Separated Spacecraft Interferometry

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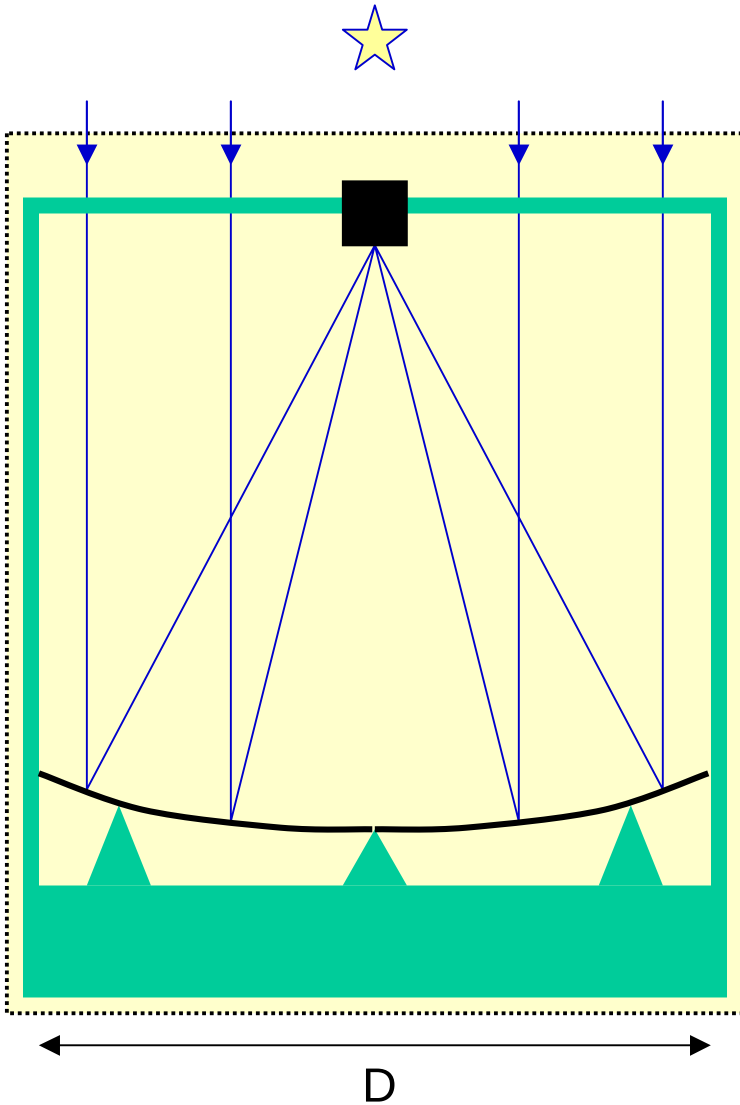
Outline

- Formation telescopes
- Configurations
- Orbits
- Formation flying
- Beam shear
- Acquisition
- Delay and delay rate
- U-V coverage
- Future formation flying missions

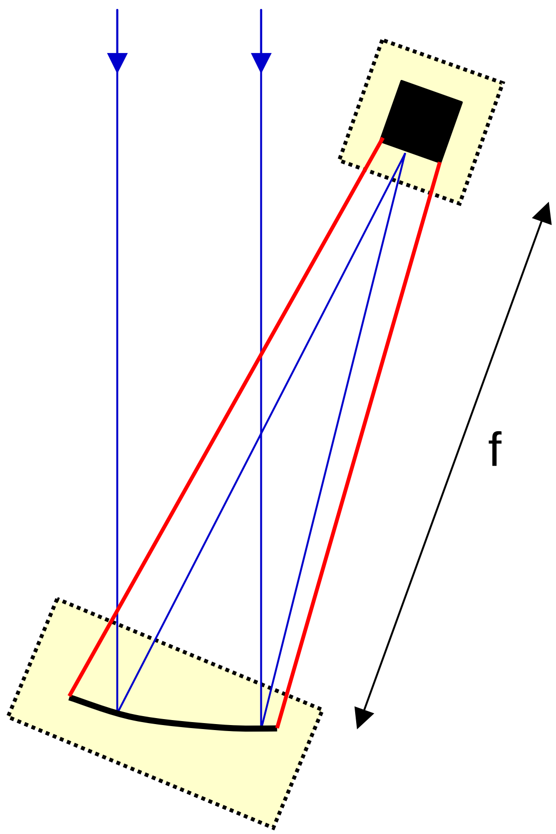
– Covers many technologies
– Highlight differences between ground and separated spacecraft
– Knowledge of basic interferometry assumed

Monolithic telescope

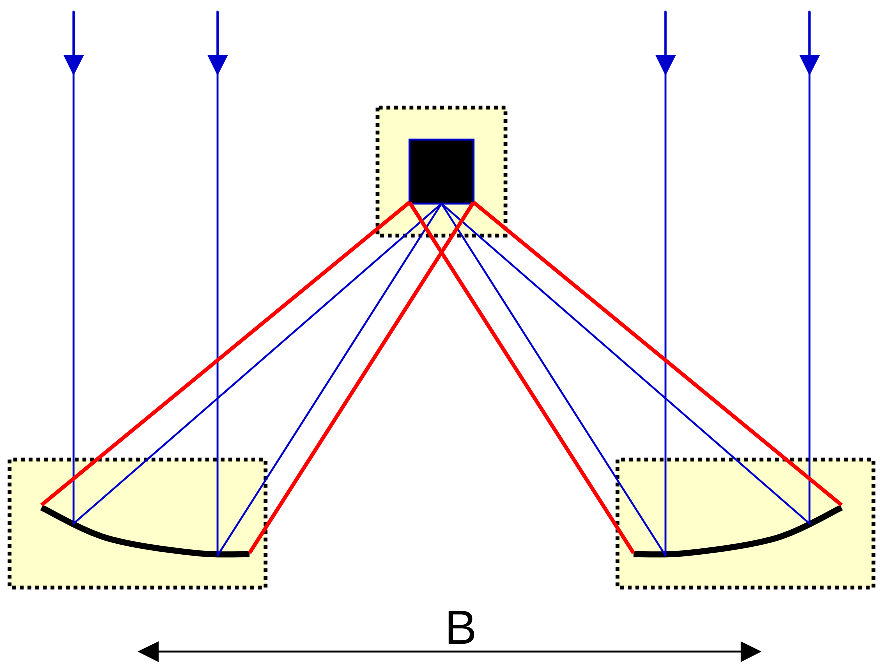


- Angular resolution ~ λ / D
- Collecting area ~ D^2
- Must maintain equal path lengths from target to focal plane
- Path lengths stabilized by rigid structure
- Single spacecraft platform limits dimensions

Formation telescope examples



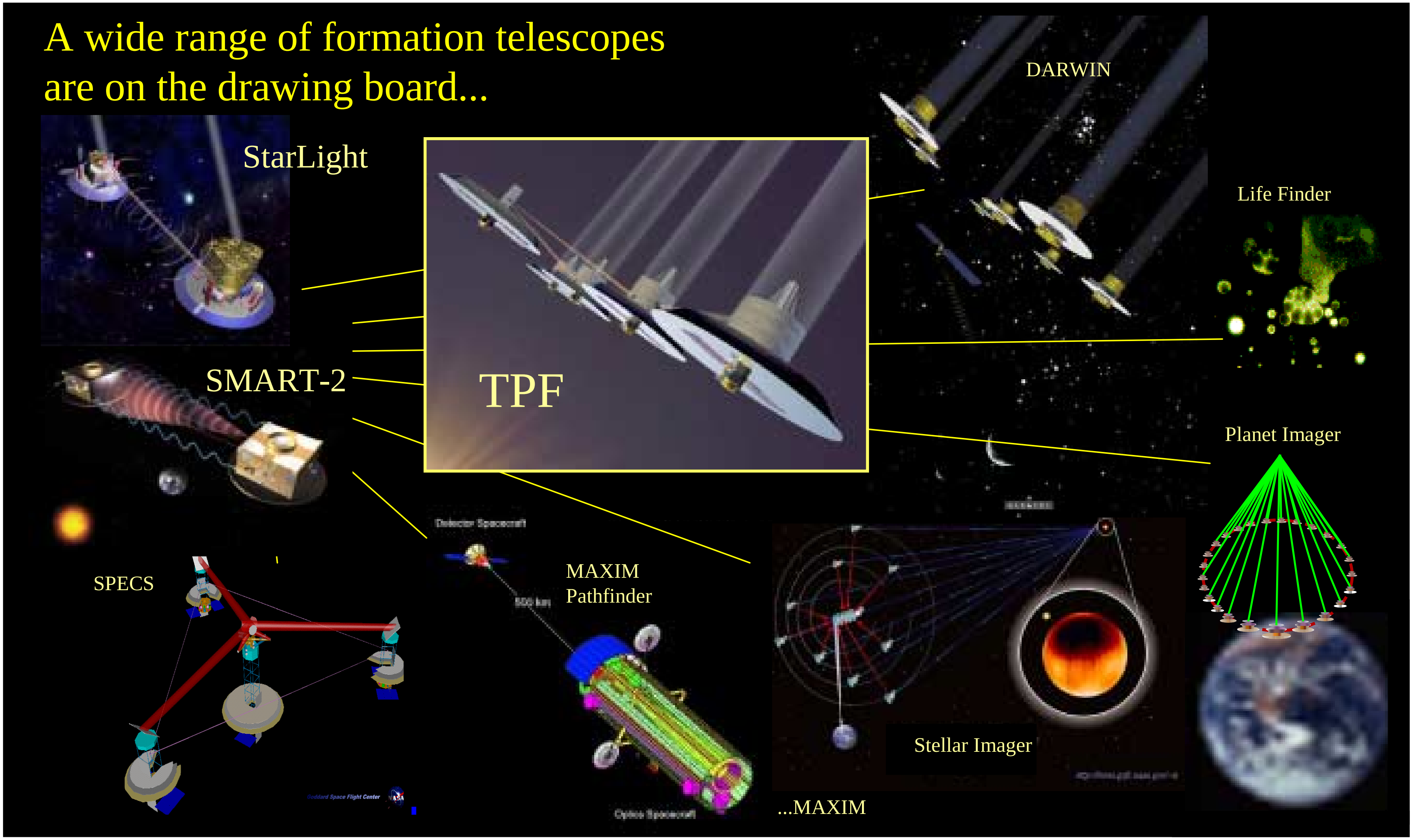
Large area, low curvature membrane reflector requires long focal length



