An Overview of the StarLight Mission

StarLight and Formation Telescopes

StarLight is the precursor to a new class of Formation Telescopes, led by TPF

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StarLight mission summary

1. Spacecraft launched together on Delta 2925

2. Checkout and formation flying experiments

3. Combiner-mode (single spacecraft) interferometry with collector parked in safe stand-off position
   - June 2006 launch to heliocentric orbit
   - Nominal 6 month mission with option of additional 6 month extension
   - Validate autonomous formation flying system
     - range control to 10 cm
     - bearing control to 4 arcmin
   - Demonstrate formation flying optical interferometry
     - wavelength 600 - 1000 nm
     - baselines 30 - 125 m

4. Formation interferometry

Original 3 spacecraft design did not fit the budget
2 spacecraft concept demonstrates all key areas of formation flying interferometry
Collector flown on the surface of a virtual paraboloid, with combiner at the focus
Gives a baseline of 125 m with a fixed delay of only 14 m

<table>
<thead>
<tr>
<th>Baseline</th>
<th>Separation</th>
<th>Bearing angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 m</td>
<td>40 m</td>
<td>46 deg</td>
</tr>
<tr>
<td>125 m</td>
<td>600 m</td>
<td>12 deg</td>
</tr>
</tbody>
</table>
Observing configuration

- Starlight field of regard
- Inter-Spacecraft Line of Sight
- Thruster stalk (8 nozzles per stalk)
- Instrument envelope
- Deployed sunshade
- 3.5 m
- 18° x 18° Star Tracker FOV (≥2 Shown)

Combiner instrument optics (unfolded)

- Left starlight (via collector)
- ~1 m
- Siderostat
- Compressor secondary
- Active delay
- Combiner sub-bench
- Fixed delay primary (14 m)
- Right starlight (direct from star)
- Siderostat (12 cm clear aperture)
Combiner instrument layout

1.3 m

Bottom side of bench

Top side of bench

Acquisition and Observation Sequence

1. Move spacecraft
2. Acquire right starlight
3. Acquire metrology
4. Acquire left starlight
5. Estimate delay & delay rate; trim formation
6. Find fringe
7. Track & Measure fringe

Target star

• Initial state

Collector

Combiner
Move spacecraft

- **Formation & Attitude Control System (FACS)**
  - Fusion of sensors inputs:
    - star trackers (~ 5 arcsec)
    - gyros
    - AFF sensor (laser metrology)
  - Actuators
    - Reaction wheels (not used for interferometry)
    - Cold gas thrusters
      - 16 per spacecraft
      - 7 mN or greater minimum impulse
  - Master/Slave architecture
  - Functions:
    - collision avoidance
    - sun avoidance
    - fuel balancing
    - minimize thruster plume impingement
  - Performance:
    - +/- 10 cm range
    - +/- 4 arcmin bearing
    - +/- 3 arcmin spacecraft attitude

1. Move spacecraft
2. Acquire right starlight
3. Acquire metrology
4. Acquire left starlight
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Autonomous Formation Flying sensor

- Ka band system (30 GHz)
- 2 Tx and 4 Rx per spacecraft
- Ranging codes based on NAVSTAR GPS
- Relative bearing from carrier phase difference
- Symmetric between spacecraft
- 2 cm range, 1 arcmin bearing (1 σ)

Prototype Ka-band Antenna with choke rings

RF signal from Collector to Combiner portion of AFF sensor
RF signal from Combiner to Collector portion of AFF sensor

Electronics mounted on back of mounting plate
Acquire right starlight

1. Move spacecraft
2. **Acquire right starlight**
3. Acquire metrology
4. Acquire left starlight
5. Estimate delay & delay rate; trim formation
6. Find fringe
7. Track & Measure fringe

- Instrument has single CCD for acquisition, angle tracking and fringes
- Acquisition field of view = 1 arcminute
- Once acquired, control loop tracks out changes of combiner inertial attitude

Acquire metrology

1. Move spacecraft
2. **Acquire right starlight**
3. **Acquire metrology**
4. Acquire left starlight
5. Estimate delay & delay rate; trim formation
6. Find fringe
7. Track & Measure fringe

- Outgoing 1.3 μm metrology beam is coincident with left combiner boresight
- Collector fold mirror houses 4-diode Metrology Pointing Sensor
- AFF sensor gives combiner - collector bearing angle
- Left combiner siderostat performs spiral search to acquire laser signal
- With metrology pointing loop locked, system can resolve 10 μm/s transverse motion @ 600 m
- Dual target linear metrology monitors external and internal paths simultaneously with one beam to 10 nm
Acquire left starlight

1. Move spacecraft
2. Acquire right starlight
3. Acquire metrology
4. **Acquire left starlight**
5. Estimate delay & delay rate; trim formation
6. Find fringe
7. Track & Measure fringe

- Left starlight boresight is locked to center of collector optics
- Collector siderostat executes a small search until star appears in combiner focal plane
- Left angle tracking control and metrology pointing loop form a coupled control system, distributed across both spacecraft
- Stray light from collector sunshade is an issue:

Estimate delay & delay rate

1. Move spacecraft
2. Acquire right starlight
3. Acquire metrology
4. **Acquire left starlight**
5. **Estimate delay & delay rate; trim formation**
6. Find fringe
7. Track & Measure fringe

\[
\text{Delay offset} = \text{Left path} - \text{Right path} = S - (S \cos \gamma + D_{\text{fixed}}) = S(1 - \cos \gamma) - D_{\text{fixed}}
\]

