Overview of Ultra-Precise Time Transfer Formation Flying, and Spacecraft-Spacecraft Tracking Systems

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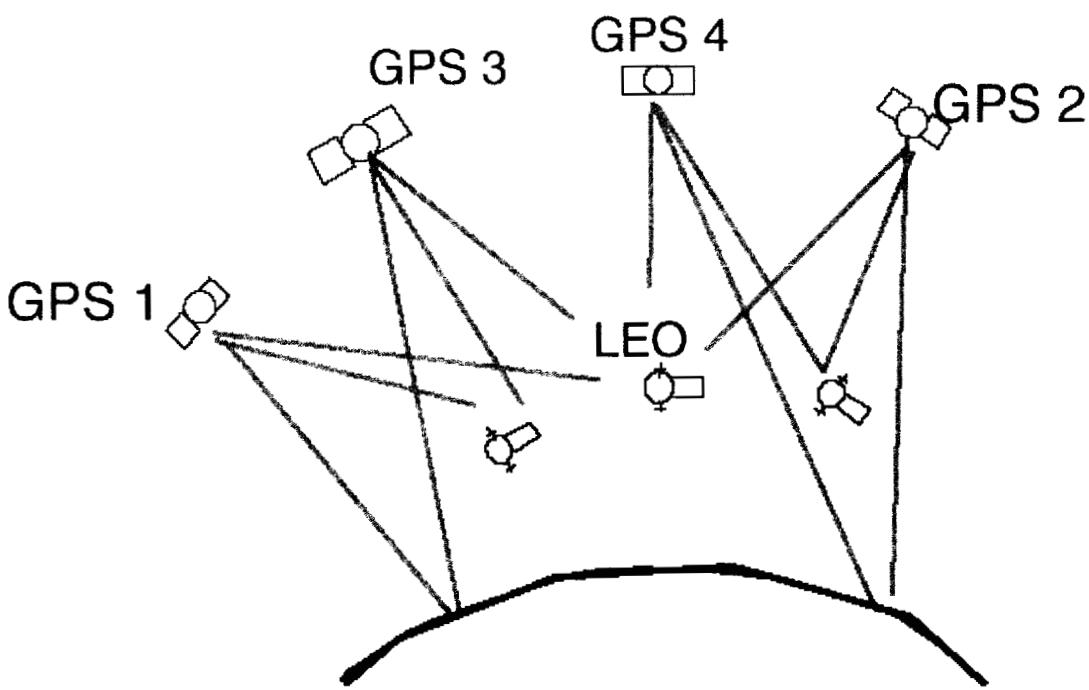
JPL

Introduction

- NASA has invested extensively in developing an advanced capability for precision spacecraft-spacecraft tracking sensors and systems
- JPL's in-house expertise has teamed with other NASA centers and with commercial partners to develop and prove these capabilities
- These technologies will be important to leverage in NASA's precision formation flying deployment in the future
  - Lead organization for precision flight GPS
  - Signal structure; innovative precision receiver/transceiver designs
  - Numerous spaceborne experiments and deployments
  - Orbit/trajectory estimation and user positioning
  - Precise spacecraft-spacecraft tracking systems
  - GPS global ground networks and automated data acquisition systems (24/7 basis)
  - Real-time and non-real-time applications; navigation; geolocation and time transfer
  - Science: atmosphere, ionosphere, gravity, geophysics
- Frequency and Timing unique core expertise
  - 24/7 mission critical frequency & timing subsystems in NASA/JPL Deep Space Network
  - Advanced atomic clock technology development; innovative oscillators and resonators; precision time and frequency measurements for NASA, USAF Research Lab and USNO
  - Underlying fields: quantum optics and electronics, laser cooling, fundamental physics
  - Advanced space clocks for GPS (Linear Ion Trap clock) and Space Station experiments

Precision LEO Positioning and Timing

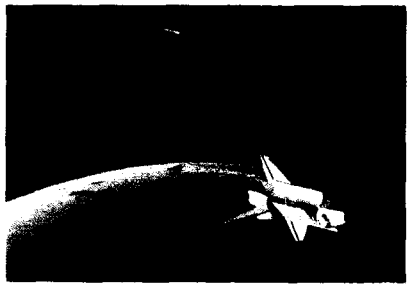
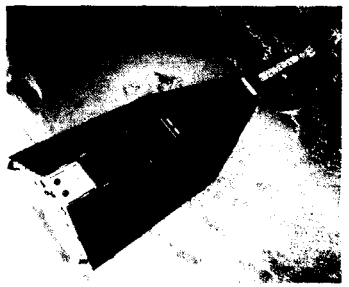
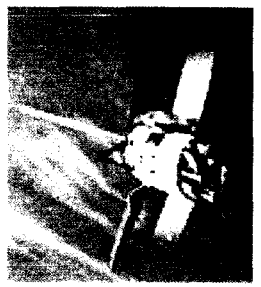
- GPS tracking maintains constant and precise knowledge of relative spacecraft positions & clocks
- JPL has specialized in high precision GPS flight deployments
  - Centimeter-level navigation
  - Science remote sensing



JPL's GPS Flight Deployments

- With the January 2003 launch of ICESat, JPL has had 16 consecutive successful GPS flight deployments into Earth orbit
  - 6 of these were in-house builds of the JPL/NASA Blackjack GPS receiver, designed for high accuracy and science applications
  - 10 were flight hardware builds to JPL's design or specification by various companies
  - All 16 have JPL flight software onboard

