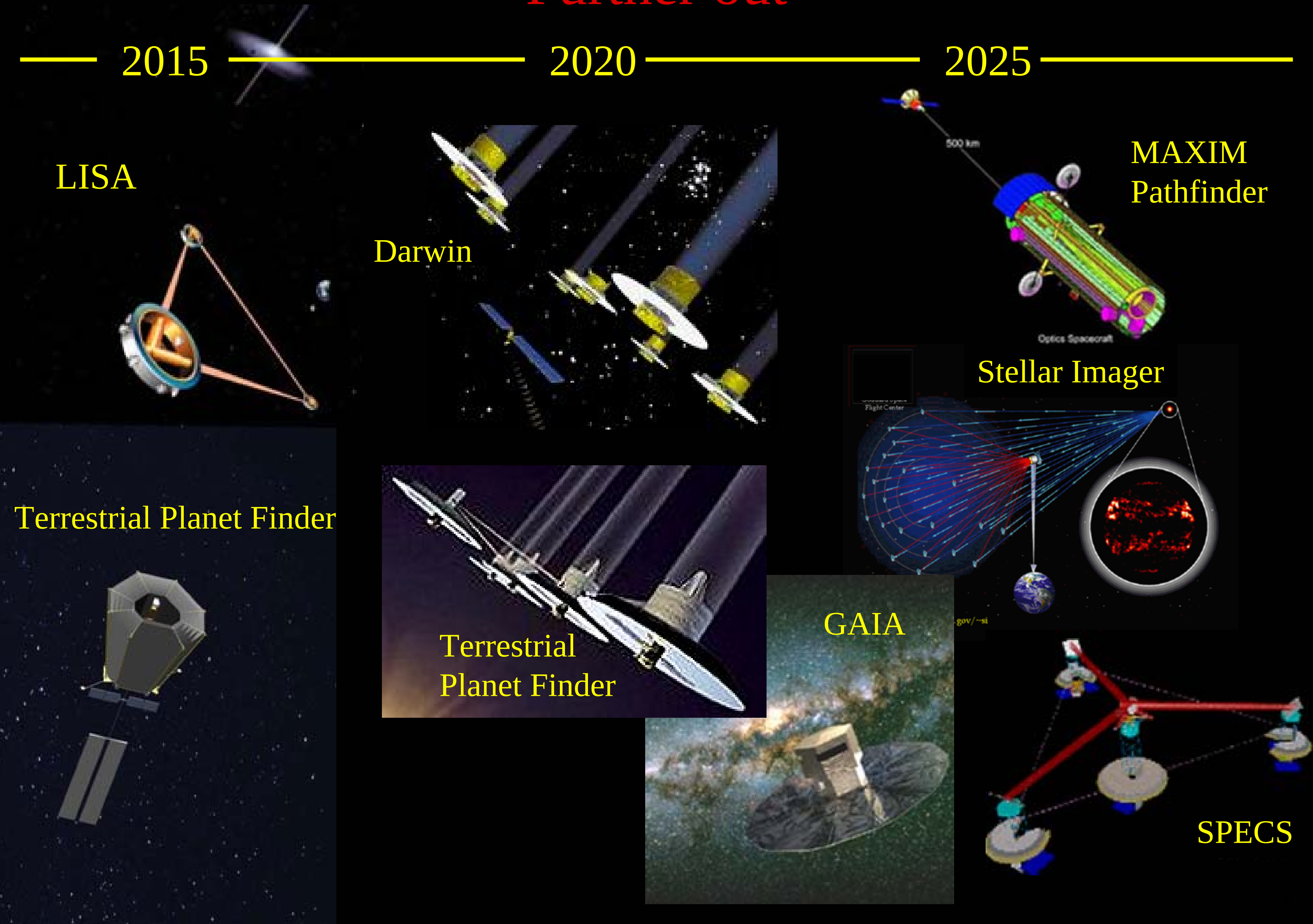
GRACE



Space Interferometry Mission

James Webb Space Telescope

Further out


2015
2020
2025
LISA
Darwin
MAXIM
Pathfinder
500 km
Optics Spacecraft
Stellar Imager
Terrestrial Planet Finder
Terrestrial
Planet Finder
GAIA
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