Interferometer has angular resolution ~ λ / B

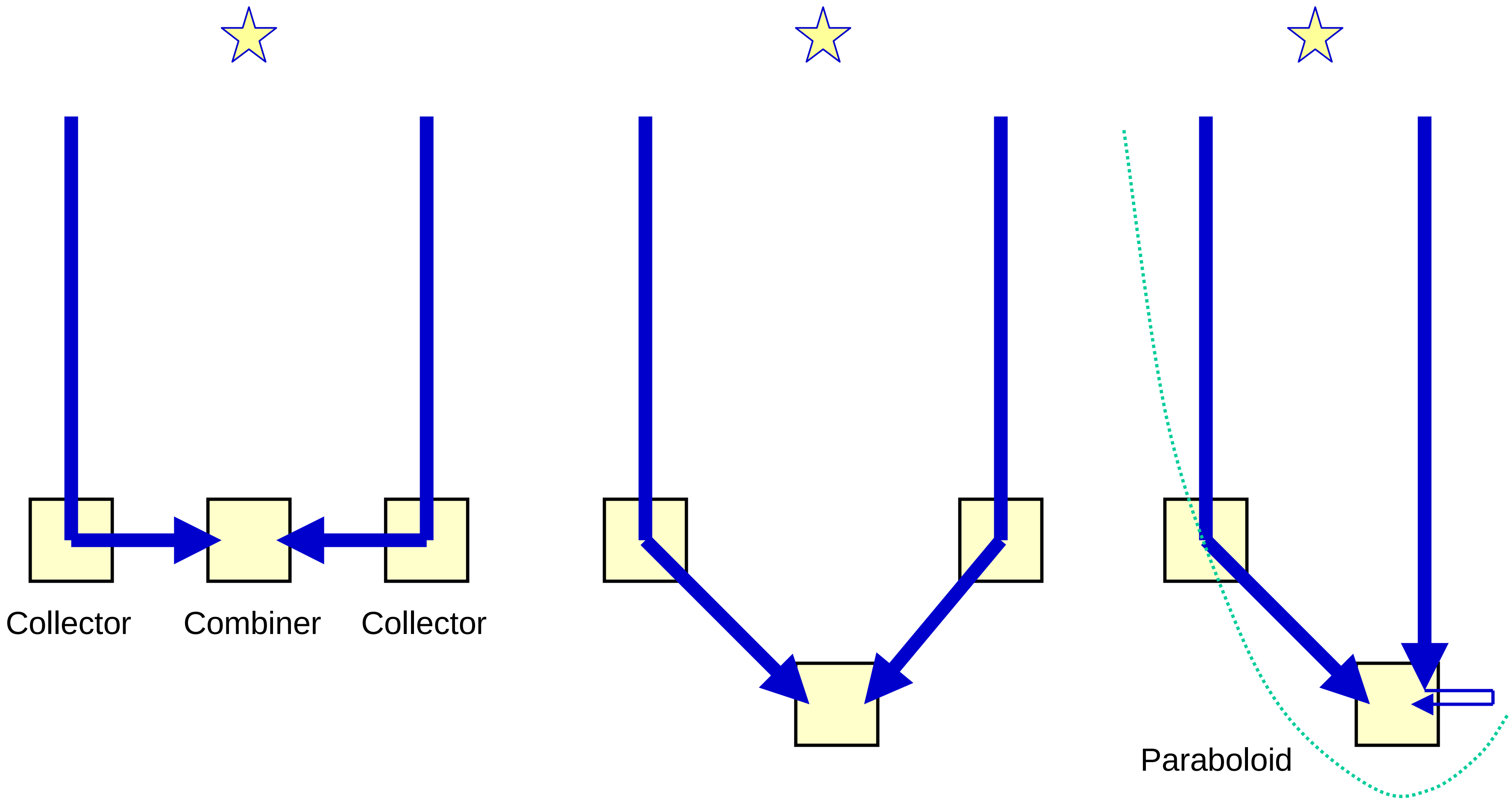
- Path lengths stabilized by laser metrology & active control

Formation Telescope Missions

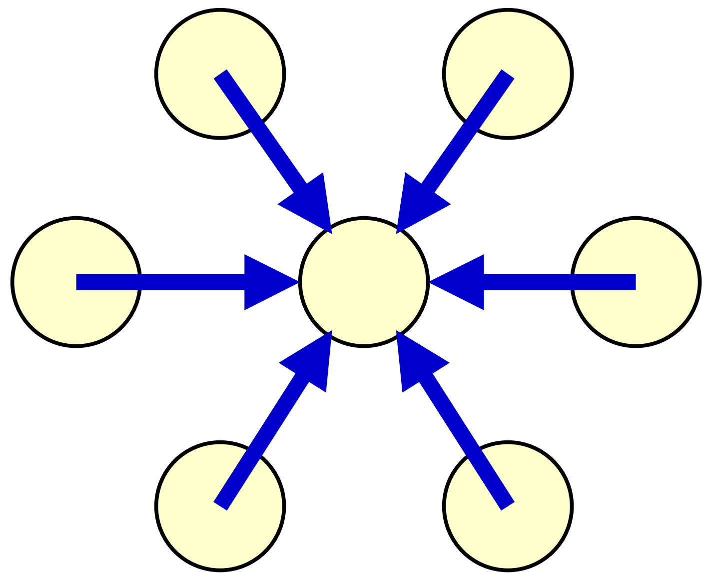


Configurations I

- Balancing path lengths is primary issue

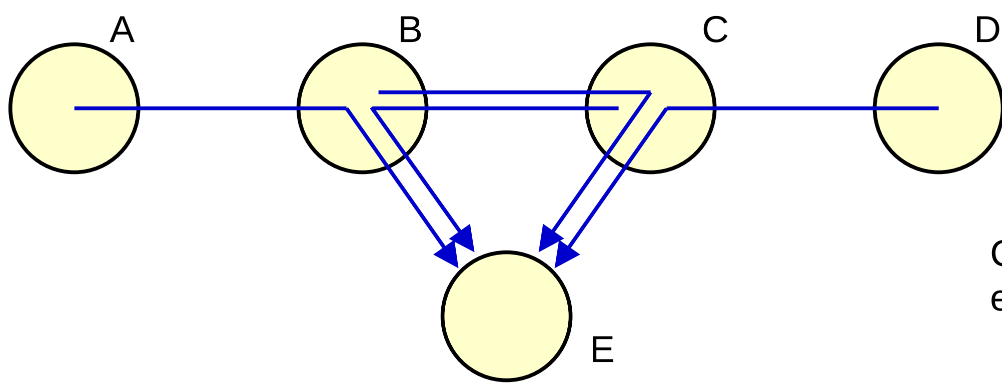


- DARWIN



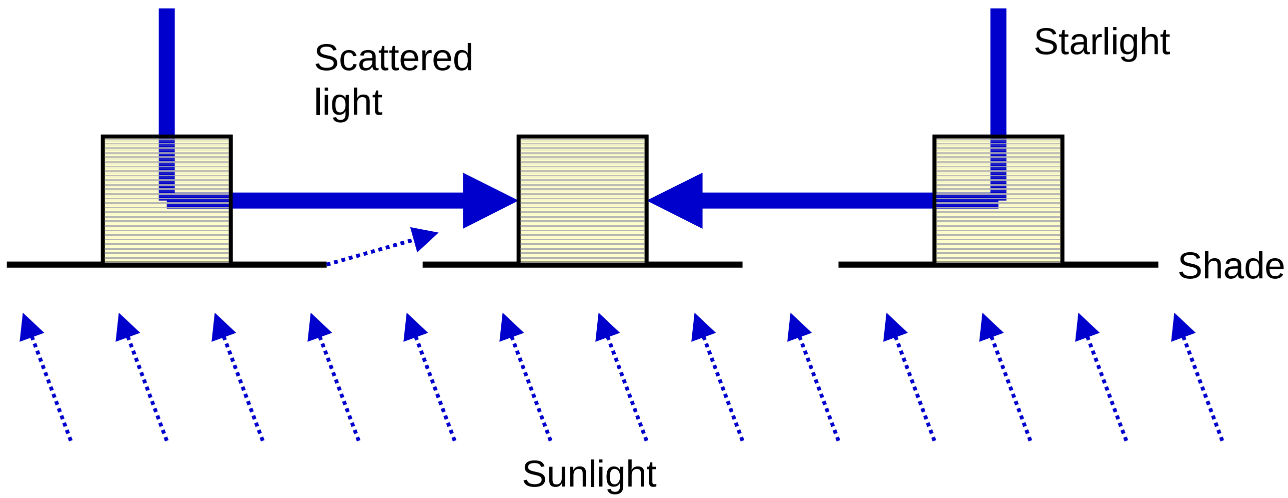
Target star direction is normal to plane of figure

- TPF

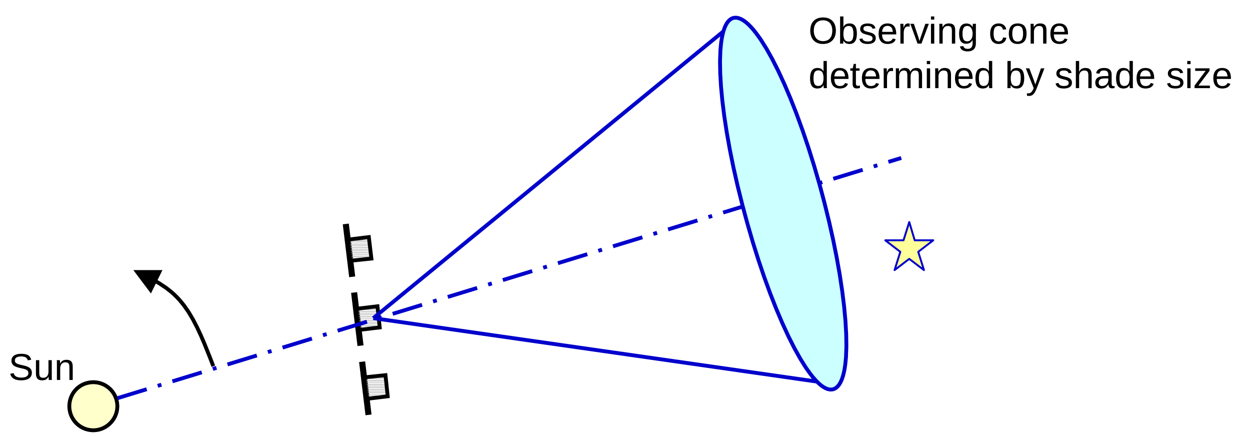


Collectors must be equally spaced

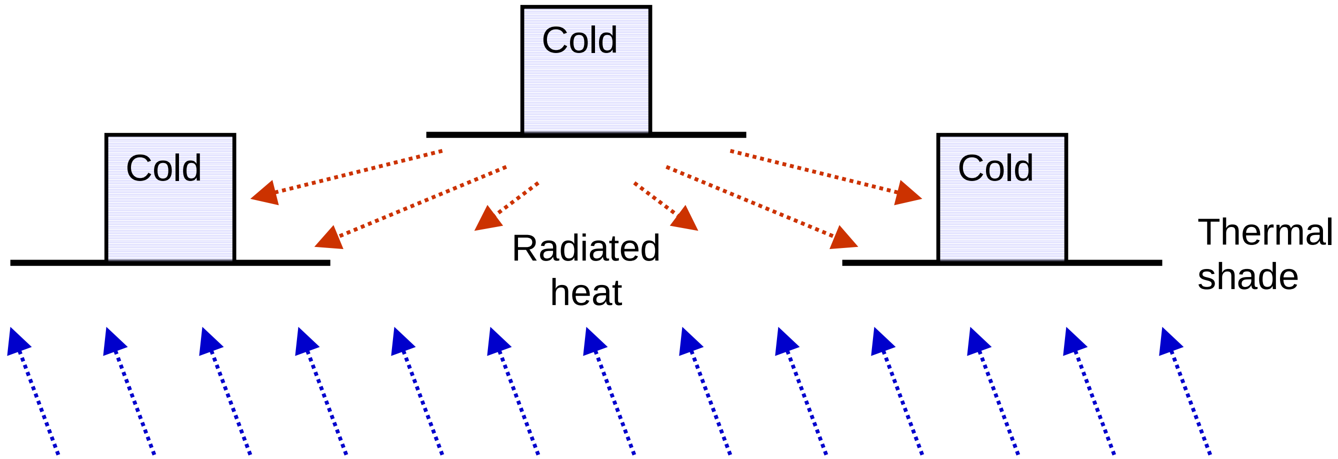
Shading issues I



- Restricted to observing parts of sky in general anti-sun direction with this configuration



