AN INNOVATIVE DEEP SPACE APPLICATION OF GPS TECHNOLOGY FOR FORMATION FLYING SPACECRAFT

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Topics

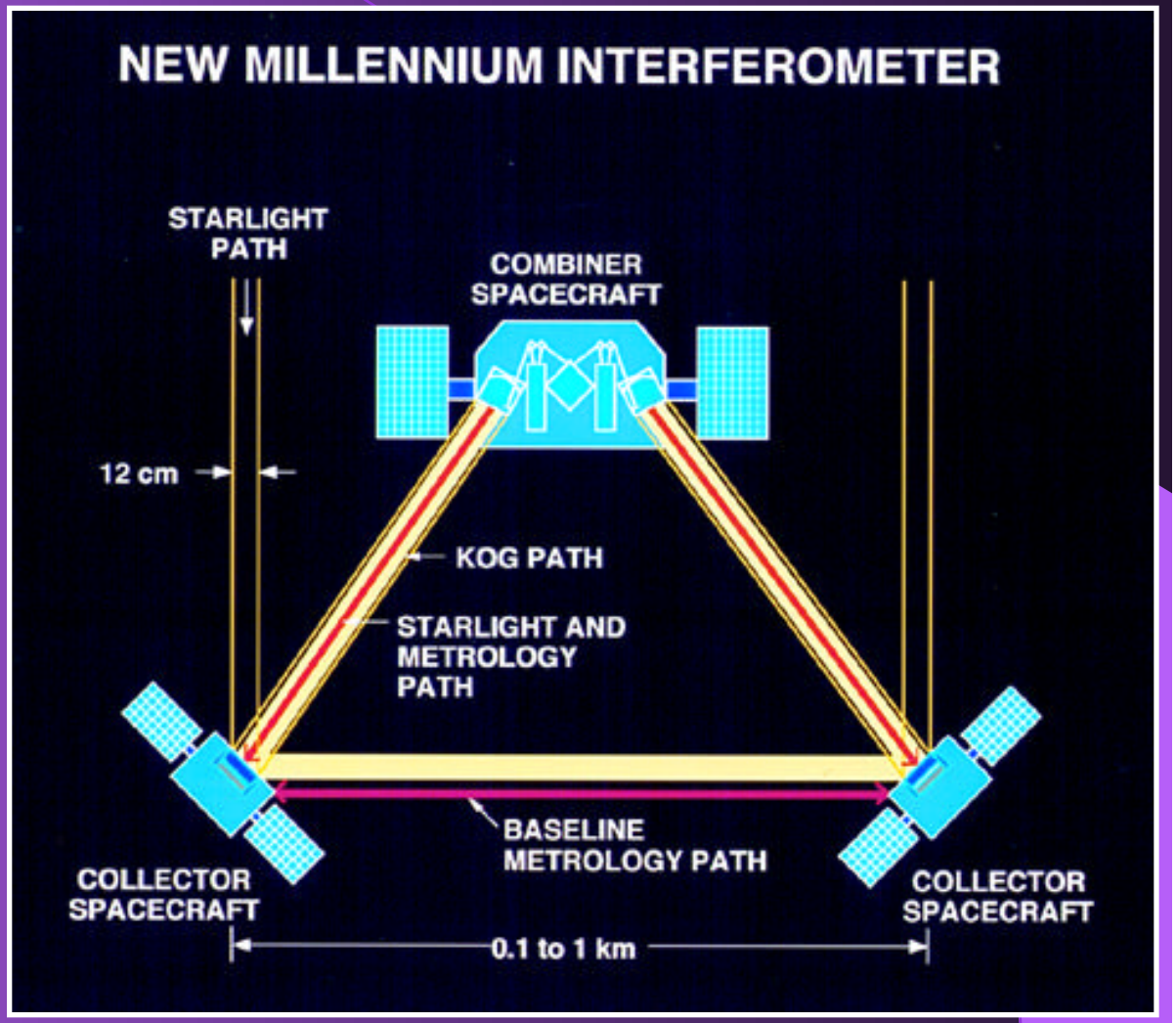
- Objective
- New Millennium Interferometer
- Background on formation flying
- The Autonomous Formation Flying GN&C sensor
- Testing the AFF