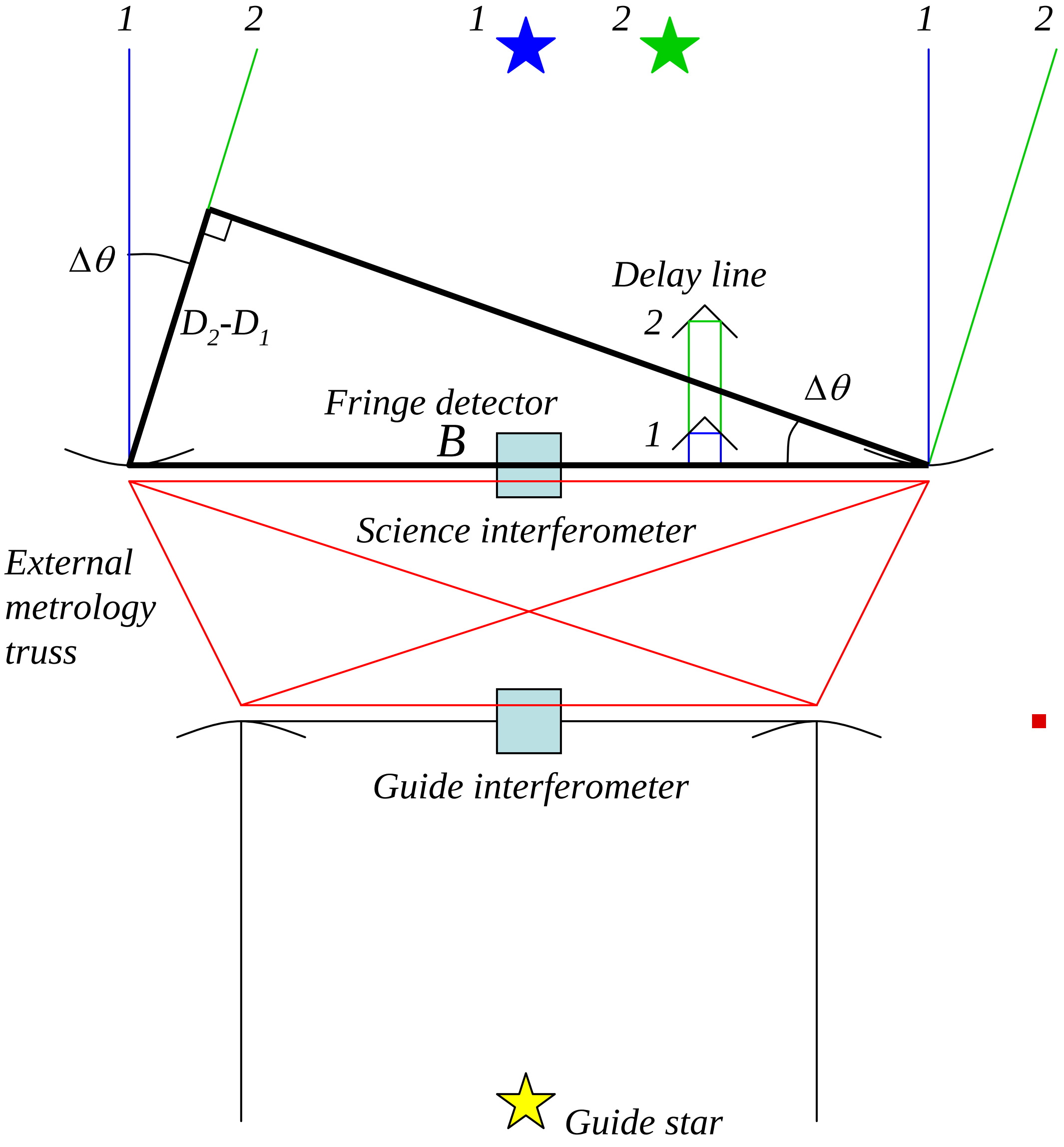
Issues for metrology designers

- 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

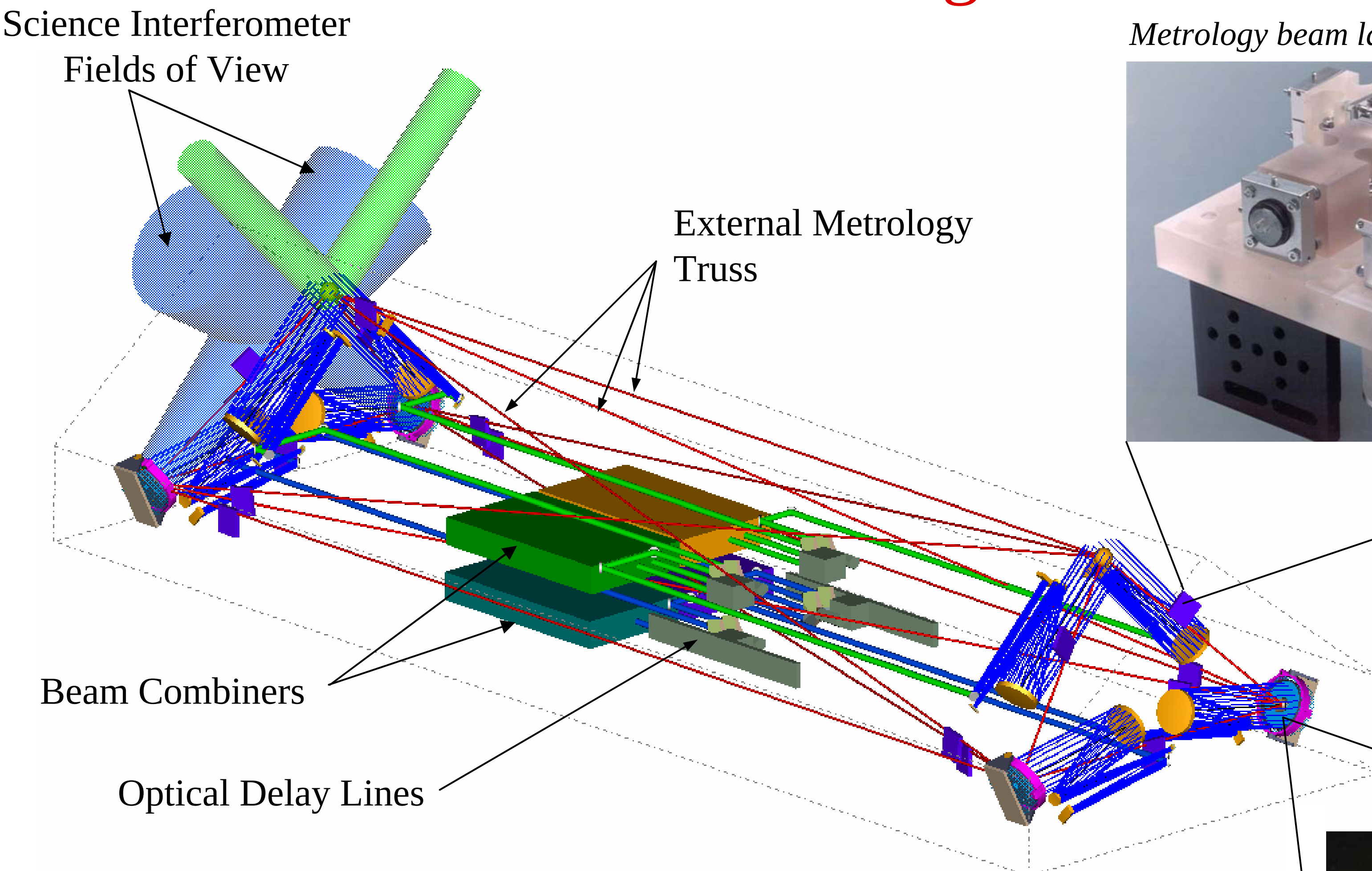


$$\sin \Delta\theta = \frac{D_2 - D_1}{B}$$

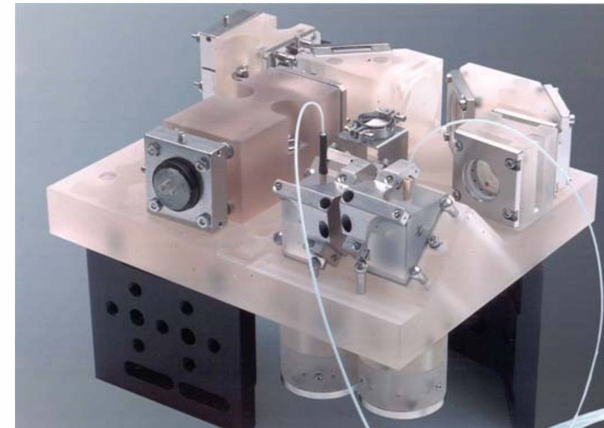
1 μas uncert => δD ~ 50 pm

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

SIM design



Metrology beam launcher (x15)



Double & triple corner cubes (x6)

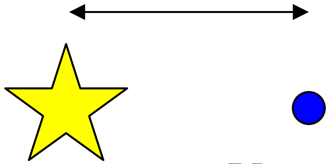
- 11 metrology gauges
- 50 pm precision
- Metrology budget ~ $100M

- 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)