Shading issues II

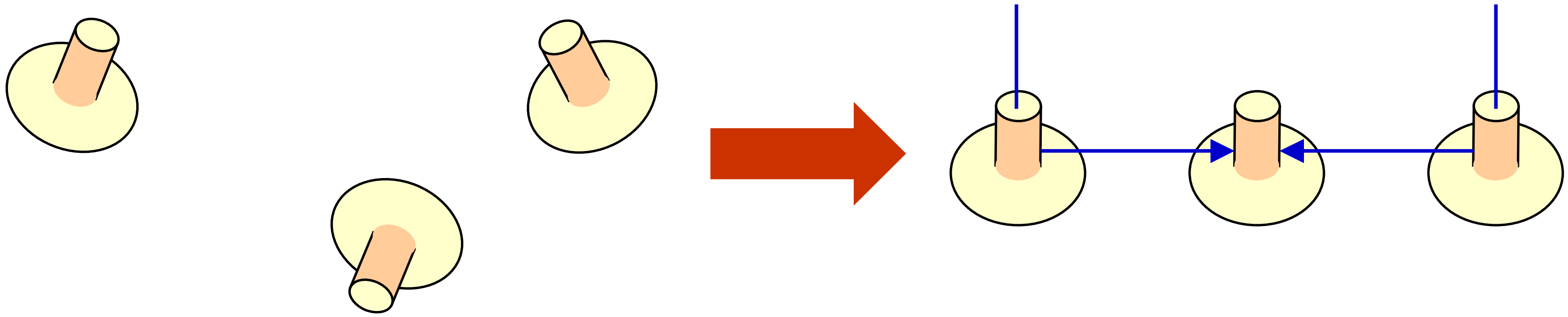


- Interferometers operating in mid and far IR need to be kept cold. Planar configurations better.

Orbits

Orbit type	Pros	Cons
Earth orbit	•Cheaper launch •Serviceable	•Strong potential gradients •Night and day
1 AU heliocentric (Earth trailing / leading)	•Good solar power •Easier communication •Multiple simultaneous launches possible	•Not serviceable •Harder to cool •Higher zodiacal dust emission
5 AU heliocentric	•Easier to cool •Lower zodiacal dust emission	•Not serviceable •Less solar power available •Multiple launches difficult •Harder communciation
L2 Lagrangian point (1.5 million km from Earth)	•Multiple launches possible at different times •Easier communication	•Not serviceable •Higher zodiacal dust emission •Additional station-keeping

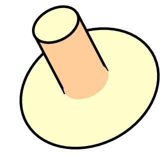
Forming an optically stable platform



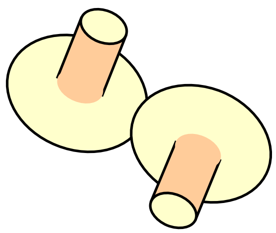
- Key elements:
  - Formation flying
    - Sensors
    - Actuators
    - Algorithms
  - Beam shear
  - Control loops

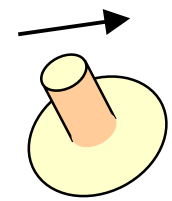
Formation Flying Sensors

- Standard sensors
  - Star-trackers: inertial attitude to ~arcsec level
  - Gyros: inertial attitude rate
  - Accelerometers: inertial velocity changes



- Coarse formation sensors
  - Functions:
    - Collision avoidance
    - Formation “evaporation”
    - Acquisition

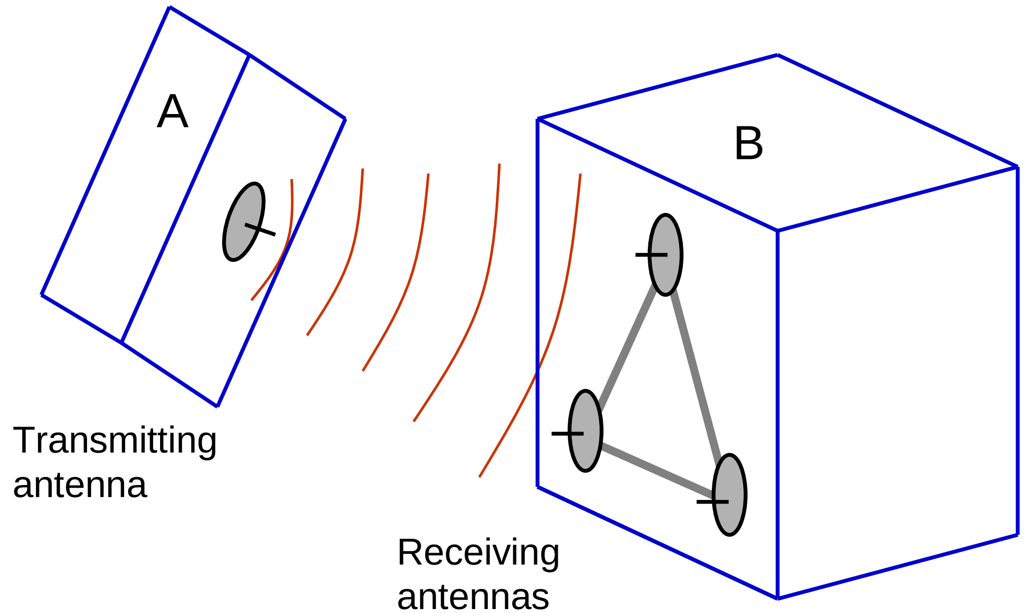




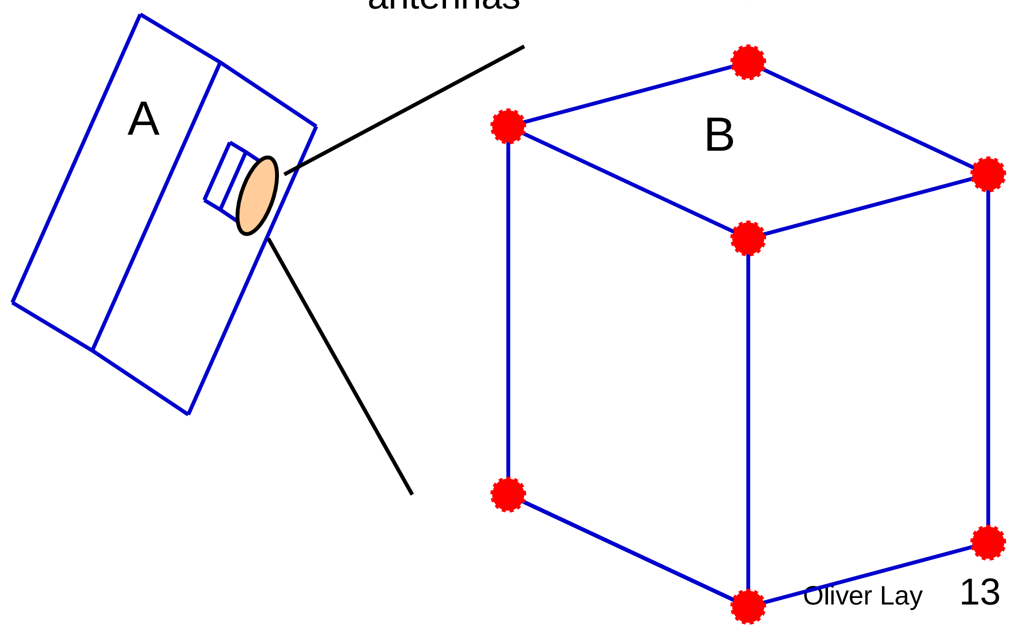
  - Requirements
    - Relative range and bearing angles
    - 4π steradian coverage
    - Separations from few meters to km or more
    - Must function in arbitrary configurations
- Fine formation sensors
  - Laser metrology (more later)

Coarse formation sensing

- Radio Frequency (RF)
  - Bearing from differential arrival time
  - Range from propagation time
  - 4π coverage requires many antennas
  - Complicated by shades & structures



- Optical
  - Wide-angle cameras looking for beacons on other spacecraft
  - Ranging difficult
  - Beacons compete with sun and illuminated parts of spacecraft