Flight Deployments of JPL's Blackjack GPS Receivers

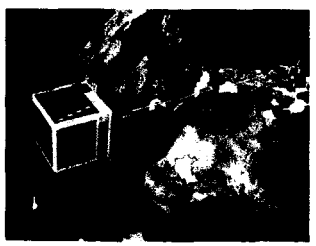




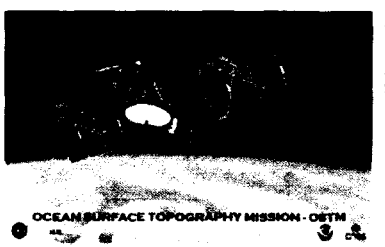
SRTM	CHAMP	SAC-C	JASON-1	GRACE
Feb 2000	Jul 2000	Nov 2000	Dec 2001	Mar 2002

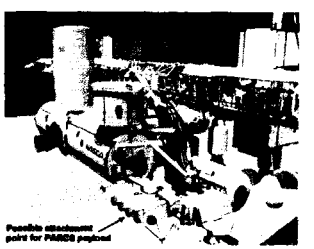
High Accuracy Spacecraft-Spacecraft Tracking

software-driven ⇒ multitude of applications

Dec 2002	Jan 2003	2003	2005	2005	2007
FedSat	ICESat	C/NOFS	COSMIC	OSTM	PARCS

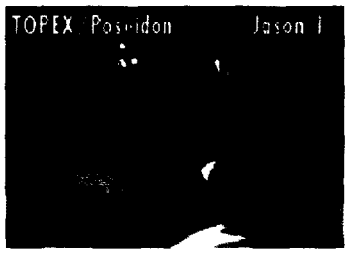






Precision Spacecraft-Spacecraft Tracking

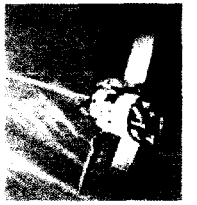
- JPL/NASA GPS deployments have realized the most accurate in-orbit spacecraft-spacecraft tracking systems
- Strong TRL 8-9 heritage/base for precision formation flying sensors
- JPL is producing real-time orbit products for SAC-C and Jason-1



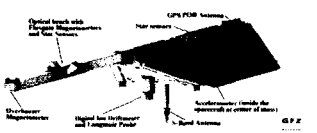
1336 km altitude

- 2-cm radial orbits (Topex GPS flight receiver, Motorola built to JPL specs)
- 1-cm radial orbits (Jason-1 GPS flight receiver, JPL Blackjack design)