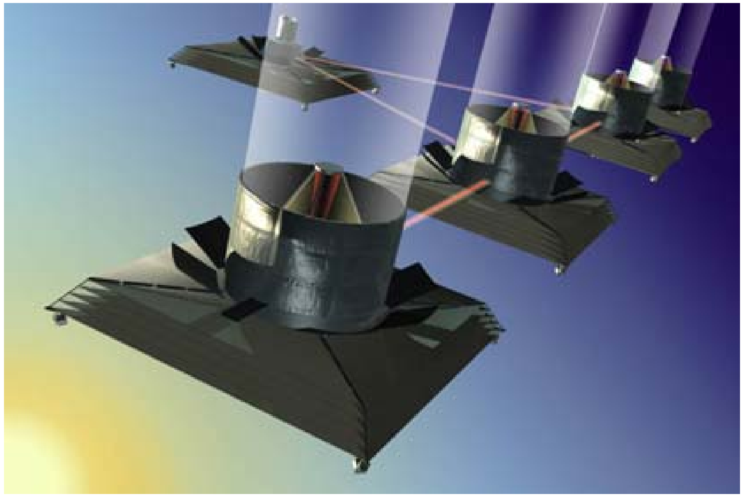


Very faint signal

Contrast ratio @ 10 μm ~ 10^7

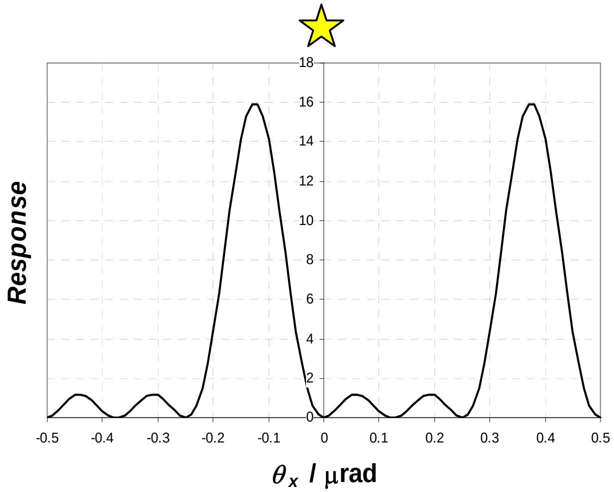
Nulling interferometry

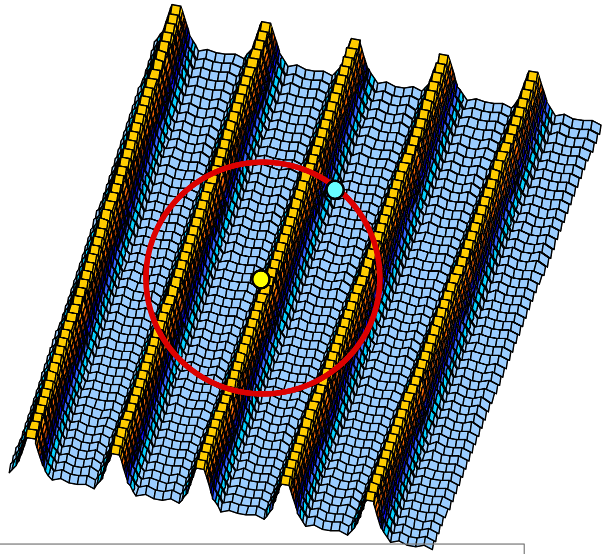
Formation-flying interferometry

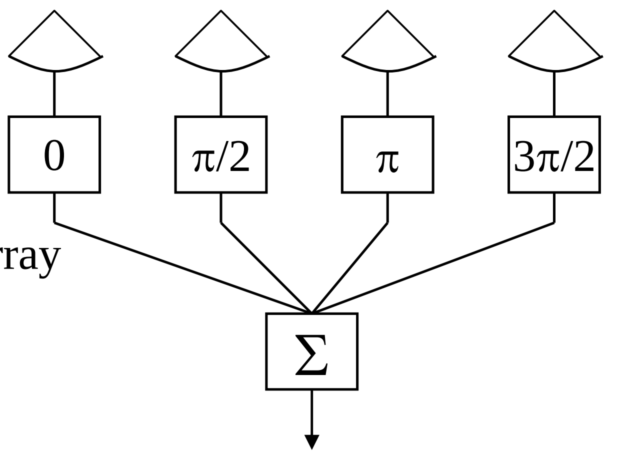


Large collecting area
4 x 4 m diameter => ~ 1 photon / s

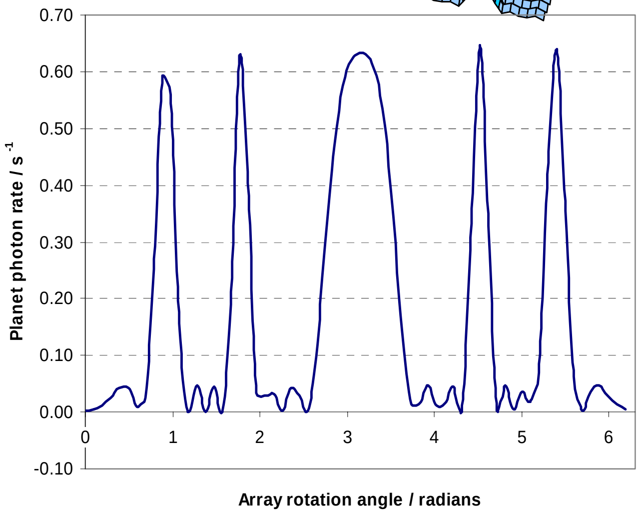
Nulling interferometry







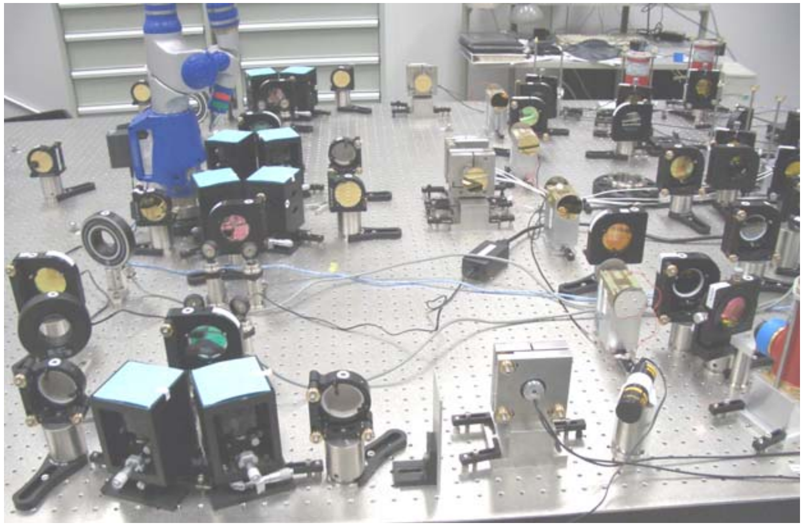
Optical phased array



- 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



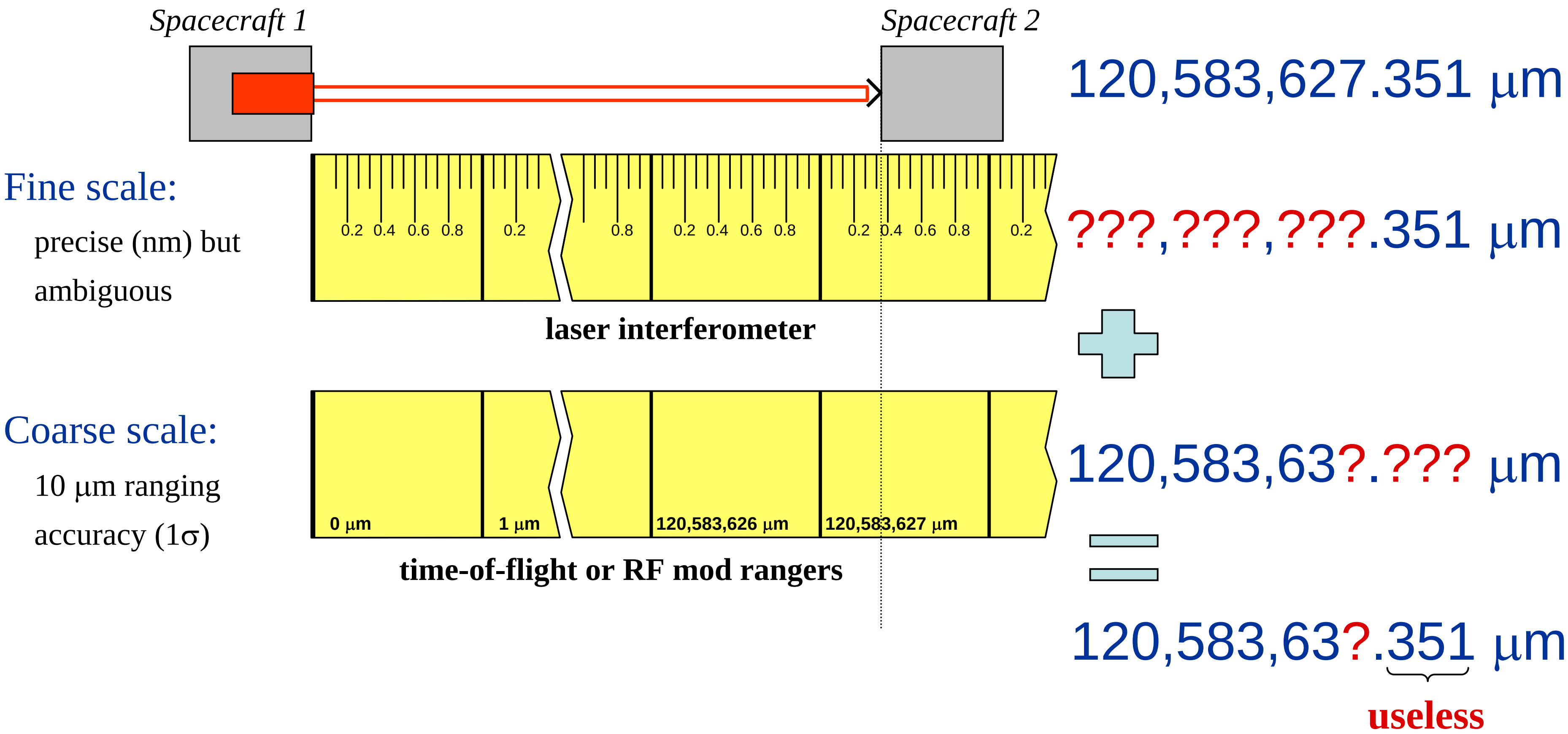
MSTAR

Modulation **S**ideband **T**echnology for **A**bsolute **R**anging