Formation flying actuators

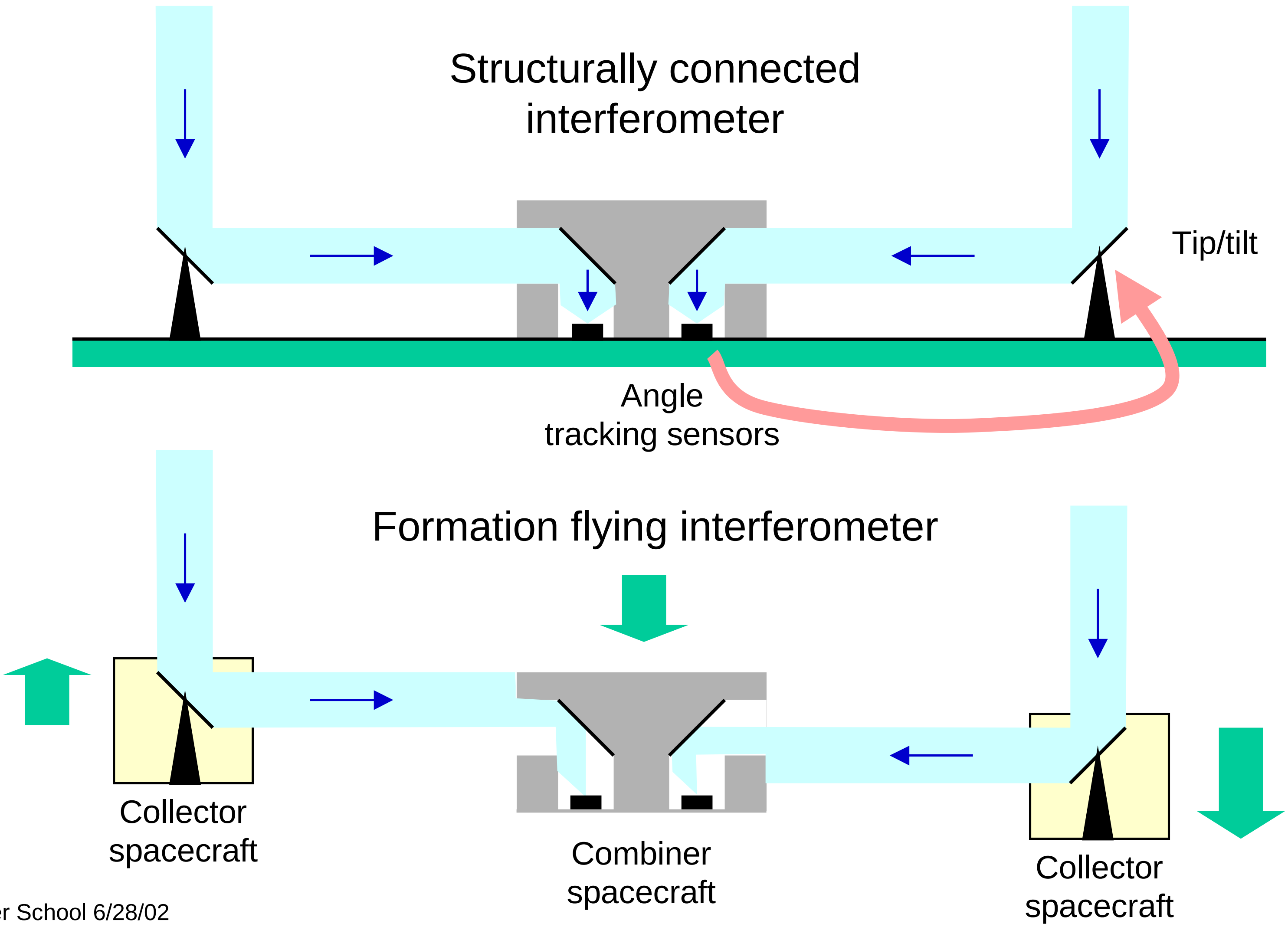
Actuator	Description	Pros	Cons
Thrusters	Many types available. e.g. chemical, cold gas, Pulsed Plasma Thrusters (PPT), Field Emission Effect Propulsion System (FEEPS)	•Can provide attitude and translation control •Micro-Newton thrusts possible	•Consumable propellant •Contamination of optical surfaces •Plumes
Reaction wheels	Electrically driven wheels. Wheel spun up one way, spacecraft turns the other way.	•Established technology	•No translation control •Source of vibration
Tethers	Cables connecting spacecraft which can be paid out or pulled in to control separation	•Saves fuel •Prevents "evaporation"	•Still need thrusters for control •Tether management issues •Source of stray light
Electro-magnets	Powerful electromagnets on each spacecraft provide mutual attraction/repulsion (see: cdio-prime.mit.edu/CDIO3/References/MagFF.pdf)	•Saves fuel •No contamination	•Currently just a concept •Less effective at large separations
Solar sails	Forces generated by momentum of solar photons impinging on large reflective sails	•Saves fuel •No contamination	•Very immature •Low thrust

Formation flying algorithms

- Must be semi-autonomous
  - No continuous link to ground
  - System on its own for hours at a time
- Must be extremely reliable
  - Prevent collisions and evaporation events over years of remote operation, sometimes in very tight formations
  - Robust to many possible failure modes
- Constraints
  - Avoid collision courses
  - Maintain shading and solar power
  - Optimize fuel used vs time taken
  - Balance fuel consumption between spacecraft
  - Prevent impingement of thruster plumes

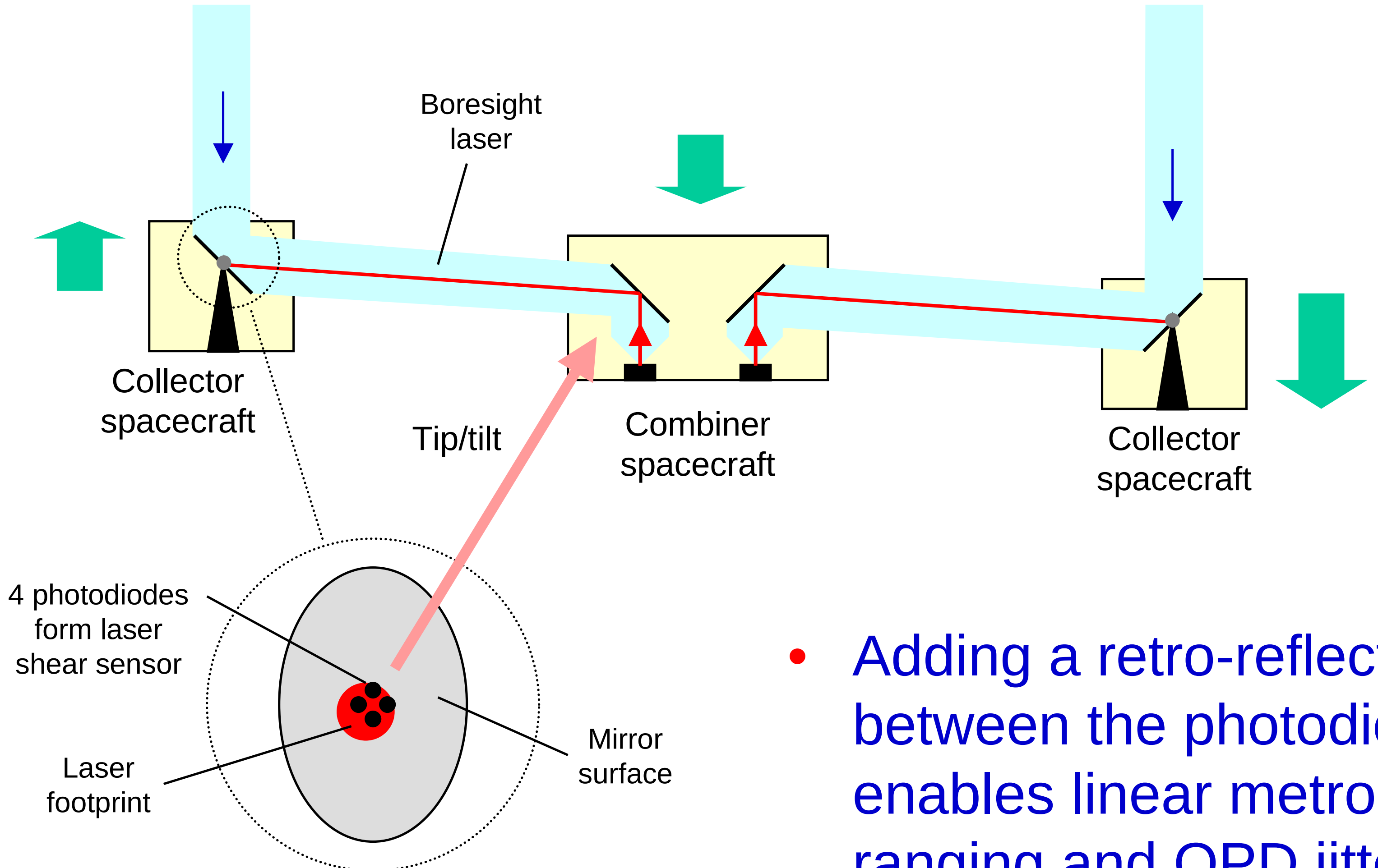
Beam shear I

- Key difference between fixed structure and formation flying systems



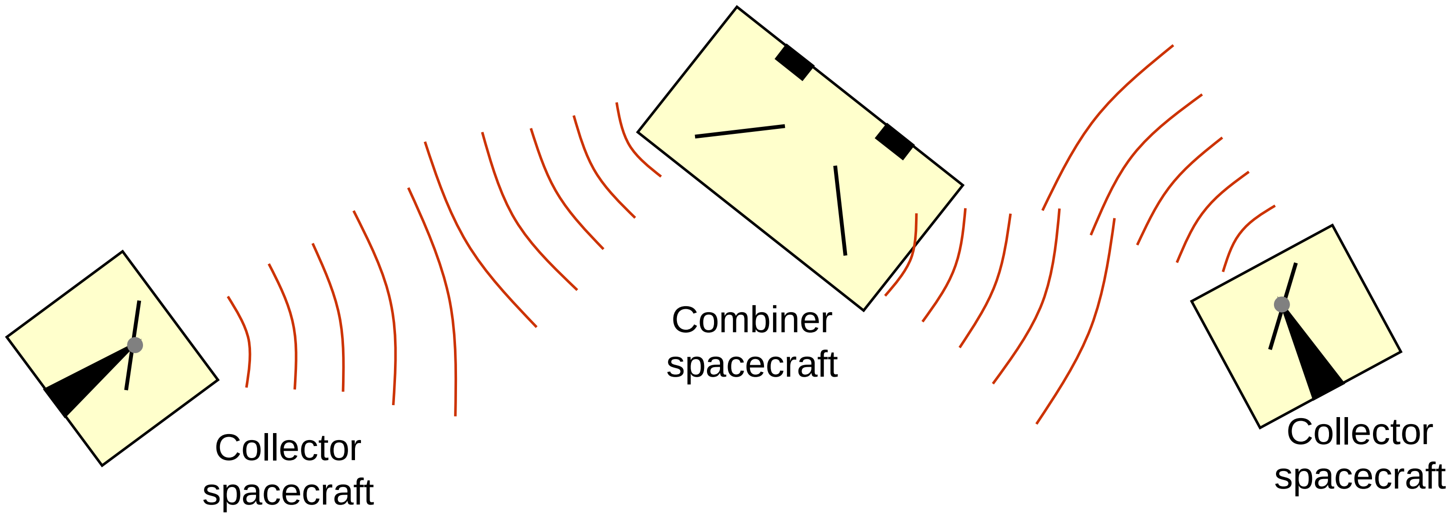
Beam shear II

- One solution:



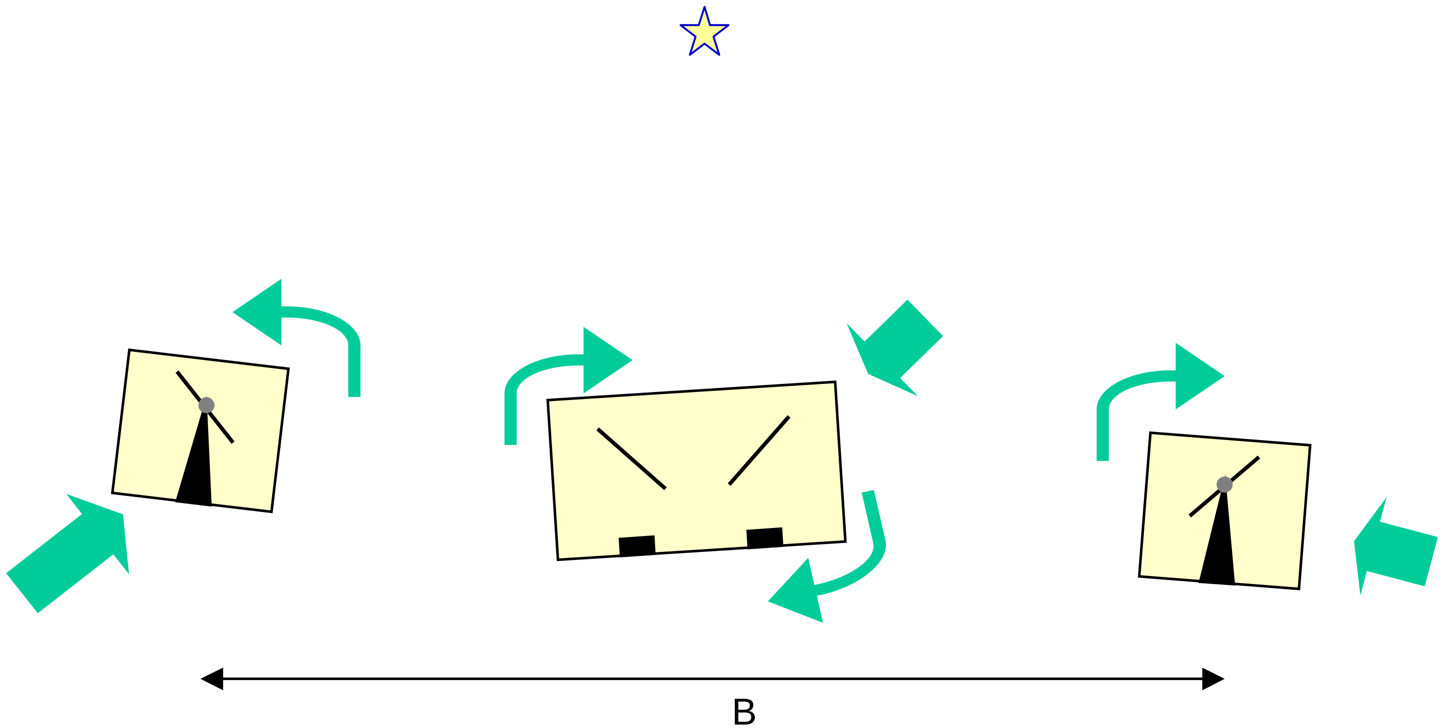
- Adding a retro-reflector between the photodiodes enables linear metrology: ranging and OPD jitter

Acquisition sequence: 1. Free floating



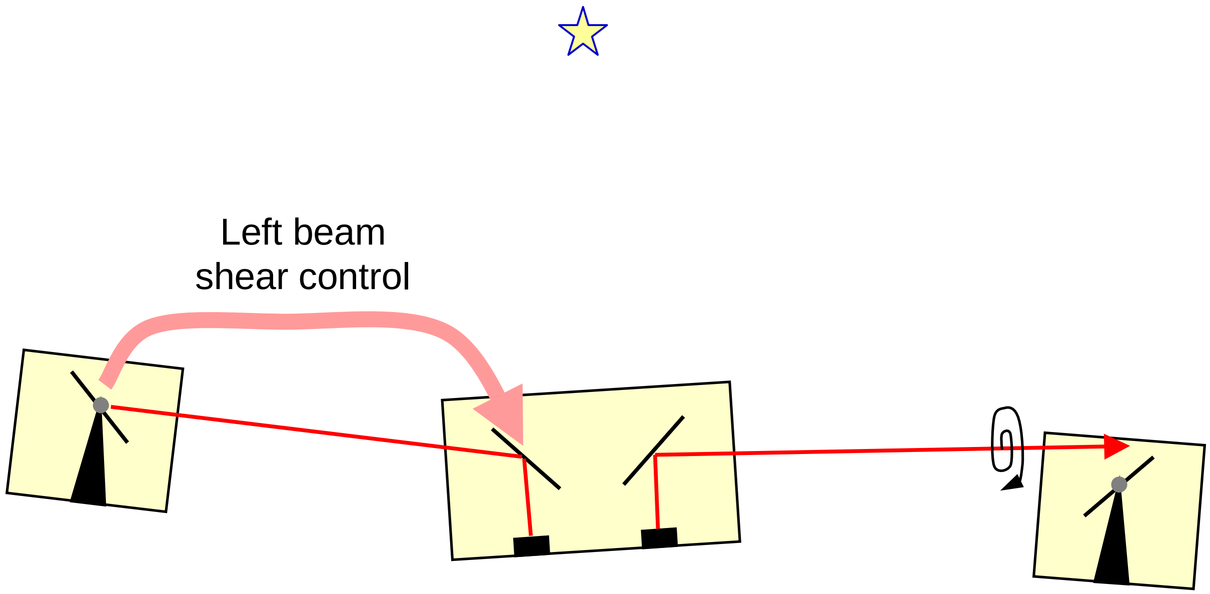
- Coarse formation sensing to determine relative locations

2. Rough formation



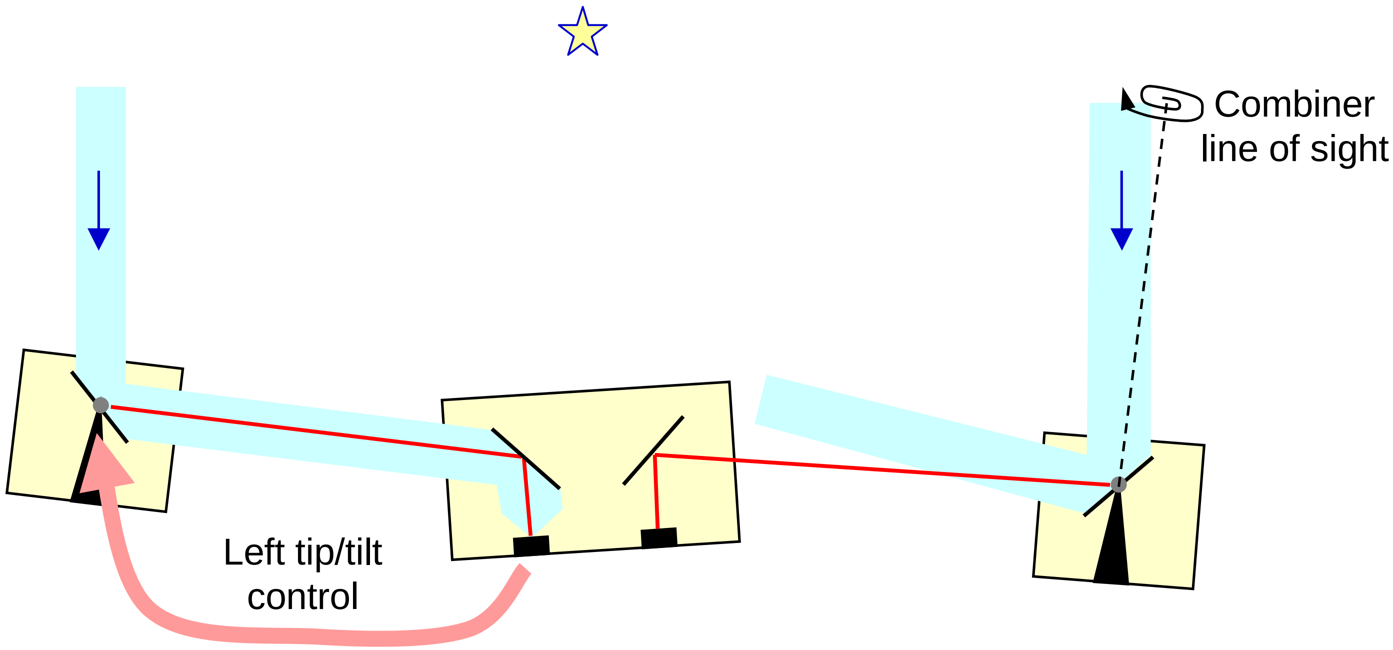
- Formation flying algorithm commands thrusters to position spacecraft with desired baseline length and orientation relative to target

3. Metrology acquisition



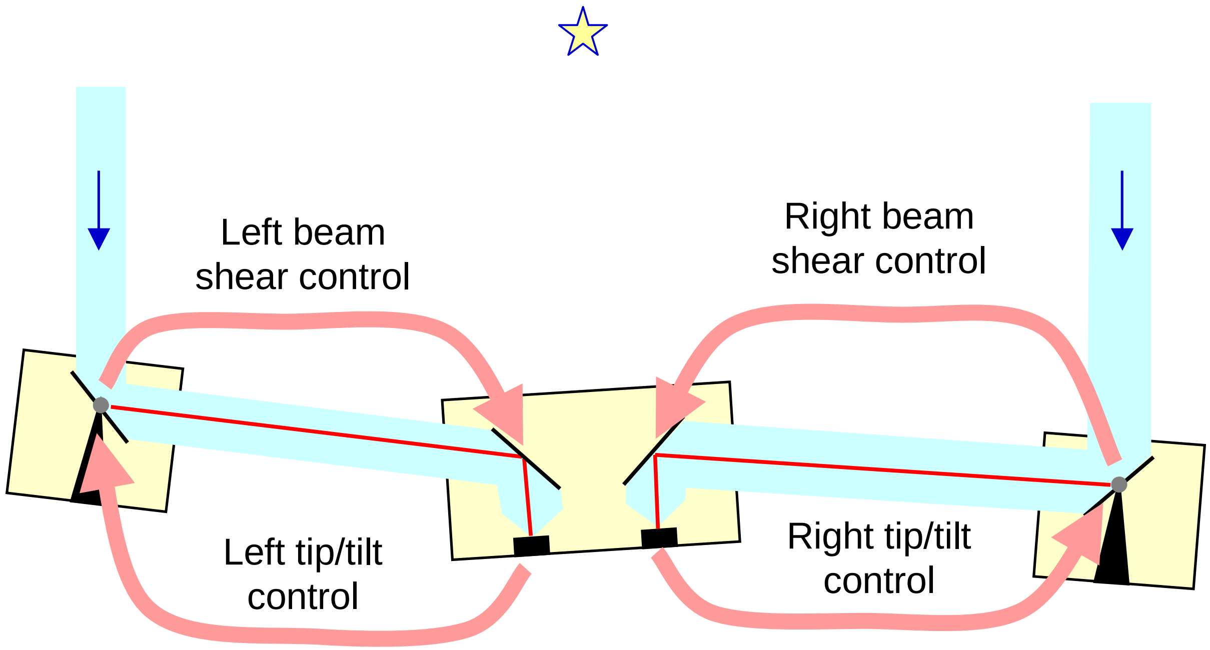
- Approximate bearing from coarse formation sensors
- Spiral search until metrology shear sensor acquired
- Control loop closed between metrology shear sensor and combiner tip/tilt mirror

