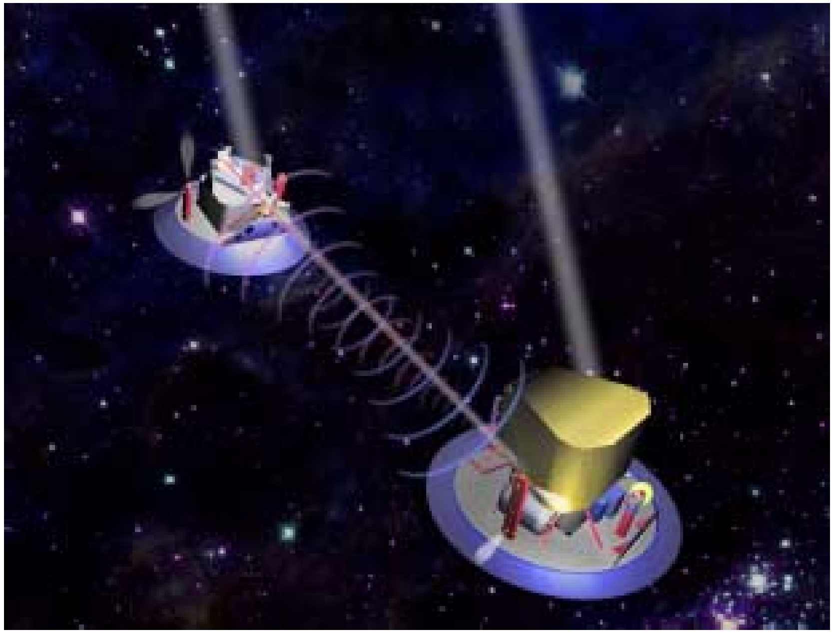
Autonomous Formation Flying (AFF) Sensor for Precision Formation Flying Missions



MiMi Aung
11/21/02

Contributors to the AFF Sensor

AFF Sensor PEM
MiMi Aung (335)
Jeff Srinivasan (335)

StarLight Flight System SE team
Ball Aerospace

AFF System Engineer
George Purcell (335)

AFF Instrument Lead Engineer
Jeff Tien (335)

Analysis & Simulations

George Purcell (335)
Larry Young (335)
Meera Srinivasan (331)
Kevin Quirk (331)
Jeff Srinivasan (335)
Jeff Tien (335)

Antennas

Luis Amaro (336)
Tom Osborne (386)
Max Vozoff (335)

Consultant:
Aluizio Prata (336)

Microwave Transceivers and Frequency & Timing

M. Ciminera (333)
Gerry Walsh (333)
Doug Price (333)
Conrad Foster (333)
Eric Archer (331)
Mary Wells (386)
C. Flores-Helizon (386)
Tony DeKorte (333)
Bud Ansley (333)
Mark Fiore (333)
Al Kirk (335)

Prototype Baseband processor H/W & SW (modified GRACE processor)

HW:
Jeff Tien (335)
Garth Franklin (335)

SW:
Jeff Srinivasasn (335)
Yong Chong (335)
Tom Meehan (335)
Tim Rogstad (335)
Charley Dunn (335)

60 MHz Baseband processor H/W

HW:
Bryan Bell (335)
Jeff Tien (335)
Bob Ahten (344)
Alberto Ruiz (335)
David Robison (335)
Keizo Ishikawa (344)
Chuck Lehmeyer (335)
Don Nguyen (335)

SW:
Yong Chong (335)
Ted Stecheson (335)
Tim Rogstad (335)
Tim Munson (335)
Jack Morrison (348)

Integration & Test

Eric Archer (331)
Jeff Tien (335)
Luis Amaro (336)
Larry Young (335)
Jeff Srinivasan (335)
Phil Mayers (335)
Hamid Javadi (336)
Randy Bartos (341)
Tim Munson (335)
Jacob Gorelik (335)
Cynthia Lee (335)
Garth Franklin (335)
George Purcell (335)
MiMi Aung (335)
Ball Aerospace