Objective

- Formation flying sensor
  - Conceptual design
  - Deep space
  - Applicable to on or near Earth applications

New Millennium Separated Spacecraft Interferometer

- Technology demonstration
  - Precision formation flying technologies
  - Interferometer components
  - Integration for space
- Future 21st century interferometers
  - Origins of stars & galaxies
  - Detect Earth-like planets
  - Higher number of spacecraft
  - Thousands of kilometer separations



NM SSI G&C requirements

- Heliocentric orbit
  - ~0.1 Au from Earth after 6 months life
- Formation of three spacecraft
  - Variable baselines
    - 100 meters to 1 kilometer
  - Precision formation flying
    - ±1 cm relative ranging
    - ±1 arcminute relative orientation
    - ±0.1 mm/sec relative velocity

NM SSI G&C challenges

- Autonomous precision formation flying
  - Real time ground operations impossible
    - Due to large distances
    - Formation resolution from ground
    - Round trip light time
- G&C challenges
  - Optimal controls
    - Initialization & maintenance
    - Efficient formation maneuvers
  - Collision avoidance
  - **Formation sensing**

What is formation flying?

- Assembly of multiple spacecraft
  - Orbit or pattern
  - Common goals
  - “Virtual platforms”, co-flying, constellation, etc.

Class	Coupling	Control Accuracy	X-link	S/C Similarities	Ex. Sensors
Coarse Intermediate **Precision**	Loose Moderate **Tight**	>1 km 1 m - 1 km **<1 m**	None/limited Moderate **Full**	None/limited Some **Full**	GPS/Others RF/GPS **Optical/RF**

Formation sensing

- Requirements
  - Satisfy performance requirements in deep space
  - Self contained system
  - Few centimeters to 10 kilometer range
  - 4π steradian coverage
  - Mass, power & complexity
- Solution
  - The Autonomous Formation Flying GN&C sensor (AFF)
    - GPS *trans*ceiver with attitude determination capabilities
      - Relative ranges
      - Relative attitudes
      - No NAVSTAR GPS signals

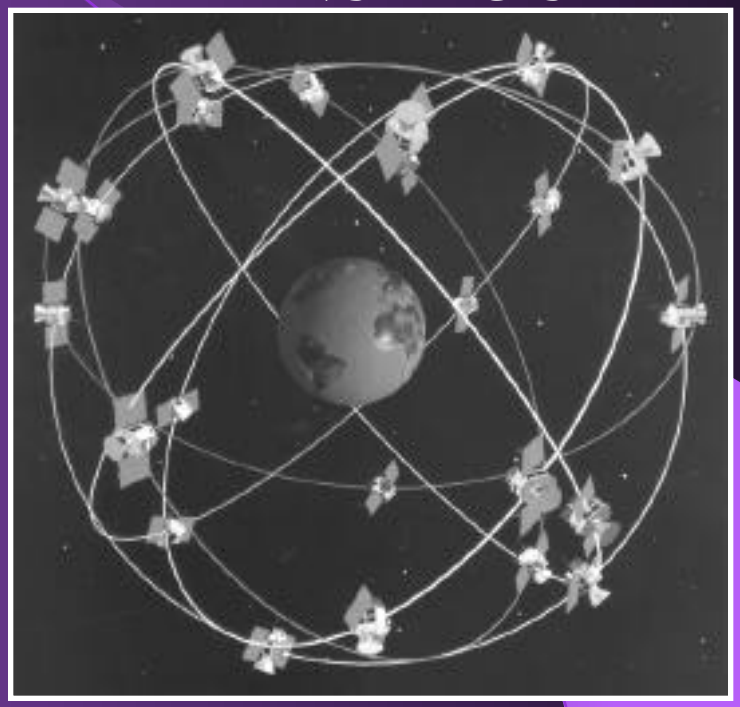
Disadvantages of other formation sensors

- Radar
  - Provide range & limited attitude
  - Limited field of view (FOV)
  - High power
- Optical Sensors
  - Limited FOV, even with fisheye lenses
    - Complexity
    - Gimbaled platform/mechanisms or spacecraft slews
  - Power (range) & mass issues