4. Starlight acquisition



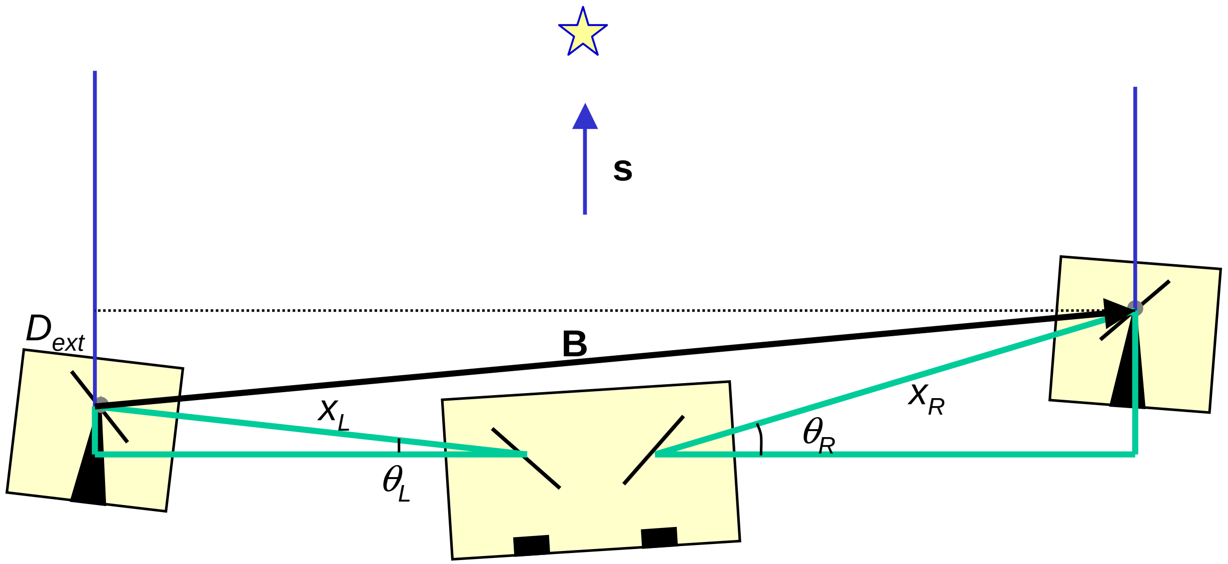
- Collector tip/tilt mirror scanned until starlight beam enters combiner optics and appears in detector field of view
- Or, equivalently, the combiner line of sight is being scanned on the sky until it points towards the target
- Starting position for search determined from readings from startrackers and tip/tilt mirrors

Station-keeping control



- Spacecraft continually moving:
  - Solar radiation pressure
  - Gravity gradients
  - Non-zero minimum thrust
- Control loops maintain angle tracking and zero beam shear
- Allowed motion determined by
  - range of tip/tilt mirrors
  - observing constraints
  - length of active delay line
- Next step: finding fringes
  - determines sensitivity

Delay uncertainty I



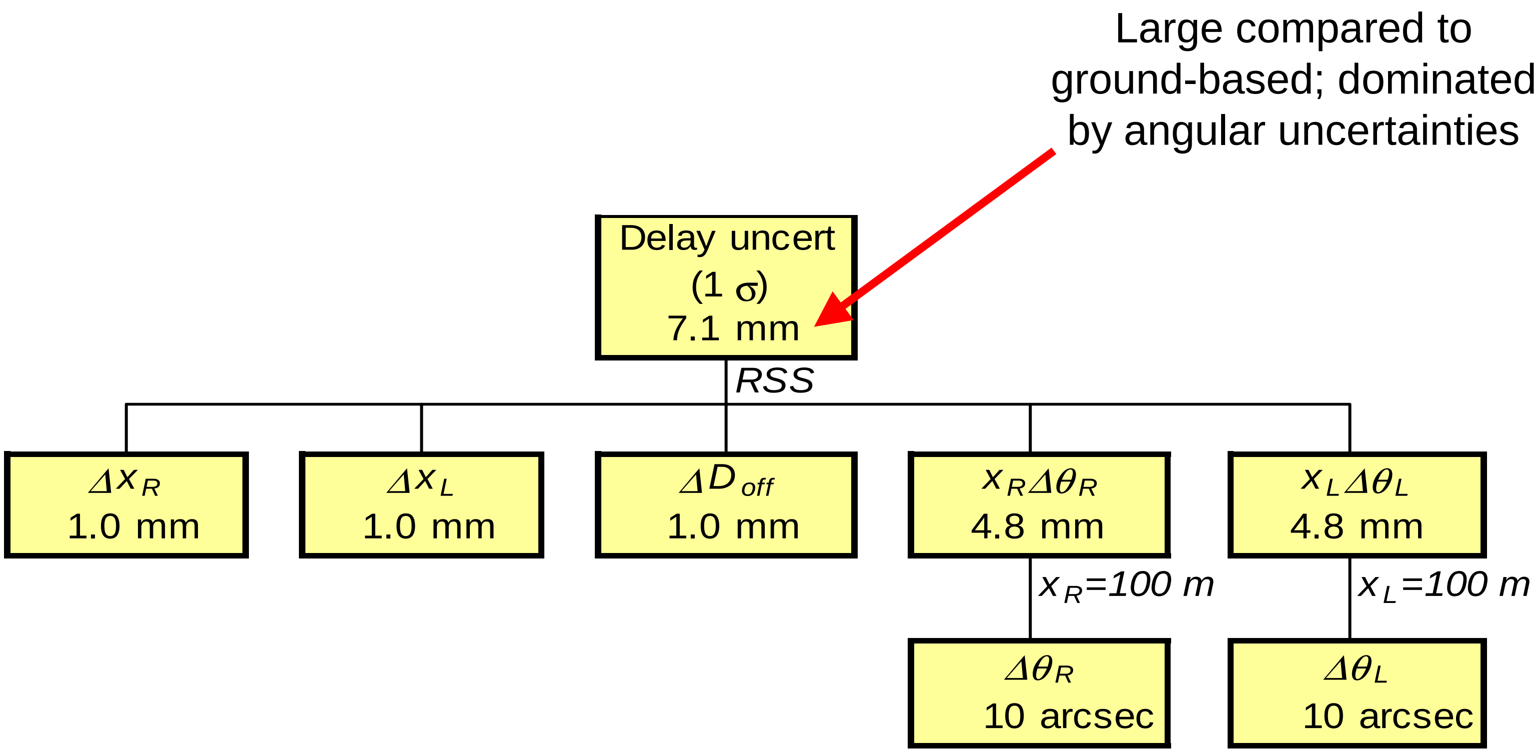
$$D = D_{\mathrm{ext}} - D_{\mathrm{int}}$$
$$= (\mathbf{B}\bullet\mathbf{S}) - (x_L - x_R - D_{\mathrm{off}})$$

- Ground-based systems:
  - x_L & x_R fixed
  - Length of **B** fixed
  - Direction of **B** well-known vs t

- Delay error for this config:

$$\Delta D = \Delta D_{ext} - \Delta D_{int}$$
$$\simeq \underbrace{(x_L\Delta\theta_L - x_R\Delta\theta_R)}_{\text{Angular metrology}} - (\underbrace{\Delta x_L - \Delta x_R}_{\text{Ranging}} - \underbrace{\Delta D_{\mathrm{off}}}_{\text{Internal metrology}})$$

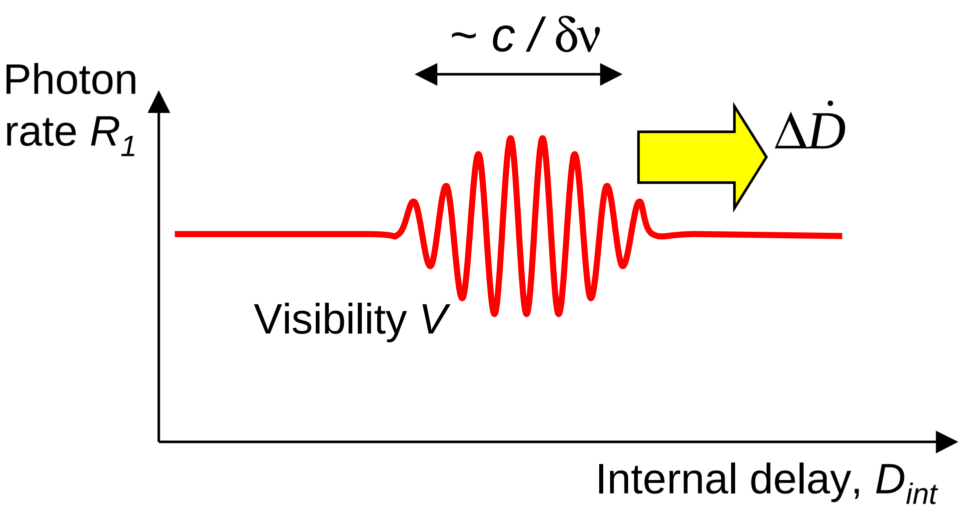
Delay uncertainty II



Delay rate uncertainty & fringe search sensitivity

$$\Delta\dot{D} \simeq \left(x_L\Delta\dot{\theta}_L - x_R\Delta\dot{\theta}_R\right) - \left(\Delta\dot{x}_L - \Delta\dot{x}_R - \Delta\dot{D}_{\text{off}}\right) \simeq x_L\Delta\dot{\theta}_L - x_R\Delta\dot{\theta}_R$$

Consider total bandwidth $\Delta\nu$ divided into n spectral channels of width $\delta\nu$, with photon rates of R_n and R_1, respectively.