- AFF sensor (20 mm)
- Angular metrology (10)
- Linear metrology (25 \(\mu \text{m s}^{-1}\))
- Angular metrology (15 mas \(\text{s}^{-1}\))
Trim formation

1. Move spacecraft
2. Acquire right starlight
3. Acquire metrology
4. Acquire left starlight
5. Estimate delay & delay rate; trim formation
6. Find fringe
7. Track & Measure fringe

- Need to get within the range and rate capabilities of the active delay line
- Instrument laser metrology provides precision range rate and bearing data to FACS
- Small thrusts to trim the delay and delay rate
- Iterative process until requirements met
- When complete we have a stabilized optical structure:
  - Tip/tilt stabilization:
    - 3 pointing loops locked (left & right stellar angle tracking, metrology beam to collector)
  - Path stabilization:
    - active delay line tracks out jitter sensed by dual target linear metrology

Find fringe

1. Move spacecraft
2. Acquire right starlight
3. Acquire metrology
4. Acquire left starlight
5. Estimate delay & delay rate; trim formation
6. Find fringe
7. Track & Measure fringe

- Delay uncert ~ 10 mm (1 $\sigma$)
- Delay rate uncert ~ $20 \mu$m s$^{-1}$ (1$\sigma$)
- Search 50 mm in delay at $100 \mu$m s$^{-1}$
- Scan the delay line across the search range
- Fringes give increased variance in detected photon rate
Track & measure fringe

1. Move spacecraft
2. Acquire right starlight
3. Acquire metrology
4. Acquire left starlight
5. Estimate delay & delay rate; trim formation
6. Find fringe
7. Track & Measure fringe

- StarLight measures visibility amplitude at each of 5 baselines (30 - 125 m)
- White light and 4-channel dispersed fringe outputs, sampled at 500 Hz
- Inherit algorithms from Keck Interferometer
- The interferometer performance will be characterized by observations of ~ 20 known stars of different size and brightness, down to about 5th magnitude

Technology development

- Formation Interferometry Testbed
- Formation Flying Simulations
- Autonomous Formation Flying Sensor tests
- Linear and angular metrology
Recently achieved white light fringe tracking
- Instrument visibility ~40% (matches the predicted value)
- All control loops operating simultaneously
- Performance limited by:
  - 20m airpath each arm
  - 50 Hz camera

Key performance metrics

<table>
<thead>
<tr>
<th>Performance metric</th>
<th>StarLight</th>
<th>TPF Planet-finding</th>
<th>TPF Astrophysics</th>
<th>StarLight Technology</th>
<th>TPF need</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Wavelength band (fringes)</td>
<td>600 - 1000 nm</td>
<td>7 - 20 μm</td>
<td>3 - 30 μm</td>
<td></td>
<td>2-spacecraft parabolic</td>
</tr>
<tr>
<td>2 Baselines</td>
<td>30 - 125 m *</td>
<td>75 - 200 m</td>
<td>75 - 1000 m</td>
<td></td>
<td>geometry</td>
</tr>
<tr>
<td>3 Separation</td>
<td>40 - 600 m *</td>
<td>25 - 70 m</td>
<td>25 - 330 m</td>
<td></td>
<td>angular resolution</td>
</tr>
<tr>
<td>4 Range control (+/-)</td>
<td>10 cm *</td>
<td>5 cm</td>
<td>5 cm</td>
<td>AFF sensor, angular</td>
<td></td>
</tr>
<tr>
<td>5 Bearing control (+/-)</td>
<td>4 arcmin *</td>
<td>1 arcmin</td>
<td>0.2 arcmin</td>
<td>metrology, formation-</td>
<td></td>
</tr>
<tr>
<td>6 Range knowledge (1 σ)</td>
<td>2 cm</td>
<td>1 cm</td>
<td>1 cm</td>
<td>flying algorithms,</td>
<td></td>
</tr>
<tr>
<td>7 Range rate knowledge (1 σ)</td>
<td>&lt; 1 μm / s</td>
<td>35 μm / s</td>
<td>1 μm / s</td>
<td>low impulse thrusters</td>
<td></td>
</tr>
<tr>
<td>8 Inertial Bearing knowledge (1 σ)</td>
<td>10 arcsec</td>
<td>10 arcsec</td>
<td>2 arcsec</td>
<td>sizes delay lines</td>
<td></td>
</tr>
<tr>
<td>9 Bearing rate knowledge (1 σ)</td>
<td>30 miliarcsec / s</td>
<td>40 miliarcsec / s</td>
<td>0.2 miliarcsec / s</td>
<td>sizes delay lines</td>
<td></td>
</tr>
<tr>
<td>10 Path length stabilization (1 σ)</td>
<td>35 nm</td>
<td>3.5 - 70 nm</td>
<td>70 nm</td>
<td>formation control;</td>
<td></td>
</tr>
<tr>
<td>11 Tip/tilt stabilization (1 σ)</td>
<td>0.1 λ/D</td>
<td>0.025 λ/D</td>
<td>0.05 λ/D</td>
<td>fringe search</td>
<td></td>
</tr>
</tbody>
</table>

* nominal performance; limits to be pushed on orbit