History and Status

- AFF Sensor is a novel design innovated and patented by the JPL GPS team (335)
  - The AFF Sensor was initially "seeded" in a small exploratory technology task within the DSN Technology Program (now called the IND Technology Program in 9xx).
  - Infused through the New Millennium Program (NMP) for the DS-3 mission (Separated Spacecraft Interferometer).
  - Moved into the Origins Program where DS-3 -> ST-3 -> StarLight.
  - 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)
- Technology development activities 1999 - 2002 (StarLight project and Code R funding)
- At this time, 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
  - With customization for individual missions.
- Being evaluated further under Terrestrial Planet Finder (TPF) pre-project technology program

AFF Sensor within a FF Mission

- The AFF Sensor is a radio-frequency sensor for multiple spacecraft precision formation flying (FF) missions. It provides:
  - Estimates of ranges and bearing angles among multiple spacecraft
  - A wide field of view for initial acquisition and lost-in-space scenarios.

StarLight: A separated spacecraft optical interferometer mission

StarLight key performance requirements	Directly facing (cone< 2°)	Nearly facing (2°< cone<45°)	Not facing (cone>45°)
*Range (cm) *Bearing angles (arc-minute)	2 1	2-30 1-600	160 5400

*1-σ accuracy

Spacecraft separation:
Nominal: 30m – 1000m
Recovery capability: 1 - 10 km

Key Features

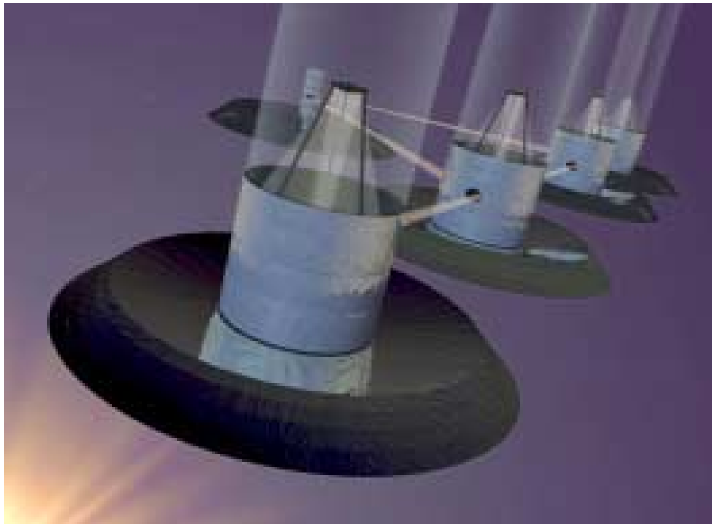
- Performance
  - (2 cm, 1 arcmin) accuracy when the spacecraft are directly facing each other
  - Wide field of view coverage (~±70° cone)
  - 3-D relative positioning (range, azimuth angle, elevation angle)

- 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

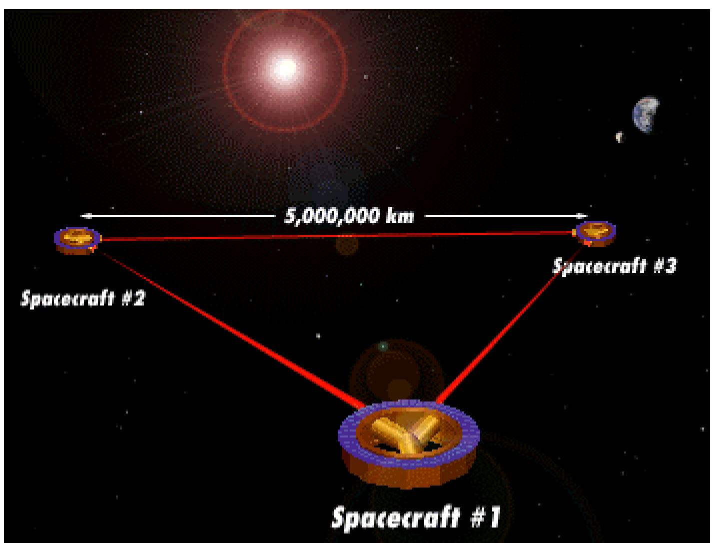
Examples of FF Missions

Terrestrial Planet Finder (TPF) ~ 2015



StarLight (flight portion cancelled)