Dwell time on fringe:

$$T \lesssim \frac{\text{fringe envelope width}}{\text{delay rate uncertainty}}$$

$$\lesssim \frac{c/\delta\nu}{\sqrt{2}x\sigma_{\dot{\theta}}}$$

where $x \sim x_L \sim x_R$

Fringe detection SNR for 1 spectral channel, with detector read noise r (assumes CCD-like detector):

$$SNR_1 \sim \frac{R_1 T V}{\sqrt{\underbrace{R_1 T}_{\text{Photon noise}} + \underbrace{4\frac{\nu}{\delta\nu}r^2}_{\text{Read noise}}}}$$

Delay rate uncertainty & fringe search sensitivity

Photon-noise dominated:

$$SNR_1 \sim \frac{R_1 TV}{\sqrt{R_1}} = \sqrt{R_1}\,TV$$

$$SNR_n \simeq SNR_1\sqrt{n} \sim \sqrt{R_n}\,TV$$

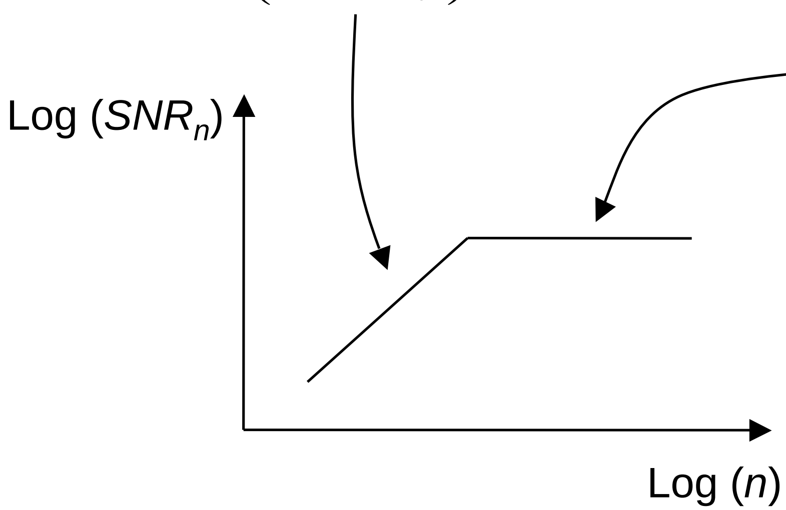
$$\sim \left(\frac{nR_n c}{\sqrt{2}x\sigma_{\dot{\theta}}}\right)^{1/2} V$$

Read-noise dominated:

$$SNR_1 \sim \frac{R_1 TV}{\sqrt{4\frac{\nu}{\delta\nu}r^2}} = \frac{R_1 TV}{2r}\sqrt{\frac{\delta\nu}{\nu}}$$

$$SNR_n \simeq SNR_1\sqrt{n} \sim \frac{R_n TV}{2nr}\sqrt{\frac{\Delta\nu}{\nu}}$$

$$\sim \frac{R_n c}{2x\sigma_{\dot{\theta}}\, r\sqrt{2\nu\Delta\nu}} V$$



For fringe search, want enough spectral channels to be read-noise dominated

Example sensitivity calculation

- Optical interferometer with 200 m baseline (x = 100 m)
- Passband 0.5 – 1.0 μm ($\Delta\nu = 3 \times 10^{14}$ Hz; $\nu \sim 4 \times 10^{14}$ Hz)
- Uncertainty in angle rates = 10 milliarcsec / s = 50 nrad / s
- Fringe visibility V = 0.5
- CCD Detector read noise = 3 electrons
- SNR for fringe detection = 5

$$SNR_n \sim \frac{R_n c}{2x\sigma_{\dot{\theta}} r\sqrt{2\nu\Delta\nu}} V$$

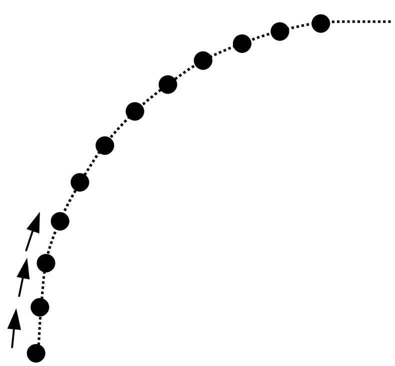
- Then require total photon rate $R_n \sim 500 / s$
- If 2 apertures of diameter 1 m, and 10% of photons reach detector,
- then required photon flux ~ 3200 photons / m^2 in total bandwidth of 3×10^{14} Hz
- Magnitude 0 star gives approx 10^{-4} photons / s / m^2 / Hz
- giving limiting magnitude for fringe detection ~ 17

Fringe tracking and measurement

- Basic principles same as for ground-based systems
- But different disturbance environment:
  - No atmospheric phase fluctuations
  - No earth rotation
  - Station-keeping maneuvers
  - Vibrations dominated by interferometer actuators
    - Tip/tilt mirrors
    - Delay lines
    - Thruster firings

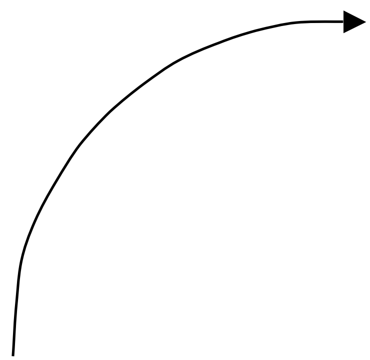
U-V coverage

- Stop-and-Stare observing



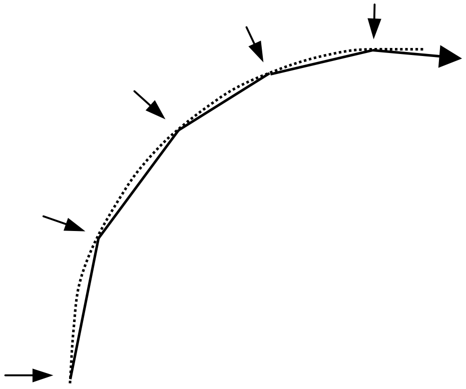
- Consumes more fuel
- Takes longer
- More stable observing environment

- On-the-fly observing, continuous correction



- Continuous disturbance
- Minimal requirement on delay line length

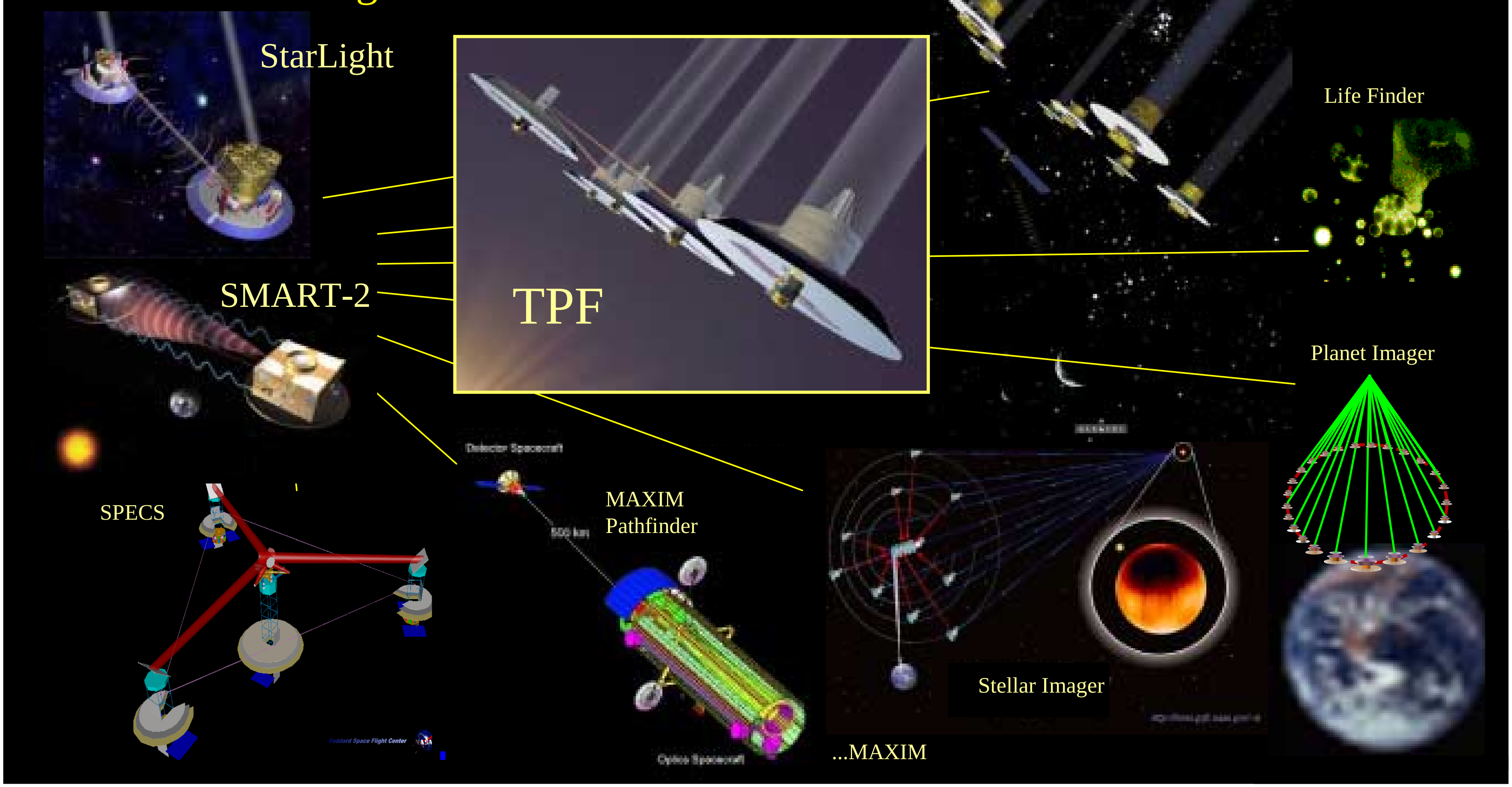
- On-the-fly observing, bang-bang control



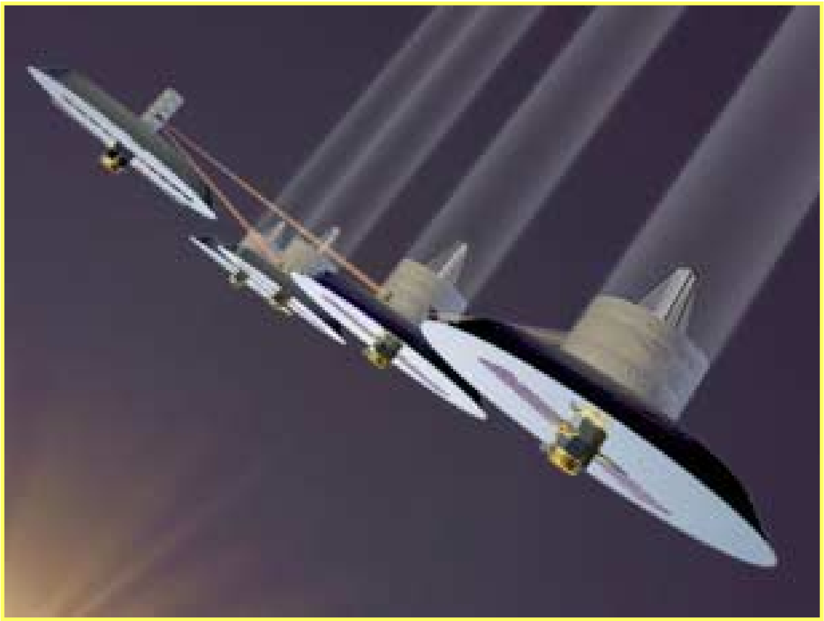
- Discrete thruster firings
- Quiet drift periods
- Settling time after each firing
- Delay line needed for non-ideal path

Formation Telescope Missions

A wide range of formation telescopes are on the drawing board...