Current GPS applications

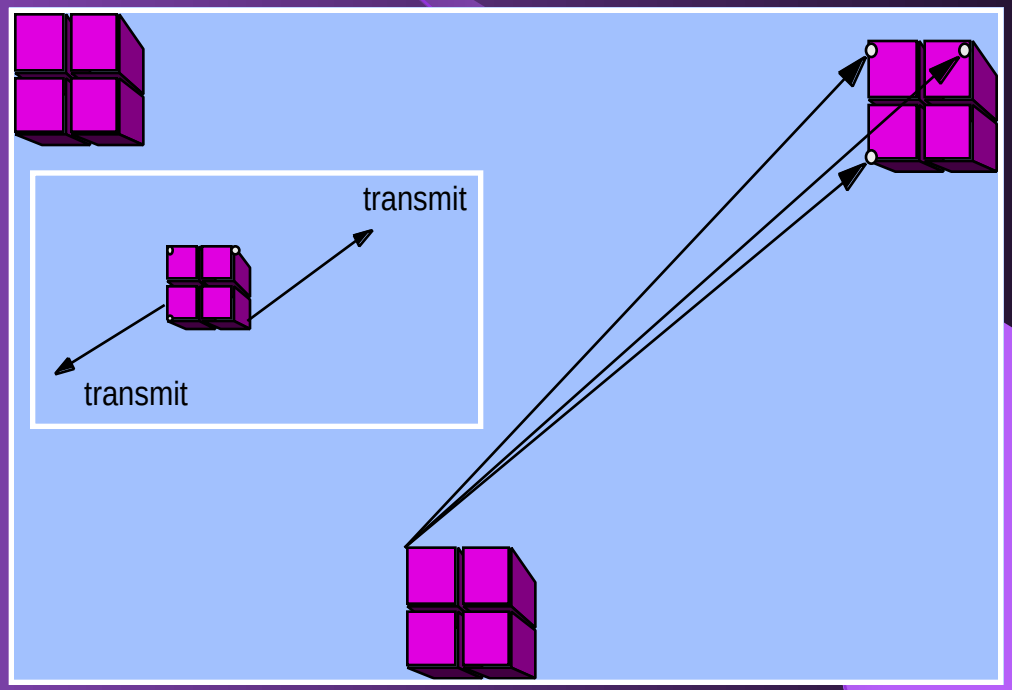
- Limited by GPS coverage
  - Satellites down-looking at 20,000 km
- Terrestrial applications
  - Land
  - Oceans
  - Air
- Space applications
  - Low Earth orbit
  - At most up to geosynchronous orbit
- **Concept applying GPS technology to deep space formation flying!**

NAVSTAR GPS



What is an AFF?

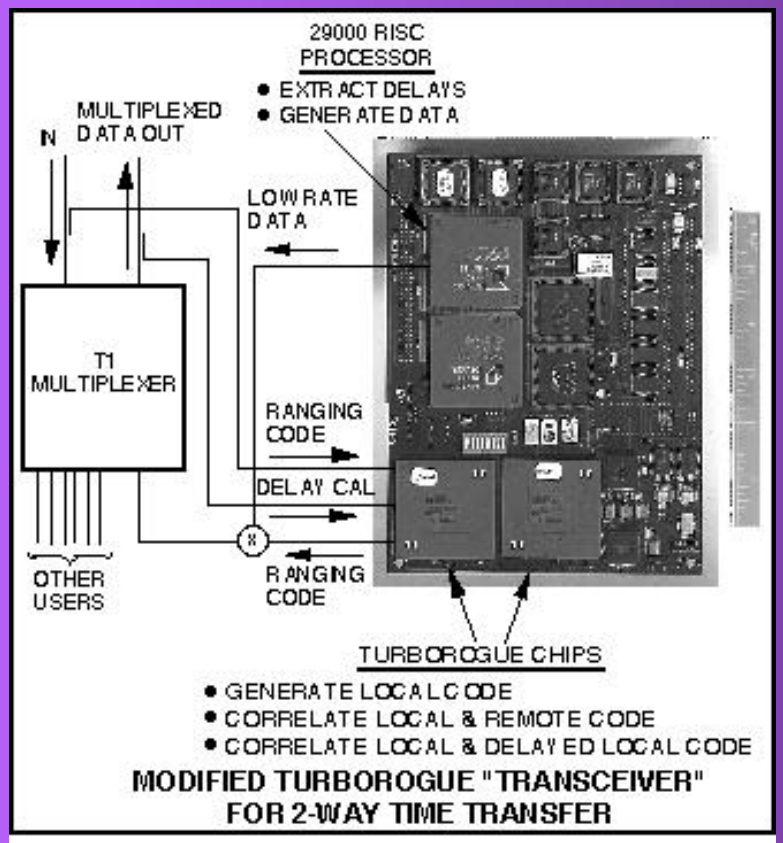
- JPL's TurboRogue™ GPS transceiver
- No NAVSTAR GPS signals
  - Can accommodate if desired
- Minimal apriori knowledge
- Characteristics per AFF
  - 6 small receive antennas
    - 3 front & 3 back
    - 4π steradian FOV
  - 2 transmit antenna
    - Ka band signal, not L band
  - < 1 Wdc, 2 kg total
  - 1300 km range
  - Design satisfies requirements