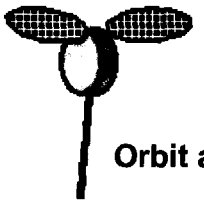
operational automated processing



SAC-C: 705-km alt
< 5-cm orbit accuracy



CHAMP:
470-km alt
< 5-cm orbit accuracy



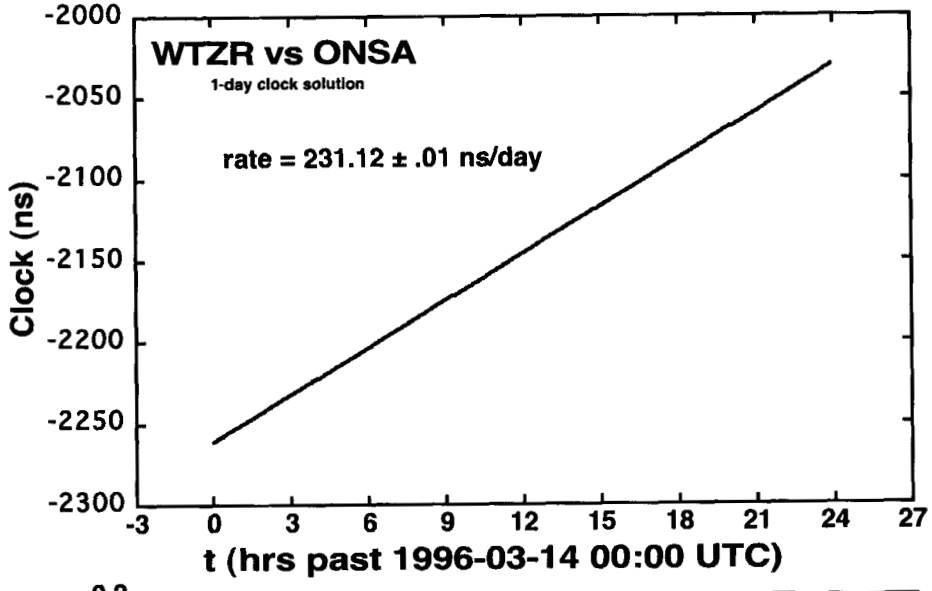
MicroLab/GPSMET
730 km altitude

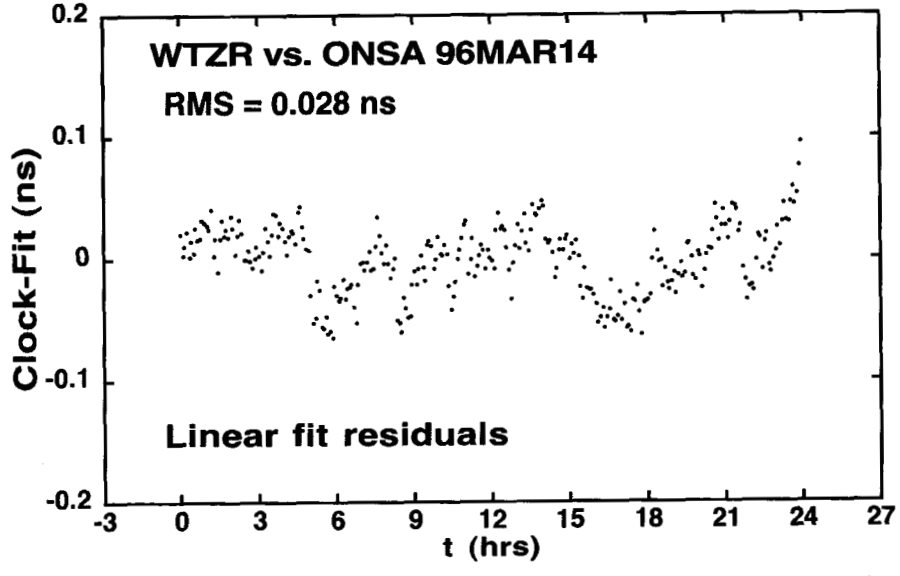
Orbit accuracy < 10 cm

GRACE: 500-km alt (2 s/c)

- 2-cm orbit accuracy
- 100-psec relative timing
- few-micron interspacecraft K-band ranging

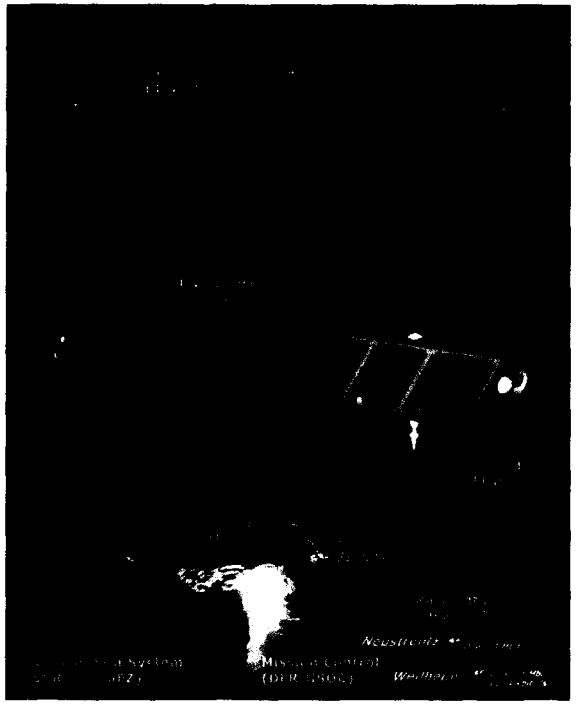
Ultra-Precise Time Transfer with GPS

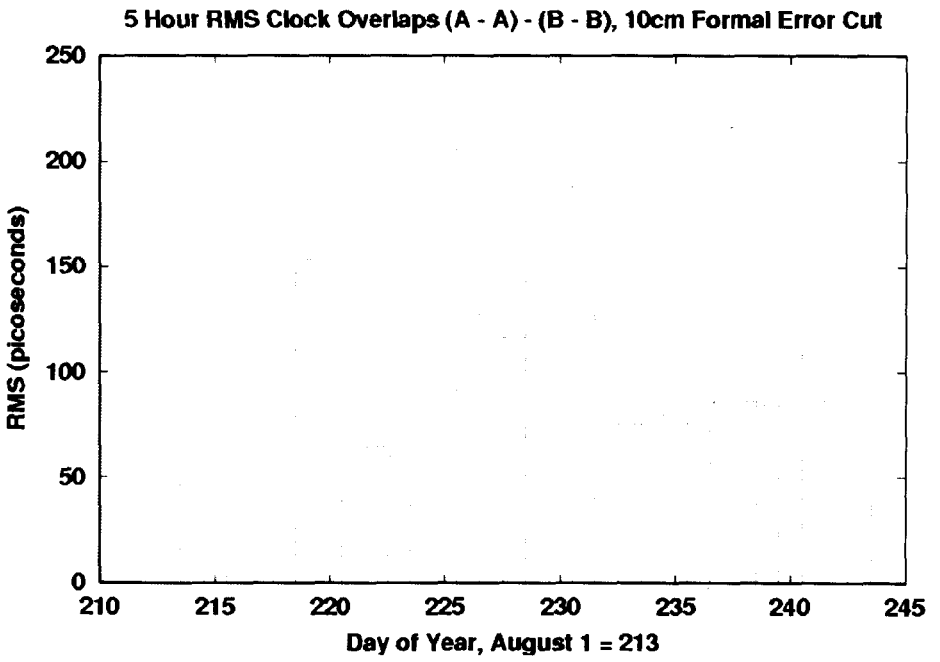




Linear fits to GPS-based clock estimates for pairs of masers worldwide (some separated by 1000's of km) show rms scatter of better than 30 picosec.