- 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

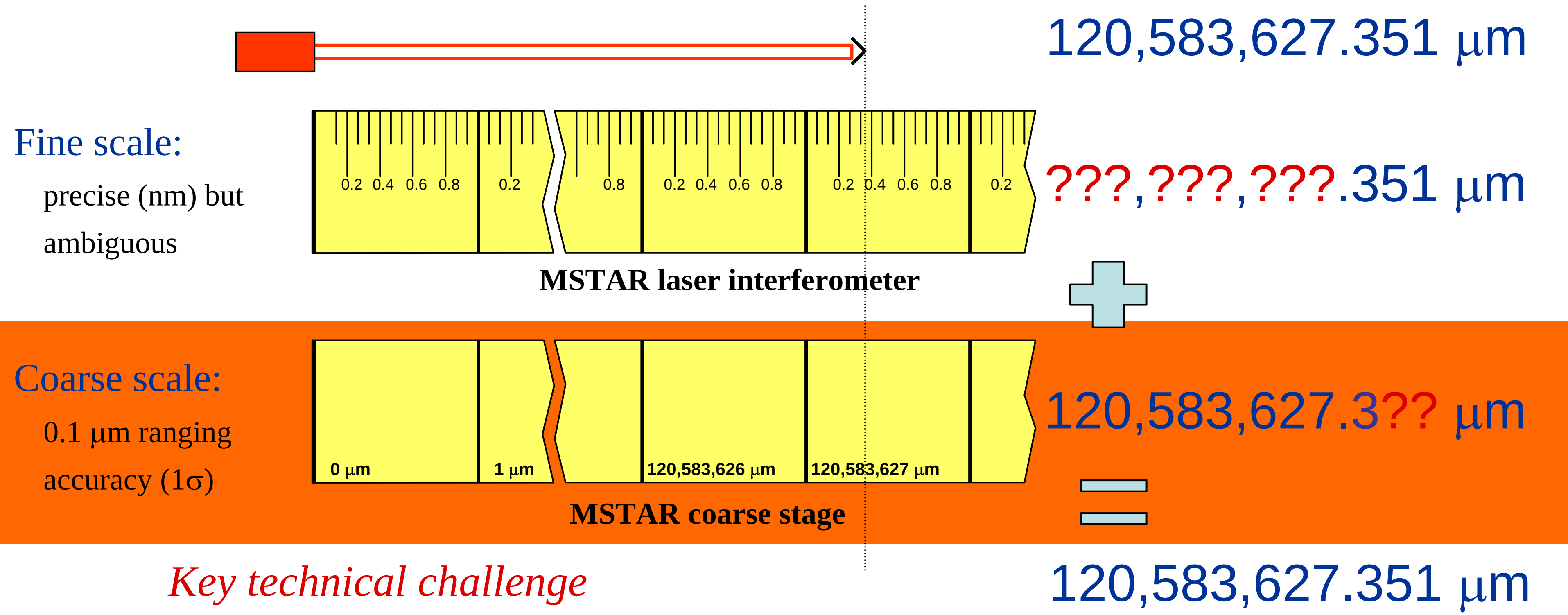
- Key challenge: resolving the integer optical cycle ambiguity

Integer cycle ambiguity: unresolved



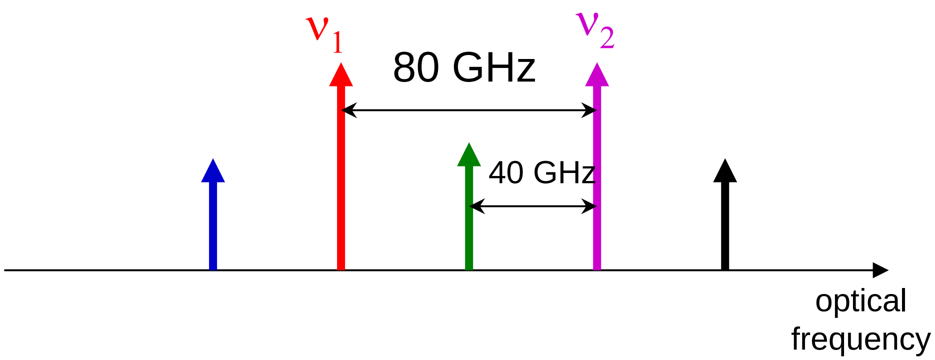
- The few micron ranging accuracy of existing coarse scale sensors is not sufficient to resolve the ambiguity of optical phase measurements

Integer cycle ambiguity: resolved



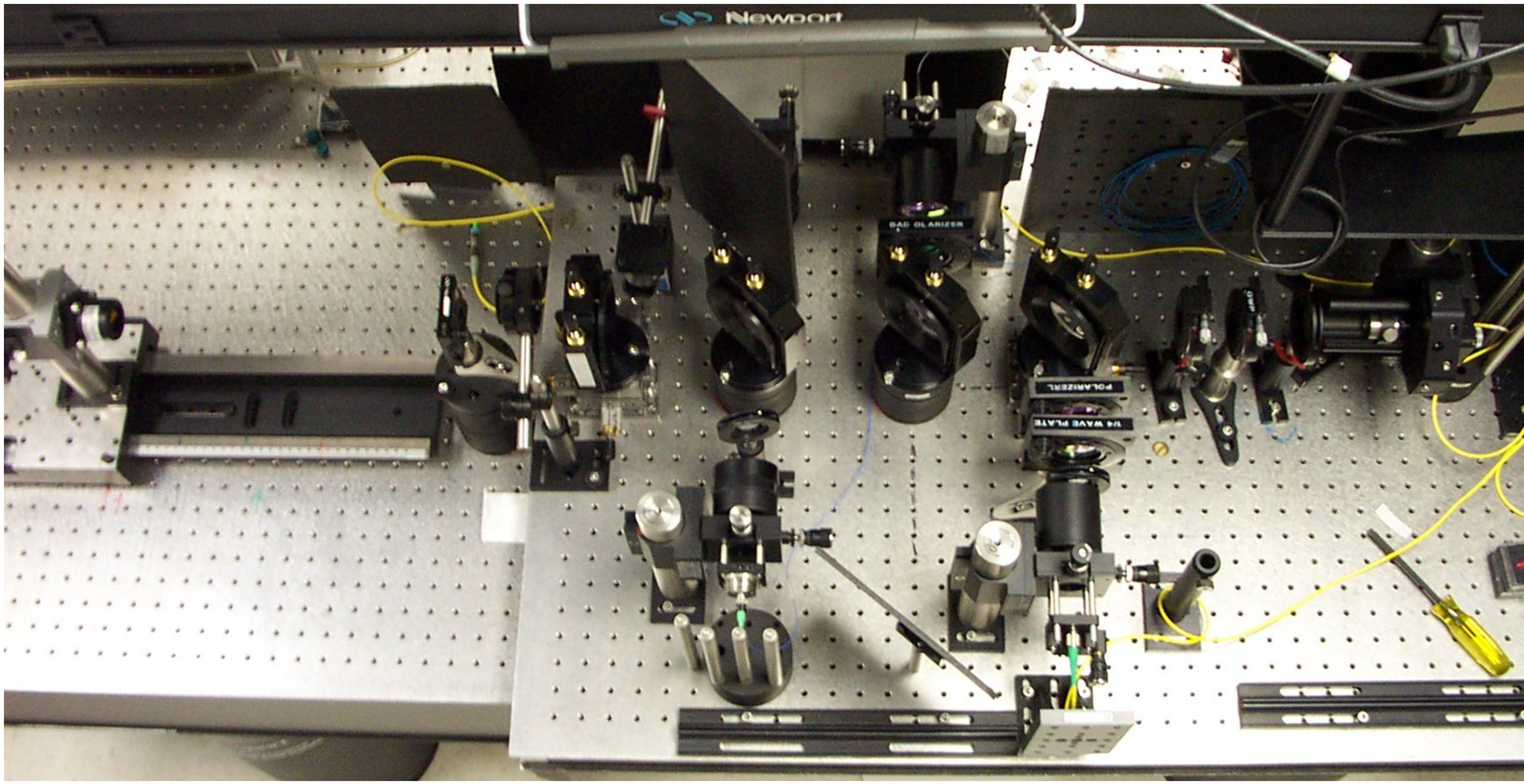
- The 0.1 µm MSTAR coarse stage ranging accuracy is sufficient to resolve the ambiguity of the fine scale gauge
- MSTAR integrates both fine and coarse sensors to enable nm accuracy