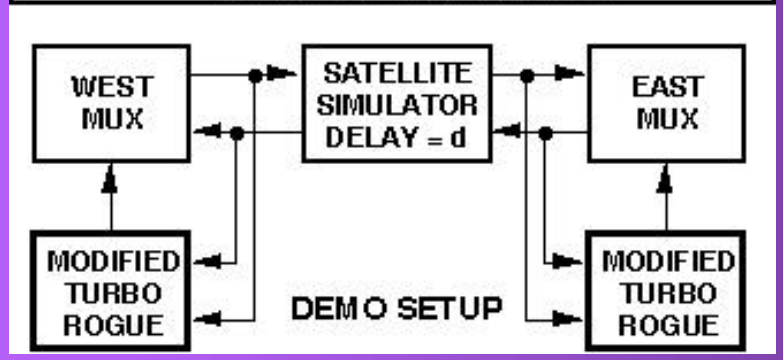


How does the AFF work?

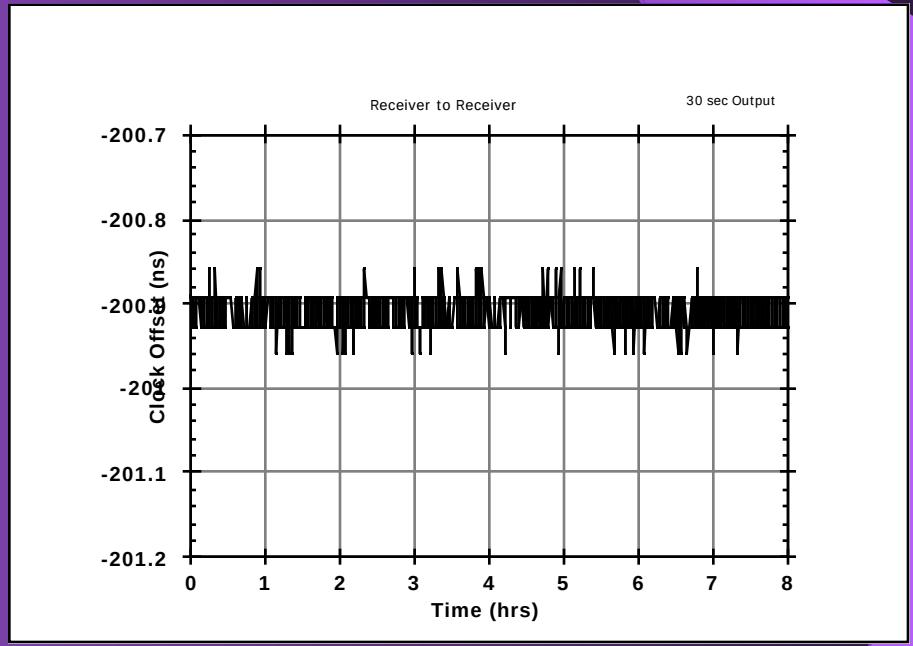
- Transmits 1 or 2 *equivalent* NAVSTAR signals to another AFF
  - Transceiver internally generates ranging codes & carrier phase for transmission
  - Second treats received signals as a regular GPS receiver
    - Pseudo range, velocity, time & attitude computations
  - Can also encode other data signals
    - Use for inter-spacecraft communications
- No limit in number of AFFs in a formation
- Extendible for absolute sensing
  - AFF dedicated channels for NAVSTAR GPS signal sensing