Ultra-Precise GPS Time Transfer on GRACE

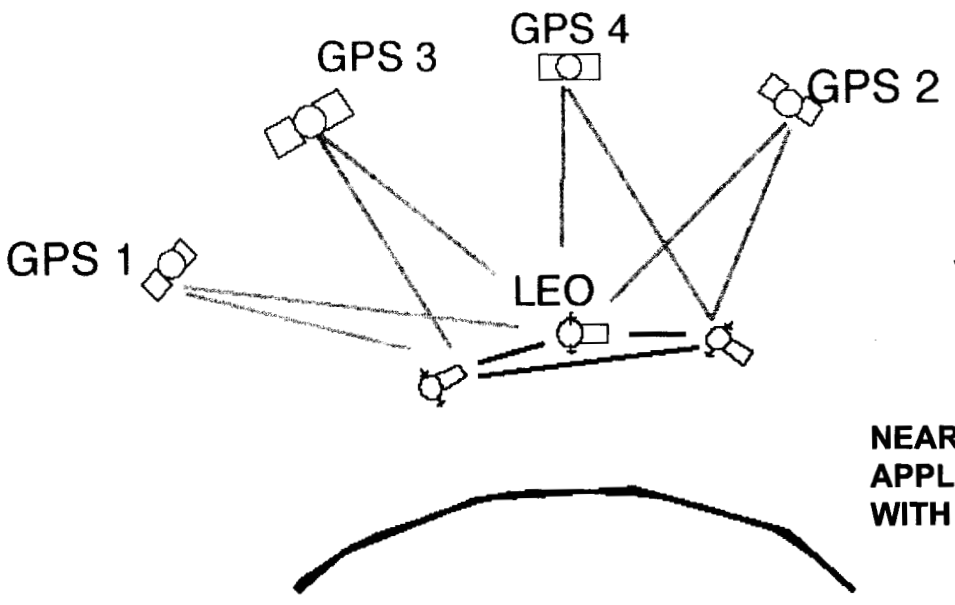




- **On the GRACE spacecraft pair at 500-km altitude, 100-picosec relative timing accuracy has been achieved (200-km separation) in low-Earth orbit. These results assume white noise for onboard clocks, even though each is a USO.**
  - **Improves to ~ <u>few tens of picosec</u> when USO stability is exploited in processing.**
  - **The GRACE mission requirement was 150-picosec accuracy**

Precision Spacecraft Positioning and Timing

- Spacecraft cross-link tracking (with or without GPS) maintains constant & precise knowledge of relative spacecraft positions/clocks



NEAR-EARTH APPLICATION WITH GPS

DEEP SPACE APPLICATION WITHOUT GPS

JPL/NASA Spacecraft Cross-Link Sensors

GRACE (in flight now): JPL GPS Receiver with integrated camera and K-band spacecraft-spacecraft tracking, is now making 1-micron accuracy measurements of range change to improve knowledge of the Earth's gravity field <u>by several orders of magnitude</u>

Terrestrial Planet Finder/Starlight (in development): precision (1-cm) formation flying

Mars Network Node: Integrated Navigation and Telecommunications (in development)

Autonomous Formation Flyer (AFF)

- AFF Sensor is a novel design innovated and patented by the JPL GPS team (335)
  - Originally "seeded" as a small exploratory technology task
  - Infused into New Millennium Program (NMP) for the DS-3 mission (Separated Spacecraft Interferometer).
  - Moved into the Origins Program where DS-3 -> ST-3 -> StarLight (TPF)
  - U.S. Patent No. 6,072,433, "An autonomous formation flying sensor for precise autonomous determination and control of the relative position and attitude for a formation of moving objects", June 6, 2000. (Lawrence E. Young, Stephen M. Lichten, Jeffrey Y. Tien, Charles E. Dunn, Bruce J. Haines, Kenneth H. Lau)
- A Ka-band prototype of the AFF Sensor has been developed and extensively characterized.
  - Fundamental algorithms have been demonstrated
- AFF Sensor is ready for adoption into future multiple spacecraft precision formation flying missions and/or flight demonstrations
  - With customization for individual missions.
- Being evaluated further under Terrestrial Planet Finder (TPF) pre-project technology program

AFF Key Features

- Performance
  - (2 cm, 1 arcmin) accuracy when the spacecraft are directly facing each other
  - Wide field of view coverage (~±70° cone)
  - 3-D relative positioning (range, azimuth angle, elevation angle)

- Autonomous
  - No real-time ground-based interaction
  - Self-contained instrument: Transmit, receive and data communication HW/SW on multiple spacecraft
  - No aid from Earth-based GPS system

- Real-time
  - Real-time determination of range and bearing angles for real-time use in the formation flying control system

AFF Description

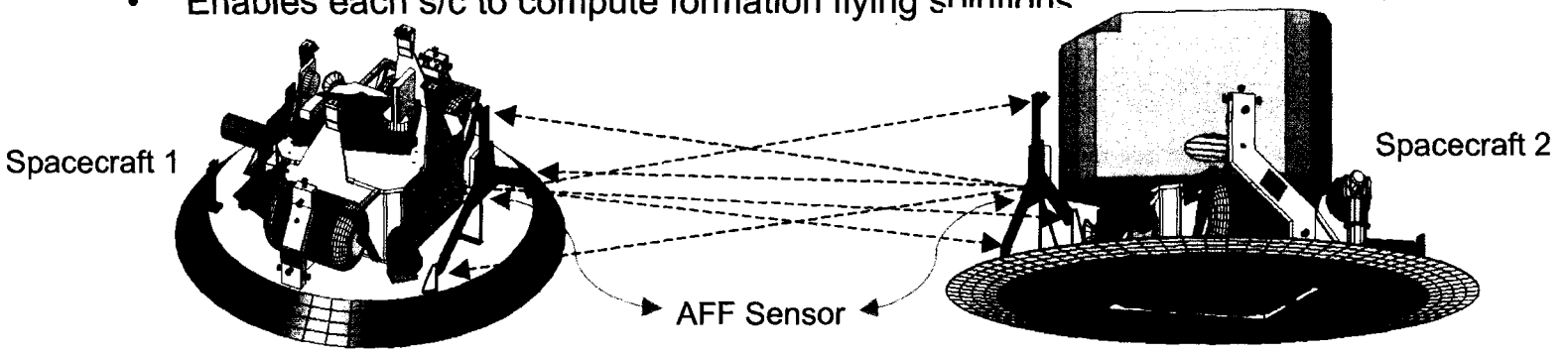
- An RF instrument that is distributed over multiple s/c.
- AFF Sensor on each spacecraft transmits and receives GPS-like signals