MSTAR concept

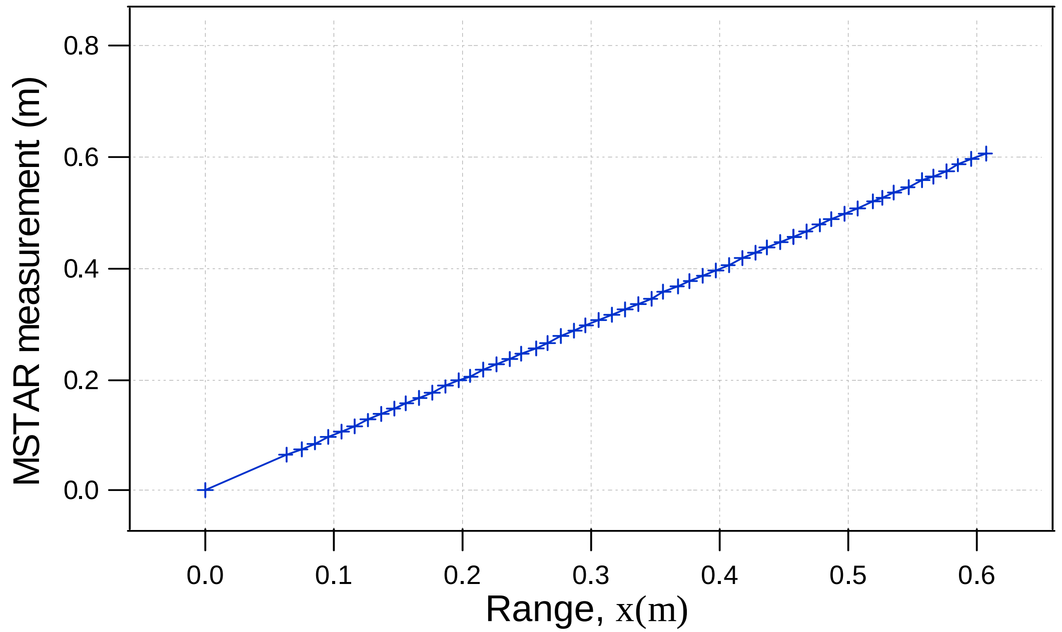


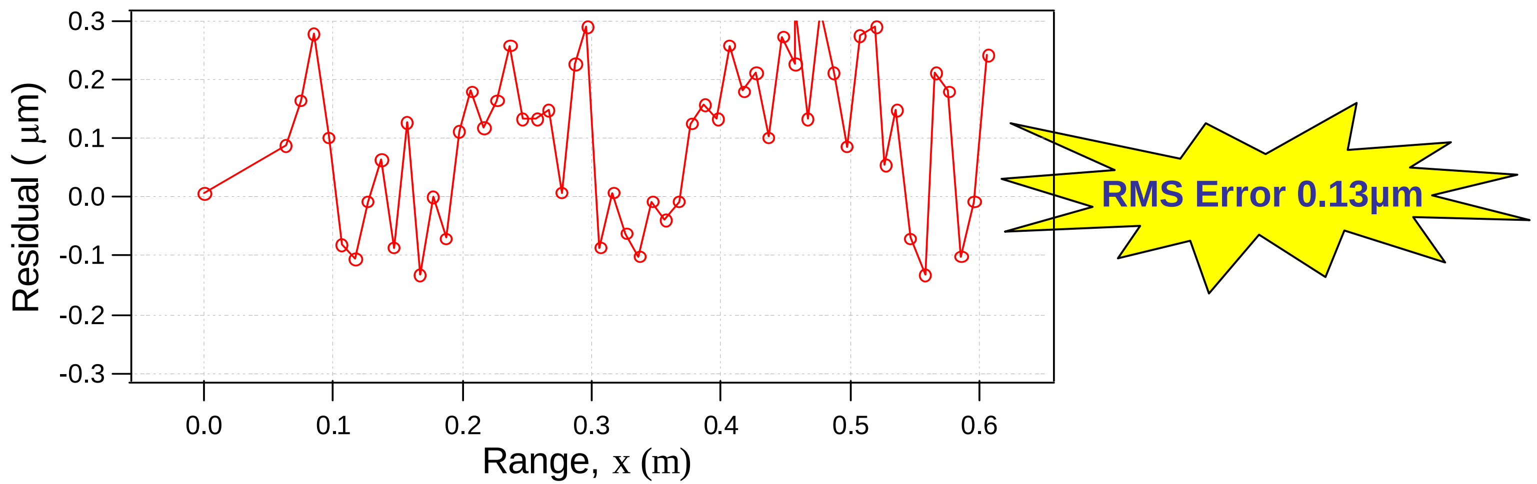
- Multi-color measurement scheme
- Colors generated by 40 GHz phase modulation of a single laser
- Synthetic wavelength 3.75 mm (first sidebands)
- Optical phase measurement accuracy of 0.3 mrad (1/20,000 cycle)
- Optical demodulation scheme allows use of slow detector and electronics (200 kHz)
- Switchable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

Lab set-up



Experimental Results



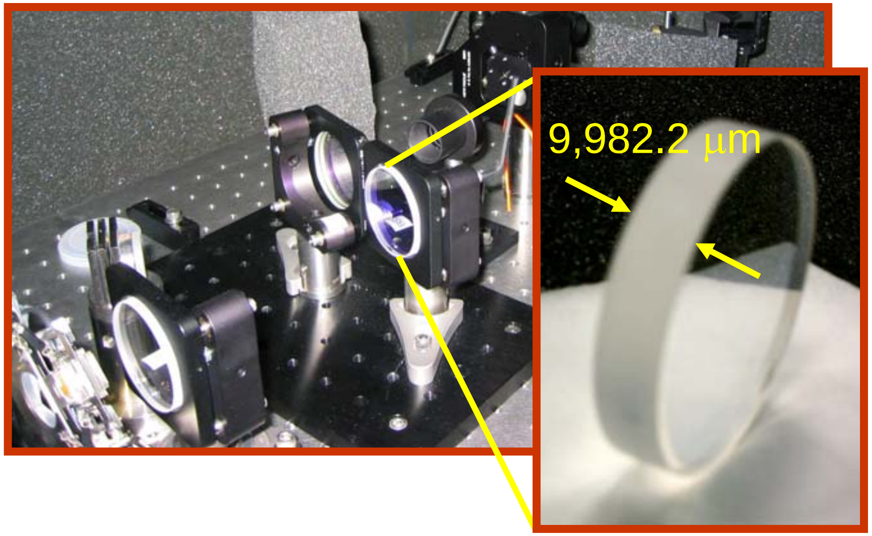


- Meets requirement for coarse scale
- Sufficient to resolve integer number of optical wavelengths

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

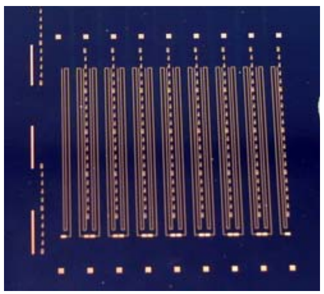
- Motivated MSTAR

Back up

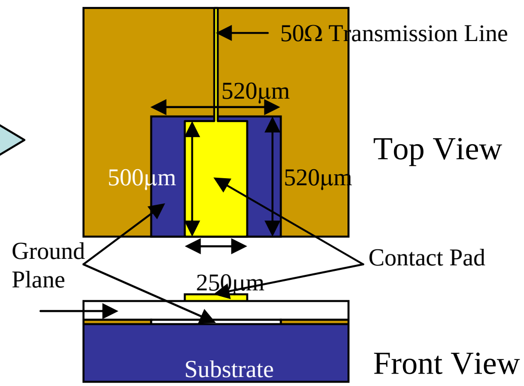
Phase modulators

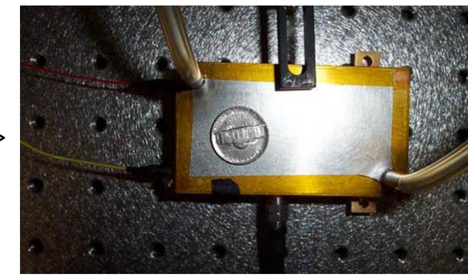
- 40 GHz modulators were not commercially available when we started
- Polymer-based modulators were designed for MSTAR, leveraging technology funded by DARPA and AFOSR at USC and UCLA