Leveraging previous research

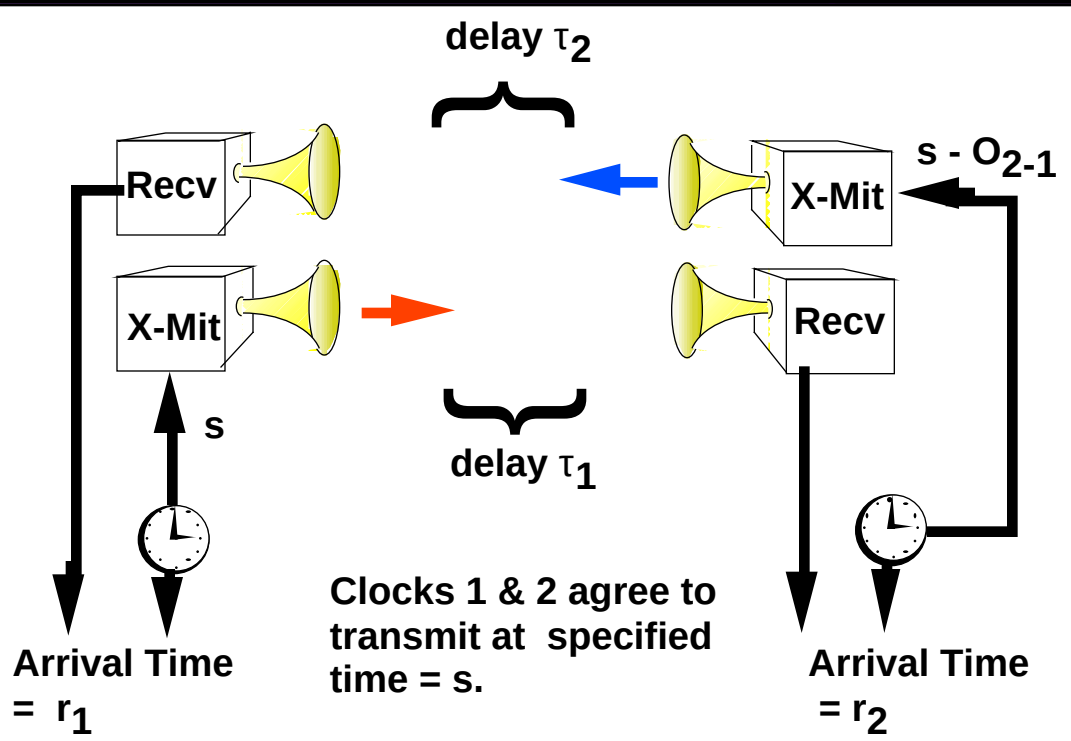




- 1994 experiment by JPL
- Sub-nanosecond dual one way time transfer
- 2 TurboRogue™ receivers transmitting & receiving
  - 6 mm range error
    - 0.02 nanosecond clock errors



Clock calibration



Clocks 1 & 2 agree to transmit at specified time = s.

$r_2 = s + \tau_1 + O_{2-1}$.