Terrestrial Planet Finder



Formation Flying design shown here is one of three architectures currently being studied (also structurally connected mid-IR interferometer & visible coronagraph)

- Objectives:
  - Direct detection of earth-like planets
  - Imaging astrophysics
- Features:
  - Mid-IR nuller
  - Separations of ~ few meters to 1 km
  - 3.5 m primaries
  - L2 or Earth-trailing orbit

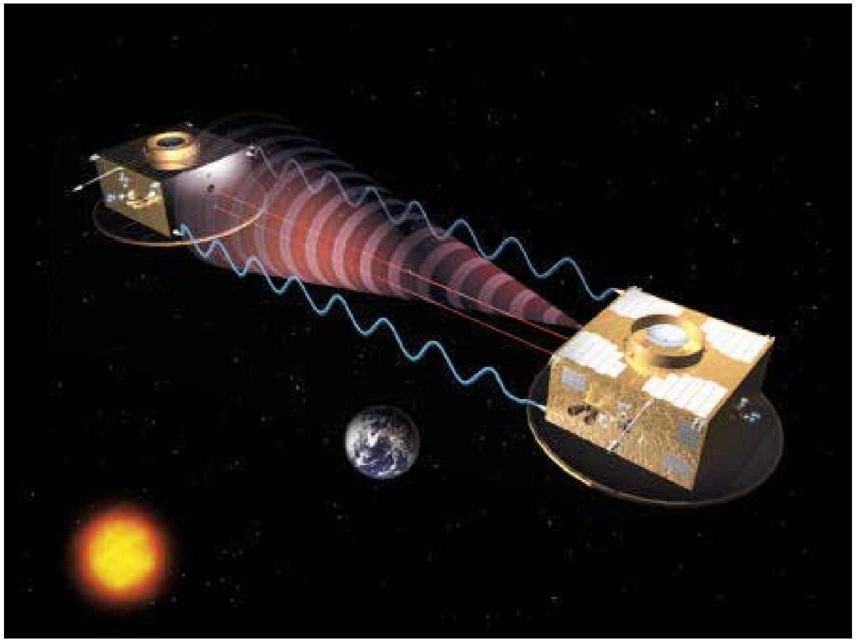
http://planetquest/TPF/tpf_index.html

DARWIN

- Objectives:
  - Direct detection of earth-like planets
  - Imaging astrophysics
- Features:
  - Mid-IR nuller
  - 6 x 1.5 m collectors
  - L2 orbit
- Similar goals to TPF

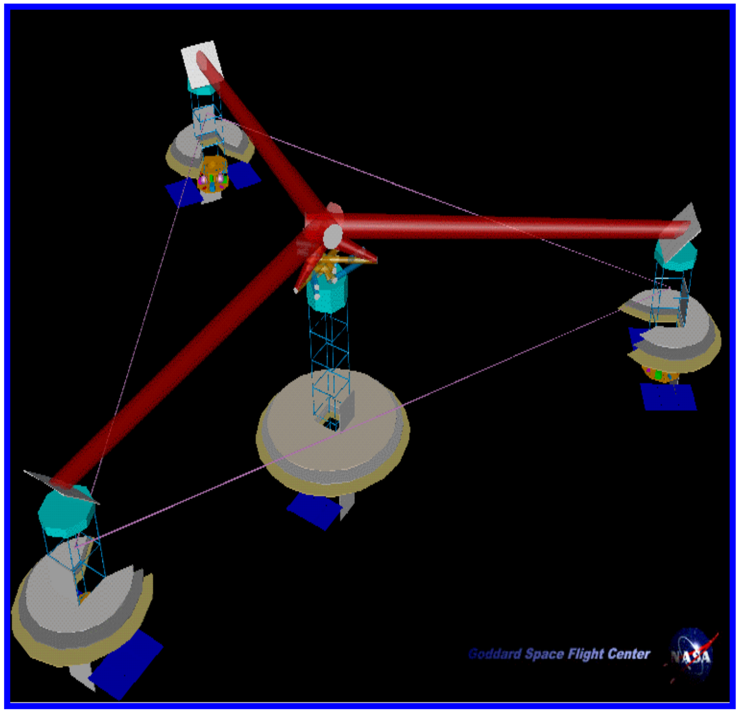
http://sci.esa.int/home/darwin/index.cfm

The ESA program



- SMART-2
  - single spacecraft?
  - inertial proof mass
  - micronewton thrusters
  - launch 2006?
  - Phase A studies
- SMART-3
  - 3 spacecraft formation flying
  - launch 2011?
- DARWIN
  - free-flying 7 spacecraft
  - launch ?

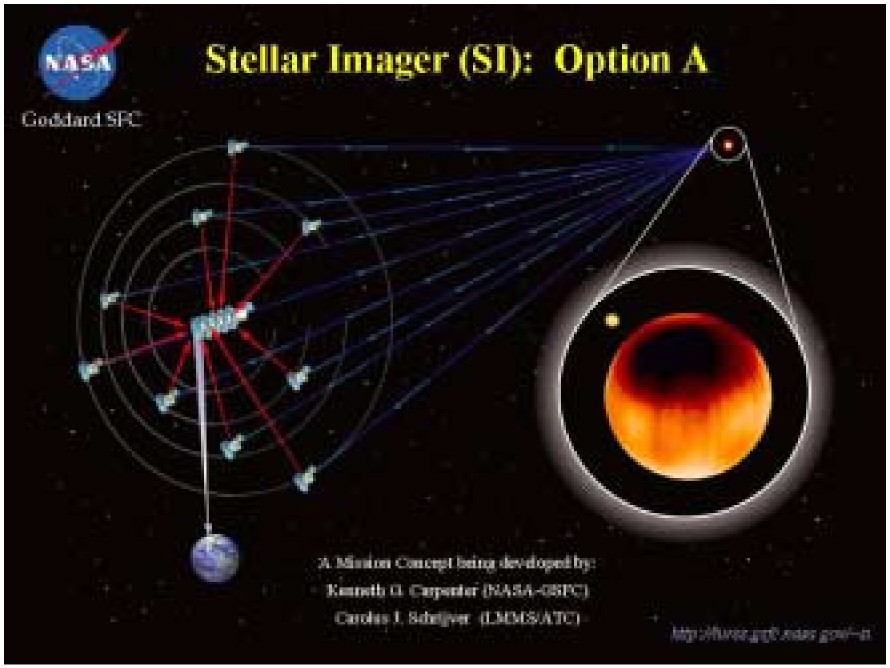
SPECS



http://space.gsfc.nasa.gov/astro/specs/

- Submillimeter Probe of the Evolution of Cosmic Structure
- Objective:
  - Study formation and evolution of stars and galaxies from primordial matter
- Features:
  - Submillimeter wavelengths
  - ~3 x 3 m mirrors
  - Separations out to ~1 km
  - Tethers
  - Wide-field imaging (0.25 degrees)

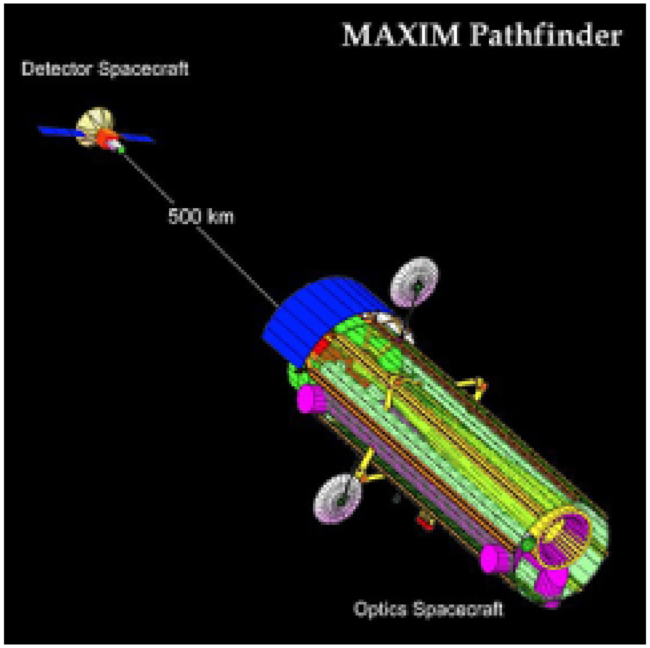
Stellar Imager



- Objective:
  - Image the surfaces of nearby stars to better understand stellar physics
- Features:
  - UV wavelengths
  - 10-30 collectors, ~1 m diameter
  - Baselines to ~500 m

http://hires.gsfc.nasa.gov/~si/

MAXIM

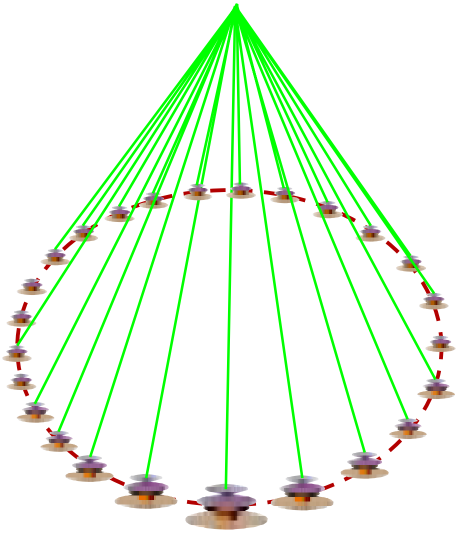


Architecture being considered for precursor mission

http://maxim.gsfc.nasa.gov/

- Micro-Arcsecond X-Ray Imaging Mission
- Objectives:
  - Probe black hole event horizons
- Features:
  - X-Ray wavelengths (0.1-1 nm)
  - 33 collectors (grazing incidence)
  - Baselines ~ 100 m
  - Distance of 500 km to combiner
  - 0.3 microarcsec resolution

Life Finder, Planet Imager



- Life Finder
  - Spectral features in planet atmospheres strongly indicative of life
  - 4 x 25 m apertures
  - 100 m baselines
- Planet Imager
  - 25 x 25 pixels over earth-like planet @ 10 pc
  - 25 x 40 m apertures
  - 400 km baselines