USC



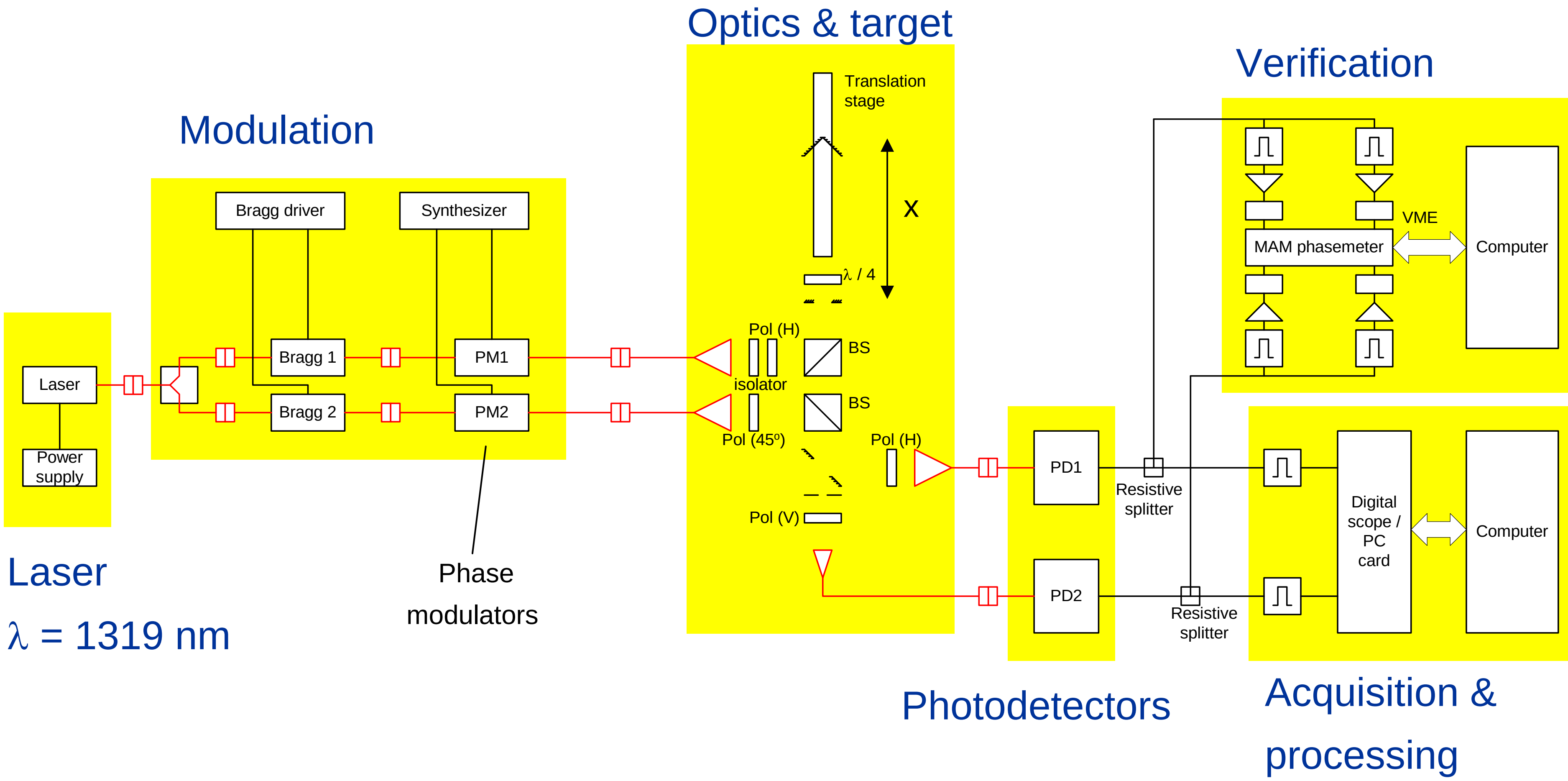
Pacific Wave





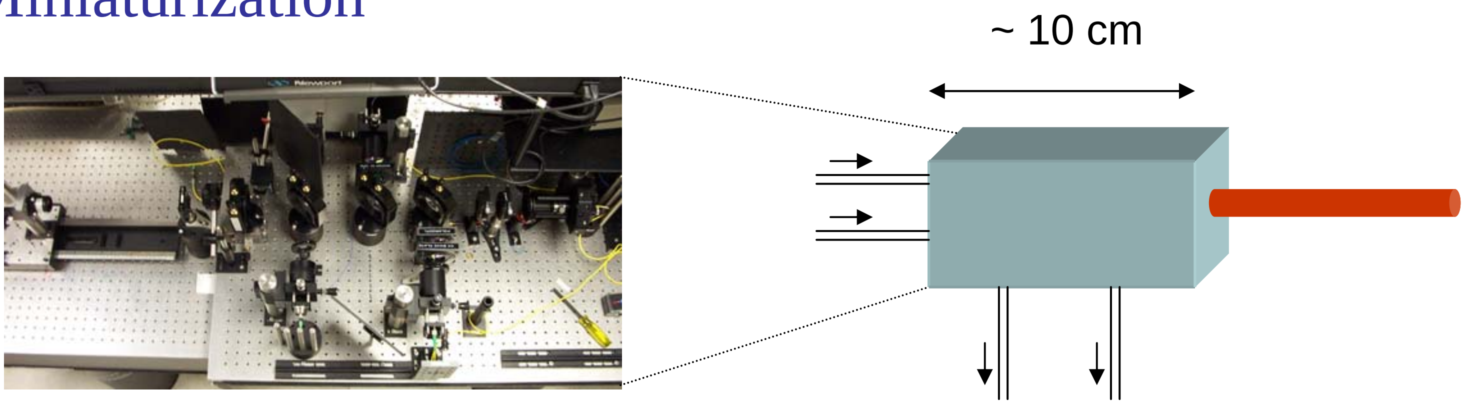
- Commercial Lithium Niobate devices recently became available, and are implemented in the current set-up