$r_1 = s - 0_{2-1} + \tau_2$.

if delays $\tau_1 = \tau_2$, then

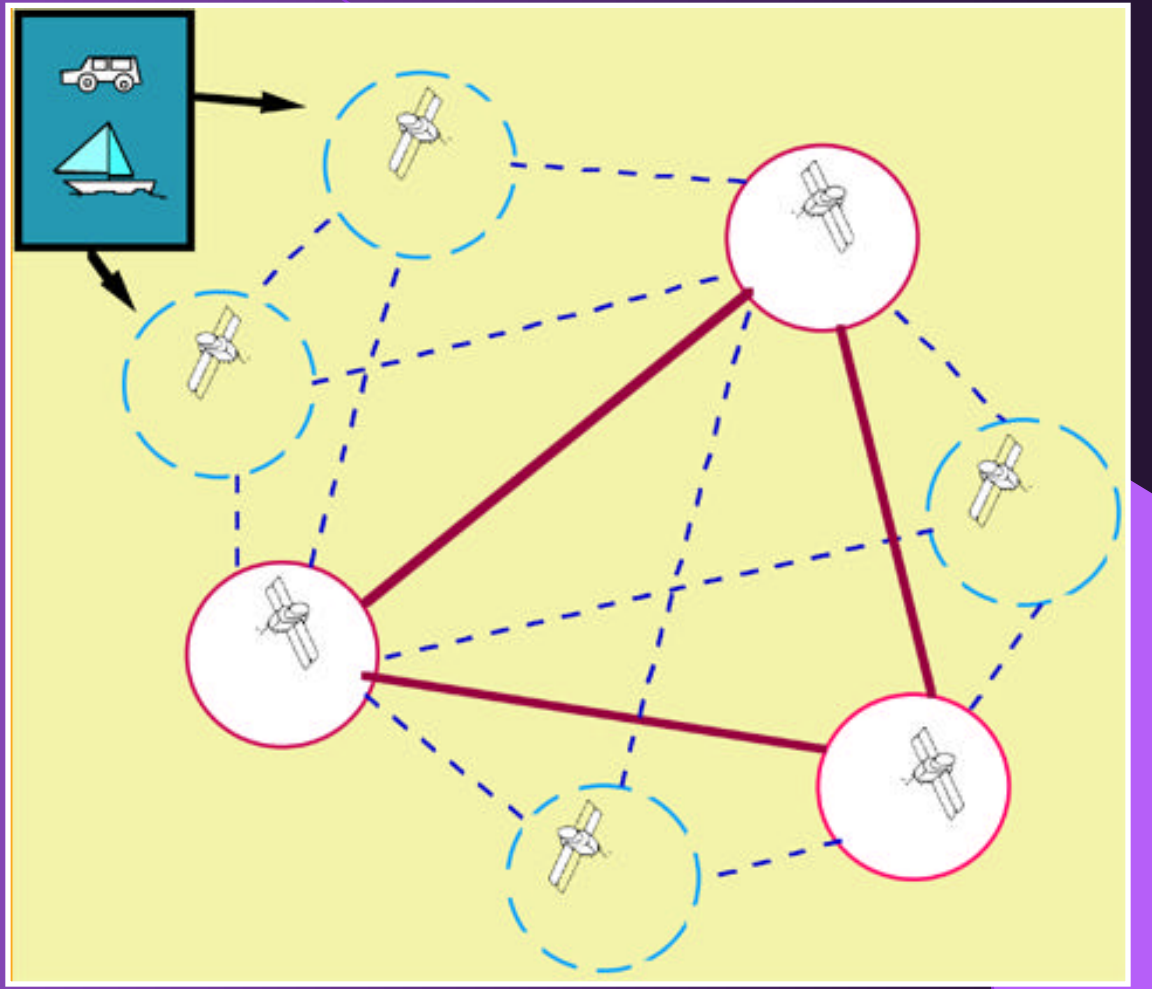
Clock offset

$O_{2-1} = (r_2 - r_1)/2$.

