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

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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
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
Feb 2000

CHAMP
Jul 2000

SAC-C
Nov 2000

JASON-1
Dec 2001

GRACE
Mar 2002

High Accuracy Spacecraft-Spacecraft Tracking software-driven → multitude of applications

FedSat ICESat C/NOFS COSMIC OSTM PARCS

Formation Flying Briefing
Lichten/Aung/Srinivasan

January 2003
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.

- 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.

GRACE: 500-km alt (2 s/c)
- 2-cm orbit accuracy
- 100-psec relative timing
- Few-micron interspacecraft K-band ranging.
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.
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 \(\sim\) few tens of picosec when USO stability is exploited in processing.
- The GRACE mission requirement was 150-picosec accuracy
Spacecraft cross-link tracking (with or without GPS) maintains constant & precise knowledge of relative spacecraft positions/clocks.
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 by several orders of magnitude.

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

[Checkboxes for addressed to-date, future work, optimize on individual mission 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)

Antenna pattern assessment Testbed
Outdoor Antenna Isolation Testbed
Indoor AFF Sensor Testbed
358-meter Range Outdoor Radiated Testbed

Formation Flying Briefing Lichten/Aung/Srinivasan January 2003
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
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.

- 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 spacecraft
- 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
- 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

**JPL/NASA Sensors**

![Graph showing spacecraft control requirement vs. linear metrology precision](image-url)
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