MSTAR schematic

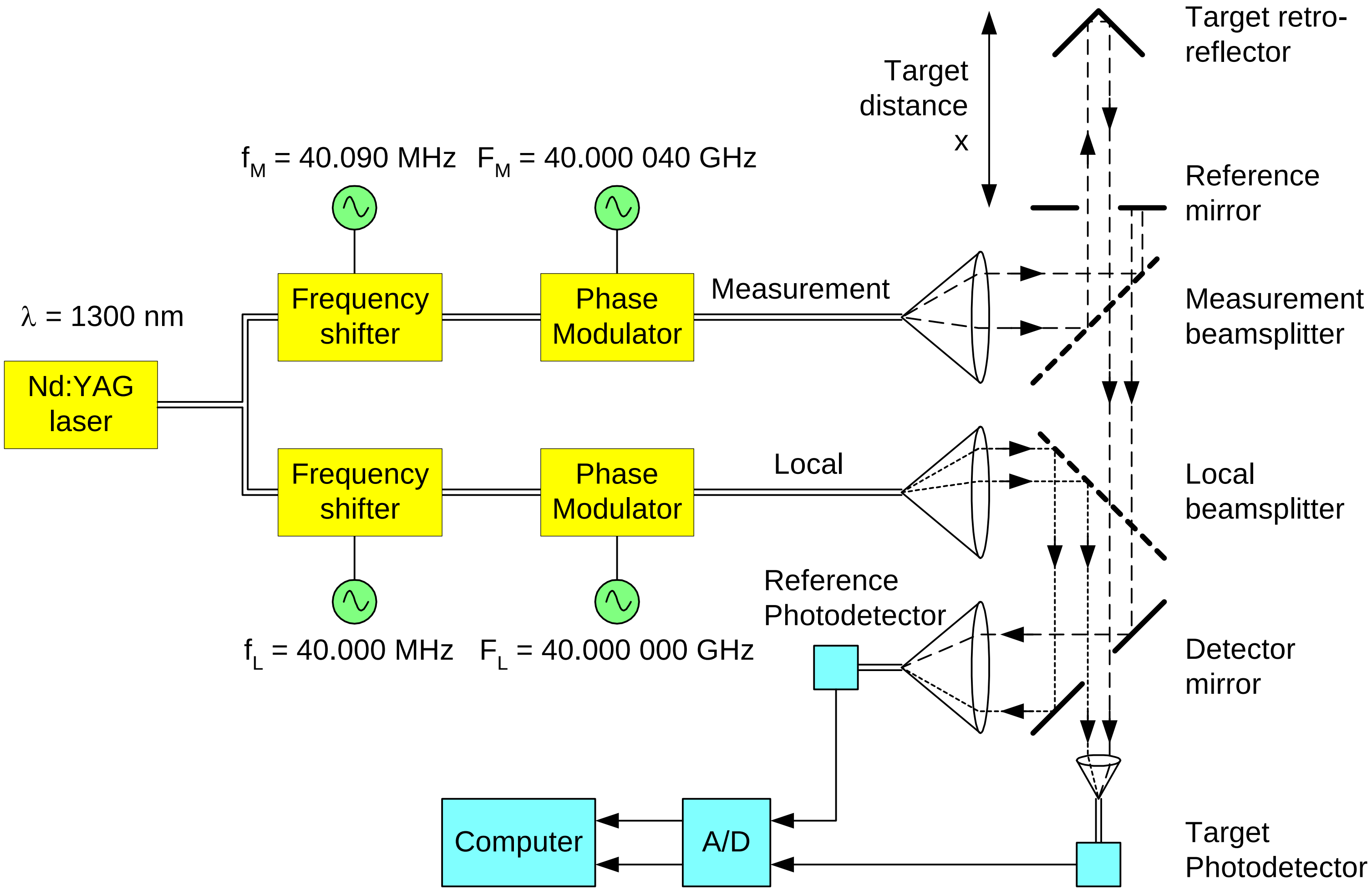


Other Features

- 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



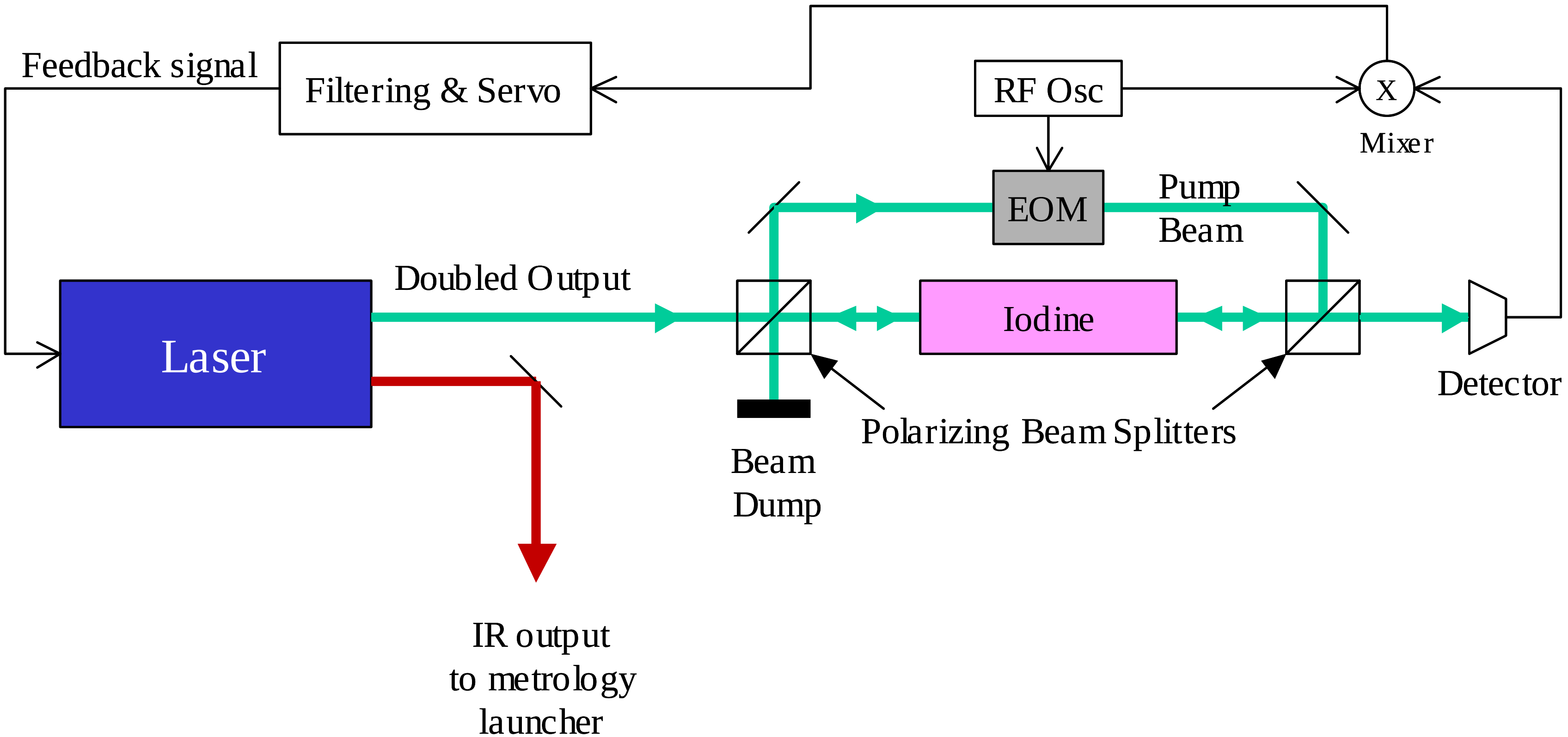
Optics schematic: data acquisition



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

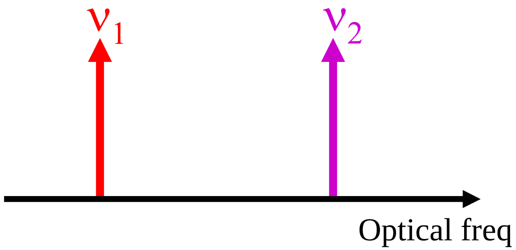
Iodine locking system

- 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

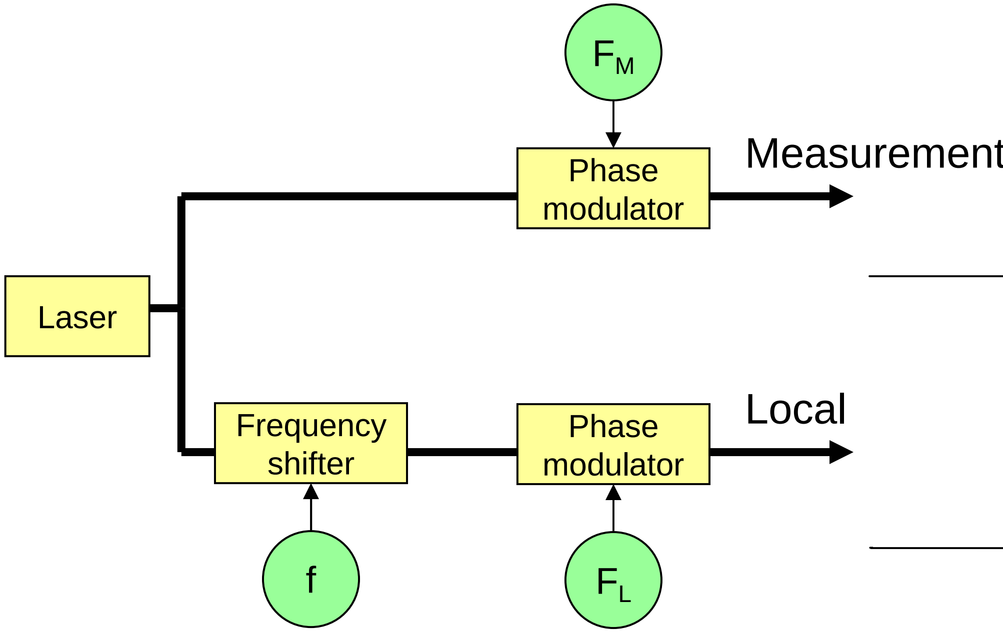
- 2-color metrology, using two or more lasers
  - Synthetic wavelength $(\nu_1 - \nu_2) / c$
  - Extends unambiguous range
  - Limited by laser frequency stability