  $S(t) = P(t)D(t)\cos(2\pi ft + \phi)$

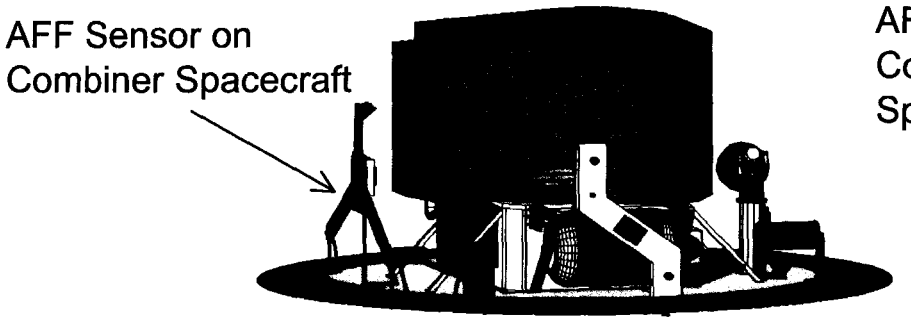
  where $P(t)$ = ranging code

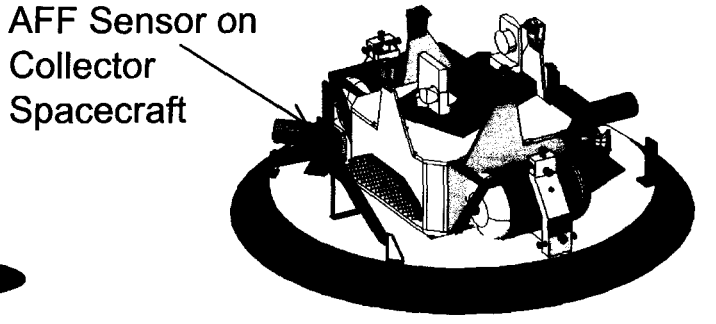
  $D(t)$ = Data bits (telemetry)

  f = carrier frequency (RF, Ka-band for StarLight)
- 1 TX and 3 RX on the front of each s/c (for determination of range and bearing angles)
- Range is derived mainly from ranging code delay between the s/c
- Bearing angles are derived mainly from carrier phase observables
- Telemetry exchanged on the RF link
  - Calibration across the two spacecraft
  - Enables each s/c to compute formation flying solutions



Challenges in a Distributed S/C Mission





Key challenges are:

- To achieve required RF performance in the presence of multipath
  - Effective antenna pattern
  - Effective isolation between TX and RX antennas
- To maintain insensitivity to thermal, electrical and mechanical instabilities
  - Continuous self-calibration techniques across multiple spacecraft
- To implement the required frequency scheme at Ka-band
- To operate as a single instrument distributed across multiple spacecraft
- Initial signal acquisition and calibration of the distributed system
- To be accommodated concurrently with other spacecraft subsystems and the interferometer, while minimizing multipath

[ ] addressed to-date (achieved in AFF testbed) [ ] future work [ ] optimize on individual missioin basis

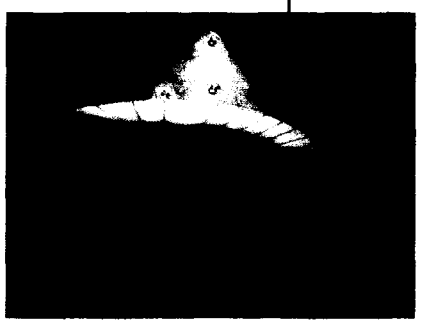
Technology Development

Key technology challenges have been addressed as follows:

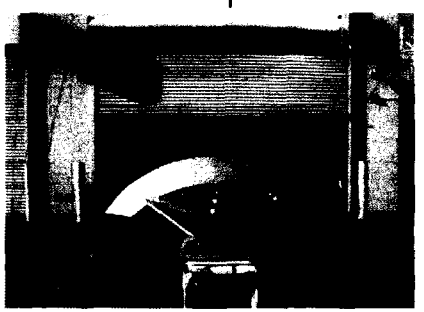
- **An end-to-end Ka-band prototype system was developed.**
- **Related spacecraft mockups were fabricated.**
- **Four testbeds were used.**

End-to-end AFF Sensor Error Budget
Max. 1-σ uncertainty: 2 cm (range), 1 arc-minute (bearing)