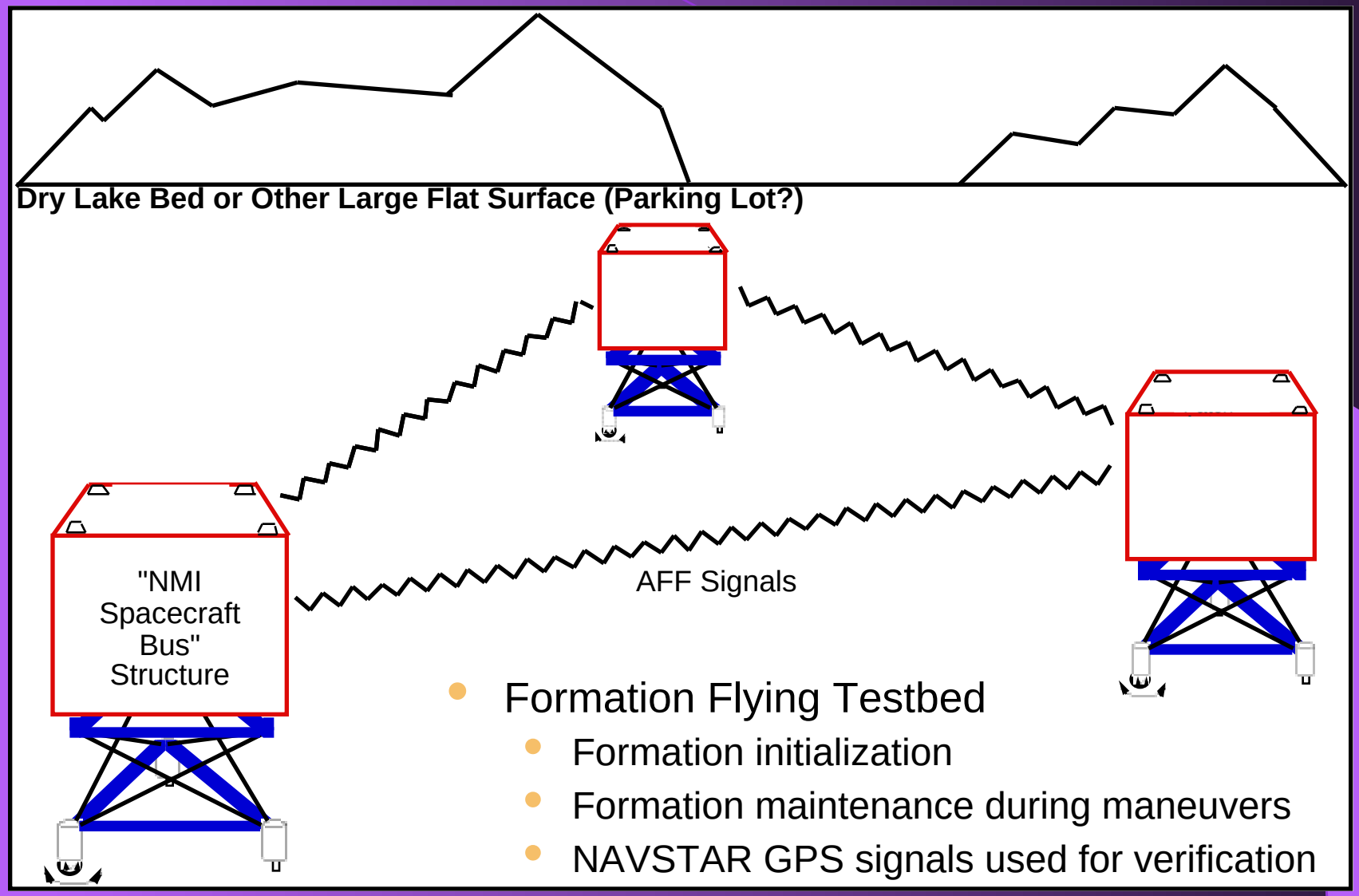
- Clock offsets uniquely determined
- Using combination of 2 one way signals

Other usage of the AFF

- Any application requiring multiple platforms
- Land
  - Robotics vehicles
- Marine
  - Ships
  - Submersible formations
- Air
  - Aircraft collision avoidance
  - Formation flying
- Space
  - Formation flying in Earth orbit
  - Rendezvous & docking sensor



Testing the AFF



- Formation Flying Testbed
  - Formation initialization
  - Formation maintenance during maneuvers
  - NAVSTAR GPS signals used for verification

Status and vision for the future

- Status
  - Completed conceptual design phase
  - Awaiting approval for engineering development
    - 1.5 years development time for 3 AFFs
    - Demonstrate in the Formation Flying Testbed
  - Patent pending
- Vision for the future
  - Leverage JPL's "GPS on a Chip" technology development
  - Incorporate deconvolution based or other promising multipath elimination algorithms
    - Patent pending for the deconvolution based algorithm