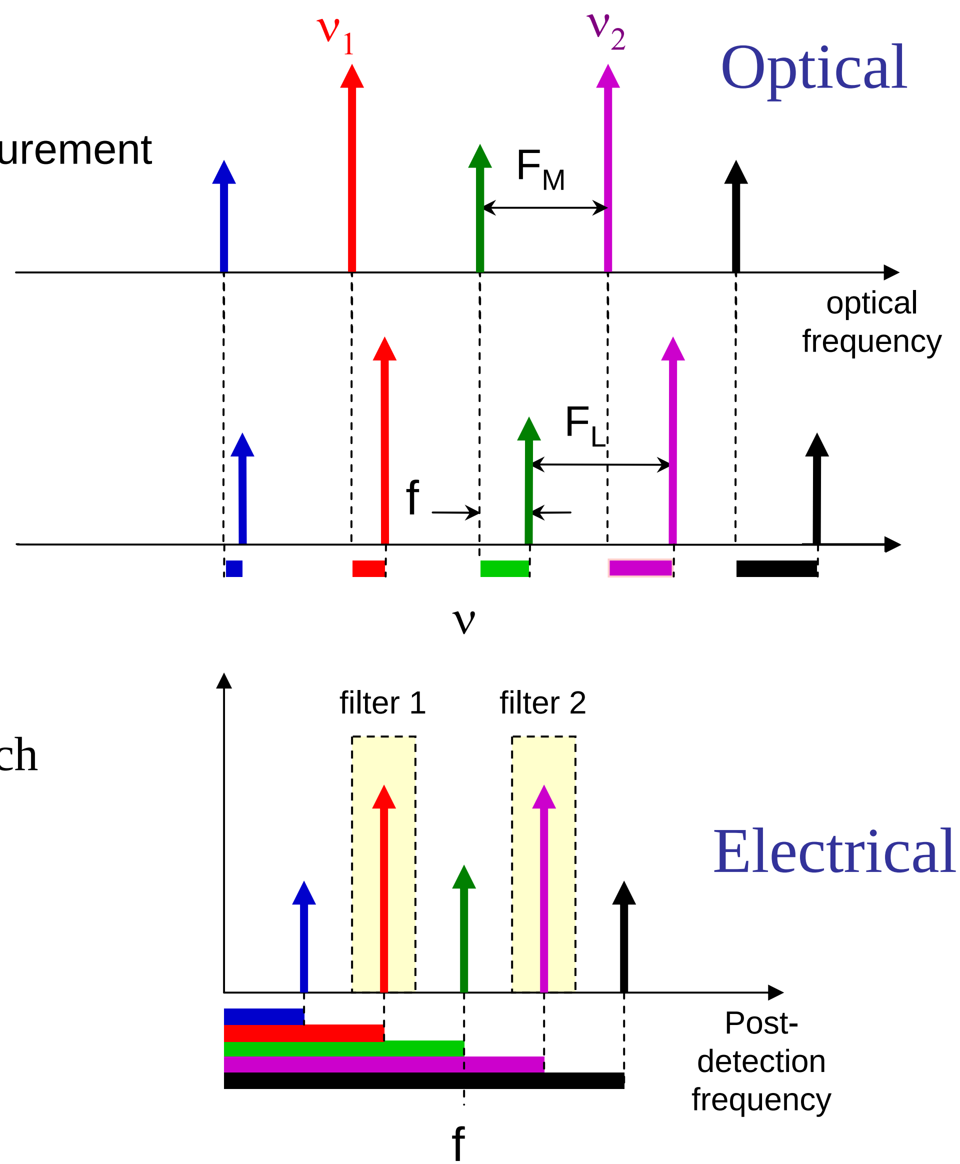


- RF modulation of an optical carrier
  - Requires high frequency detection and processing

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

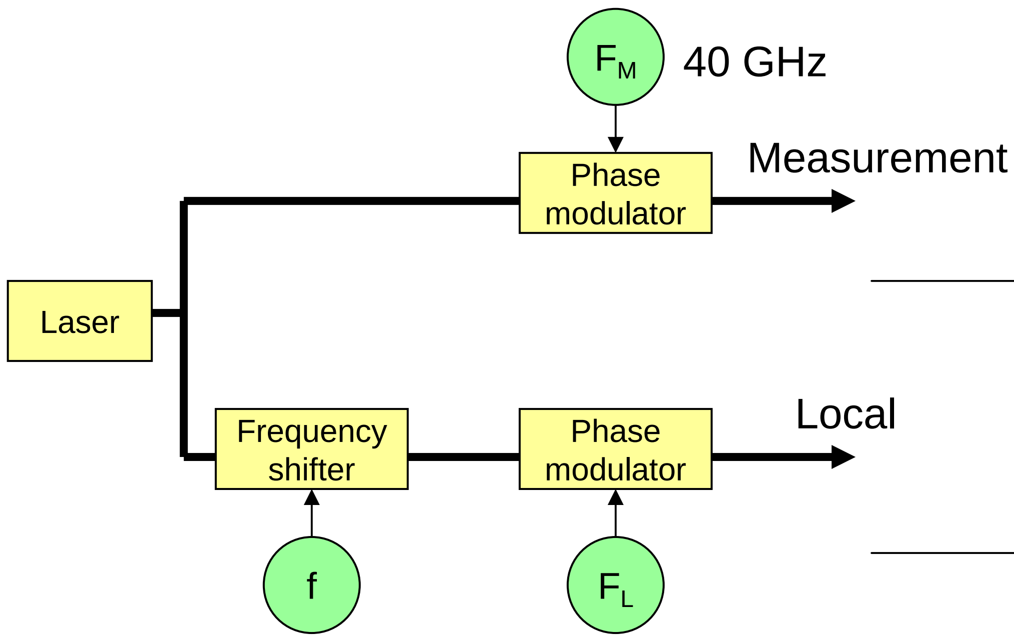
MSTAR Sensor Concept

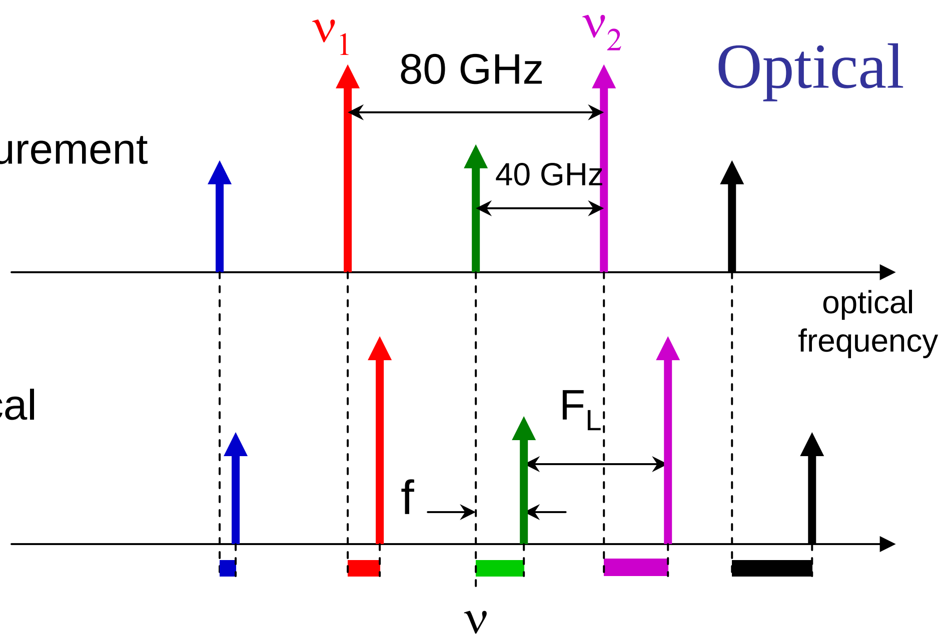


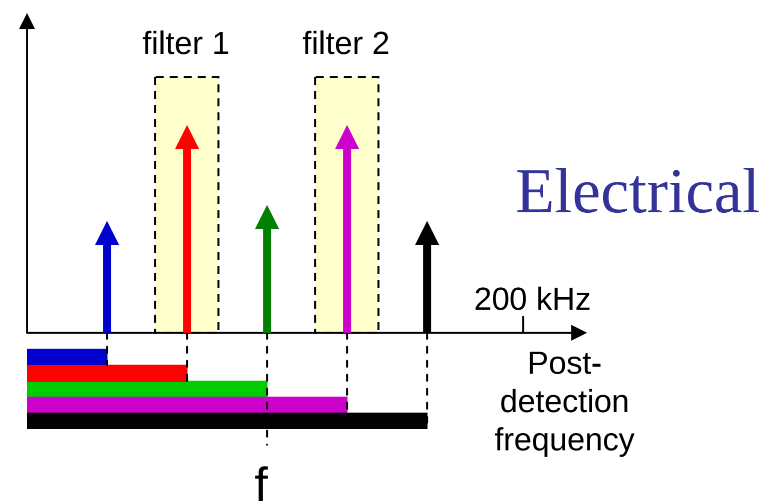


- Measurement and Local beams mix to produce a ***unique beat frequency*** for each ***optical sideband***
- ***Electrical spectrum*** is filtered to isolate beats resulting from desired ***optical sidebands***

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