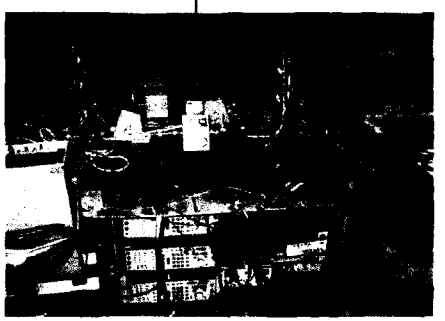
Analysis



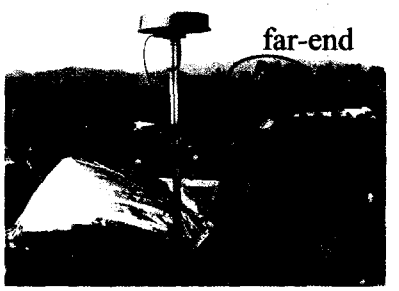
Antenna pattern assessment Testbed



Outdoor Antenna Isolation Testbed

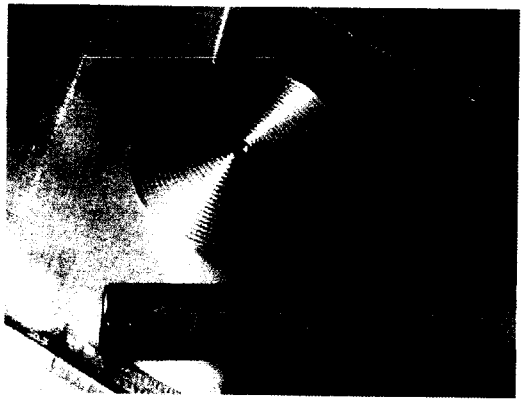


Indoor AFF Sensor Testbed

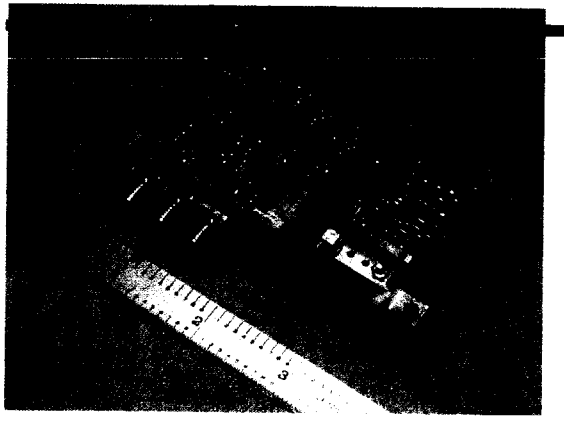


358-meter Range Outdoor Radiated Testbed

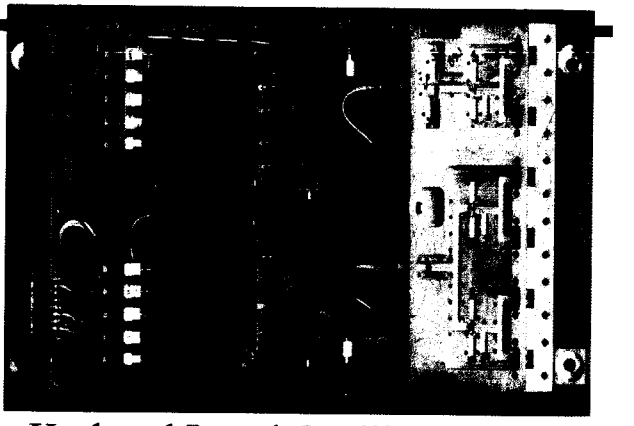
Prototype AFF Hardware



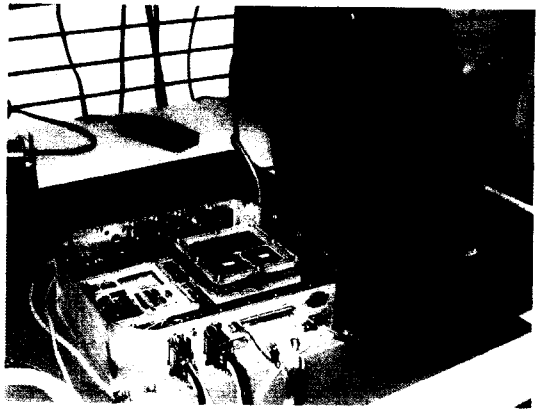
Prototype Ka-band antenna with choke rings



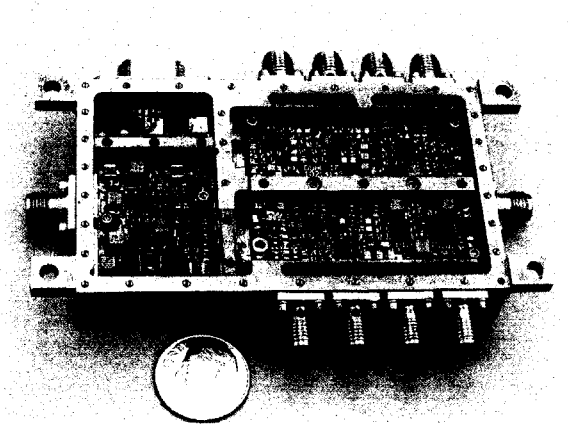
Ka-band Transmitter:
Output: 32.64 GHz RF signal at 13 dBm



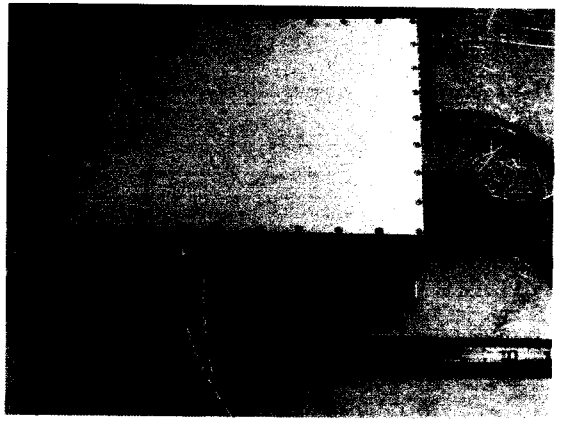
Ka-band Local Oscillator:
Output: 32.64 GHz generated from 120 MHz input.



Prototype Baseband Processor – modified GRACE baseband processor (IPU)



Ka-band Receiver:
Input 32.64 GHz,
Output: 60 MHz 1-bit I and Q samples



Reference oscillator:
120 MHz

AFF Sensor Indoor Testbed (JPL 138-116 Lab)

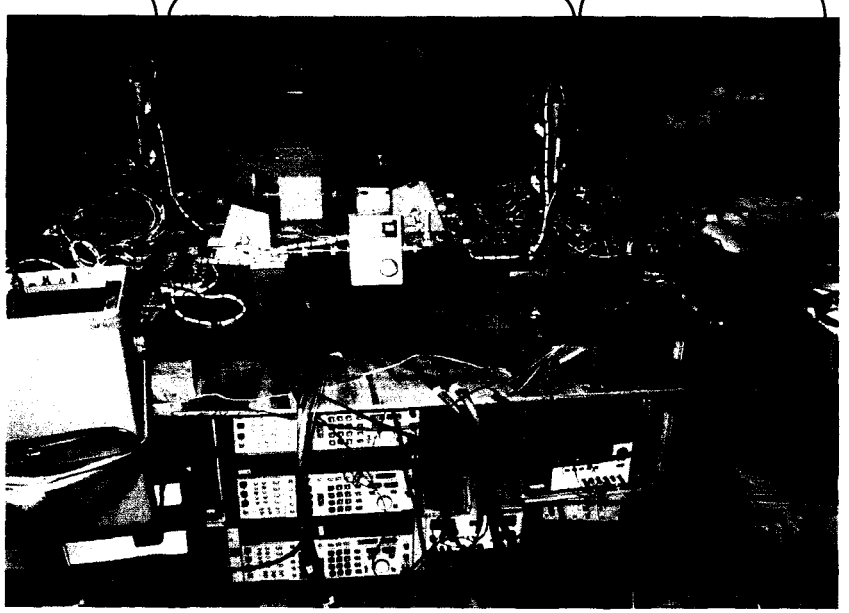
Objective:

Verify fundamental algorithms distributed across multiple spacecraft.

Approach:

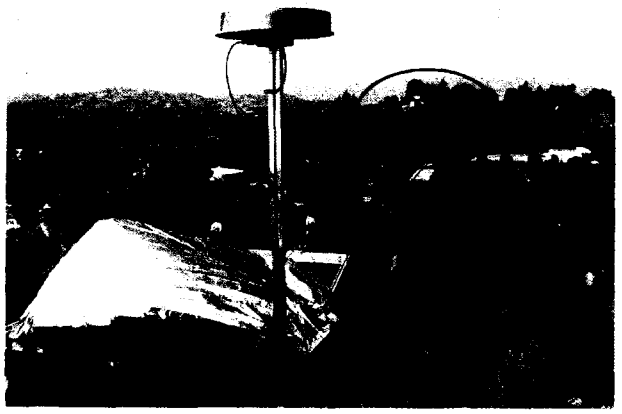
- Integrate an indoor testbed representative of the AFF Sensor distributed on two "spacecraft."
- Composed of Ka-band and digital modules on two sides connected by adjustable waveguide attenuators representative of the space loss.
- Each half of the sensor is operated from an independent frequency reference.

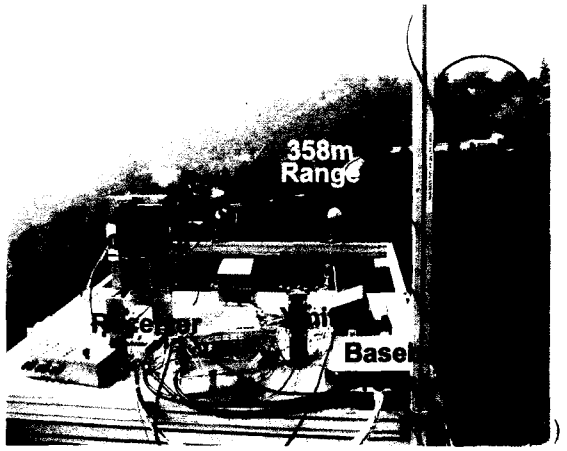
AFF Sensor on Spacecraft #1 | representative space-loss | AFF Sensor on Spacecraft # 2



- **Verified fundamental, distributed sensor algorithms**
- **Verified carrier-aided smoothing algorithm**
- **Verified continuous self-calibration across two halves (phase & range observables)**

End-to-End AFF Functionality Field Test Across 1200-foot Outdoor Range





Approach:

- Operated prototype AFF Sensor distributed over two halves across 1200-foot outdoor range.
- Introduced changes in ranges and bearing angles.
- Estimated range and bearing angle from observables measured during end-to-end operation.

Conclusion:

- Verified end-to-end functionality of AFF Sensor successfully
  - Measured ranges matched the GPS-surveyed "truth" ranges (within limits from local multipath)
  - Range-change and bearing angle estimates matched the "truths" in the experiment.
  - Full end-to-end performance to be determined by operation across a large (>30 m) range with space-like conditions.

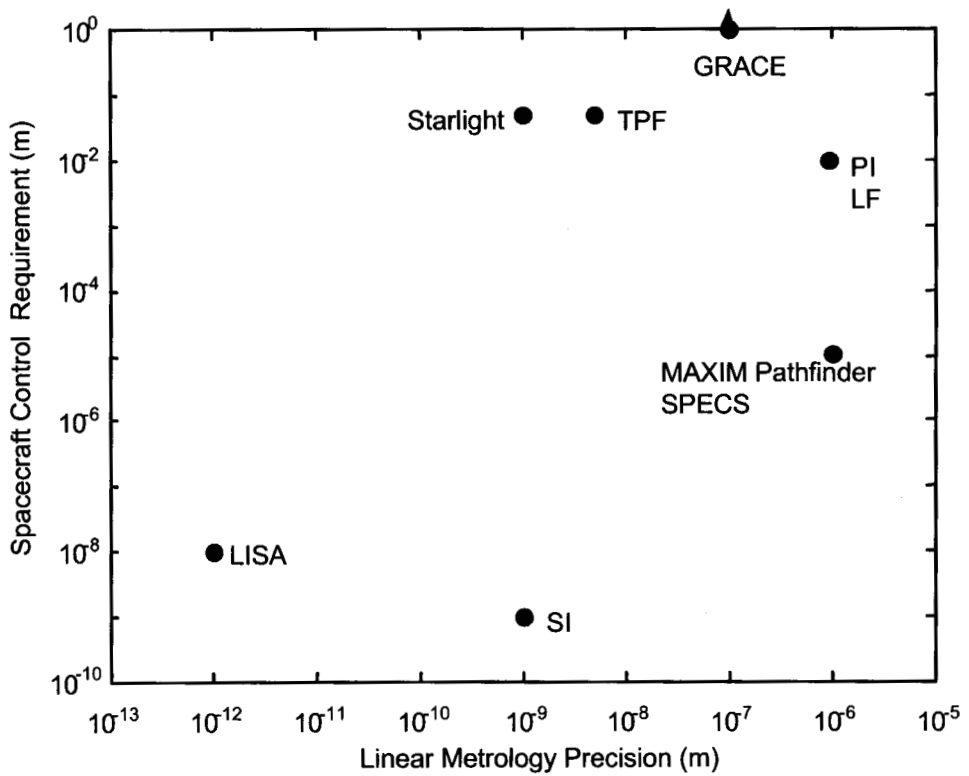
Summary

- Precision s/c-s/c tracking (cm-level) demonstrated in space via repeated deployments of JPL/NASA GPS flight receivers into Earth orbit
- GRACE mission utilized two spacecraft with JPL/NASA precision GPS and micron-level ranging between the spacecaft
- Ground prototyping of formation flying sensor (AFF) has proven functionality
  - Fundamental algorithms have been verified for operation in a distributed spacecraft environment and sensor is ready for a space application
  - Real-time, autonomous; deep space, near-Earth, or regions with no GPS access
  - Flexible FPGA-based signal processing
  - Can be augmented with star-trackers, GPS receivers (for near-Earth application)

- **NASA's investment in precision s/c-s/c tracking and timing technologies can now be realized by a flight deployment on ST9**

JPL/NASA Sensors

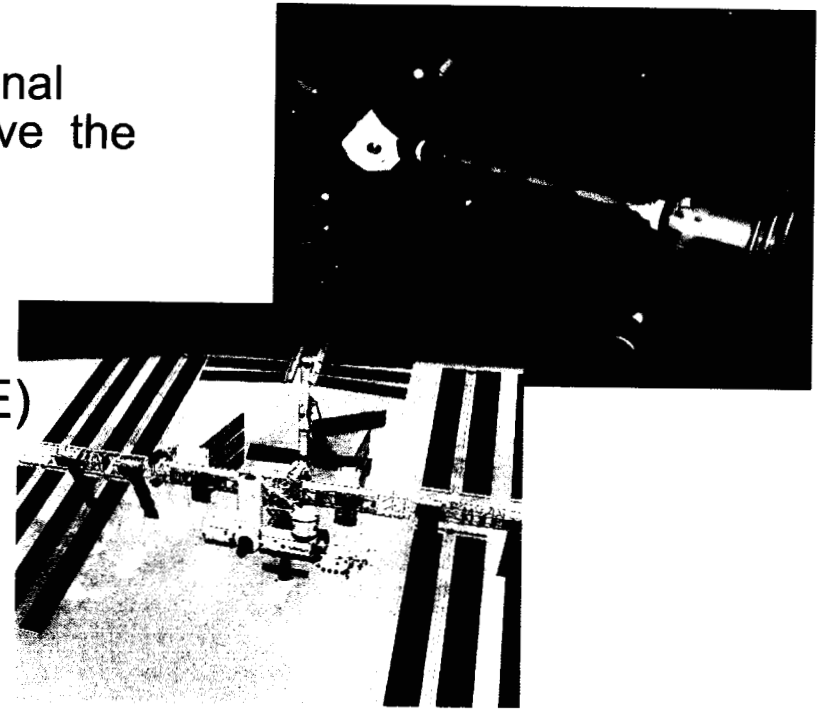
- GPS
  - cm-level metrology demonstrated for low-Earth orbit
  - Control TBD
- GRACE/GPS
  - micron-level (range-change) metrology demonstrated
- AFF
  - cm-level metrology demonstrated in ground testbeds
  - Control TBD
  - Architecture is adaptable to changing front end to meet more demanding system requirements



Major Clock Flight Projects at JPL

GPS Linear Ion Trap Frequency Standard

- Continuous, reliable operation, high stability
- Designed for existing clock footprint
- Ready for flight in ~ 2006



Primary Atomic Reference Clock in Space (PARCS)

- Laser cooled cesium clock for the International Space Station (ISS) with capability to improve the realization of "second" by a factor of 20
- Parts in 10^{15} to 10^{17} stability
- Selected for ISS flight in ~ 2006

Rubidium Atomic Clock Experiment (RACE)

- Laser cooled rubidium clock with potential stability and accuracy at parts in 10^{17} level
- Selected for ISS flight in ~ 2008