Planet Imager (PI) ~20XX



Laser Interferometer Space Antenna (LISA) ~ 2008

Design Description

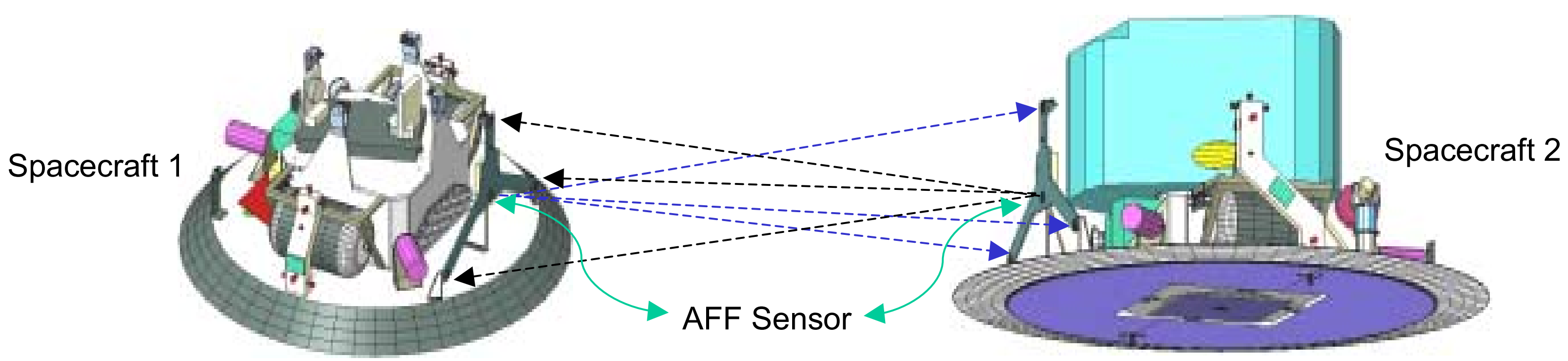
- An RF instrument that is distributed over multiple s/c.
- AFF Sensor on each spacecraft transmits and receives GPS-like signals

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

  where $P(t)$ = ranging code

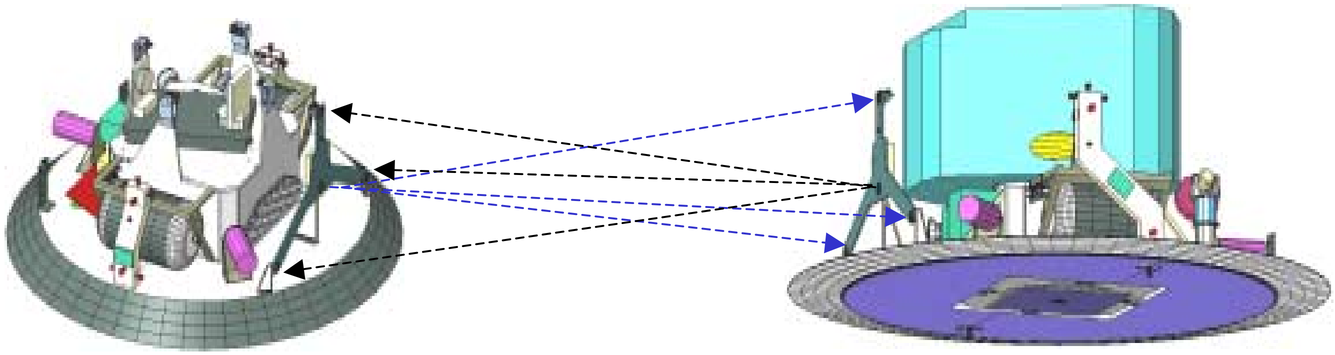
  $D(t)$ = Data bits (telemetry)

  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

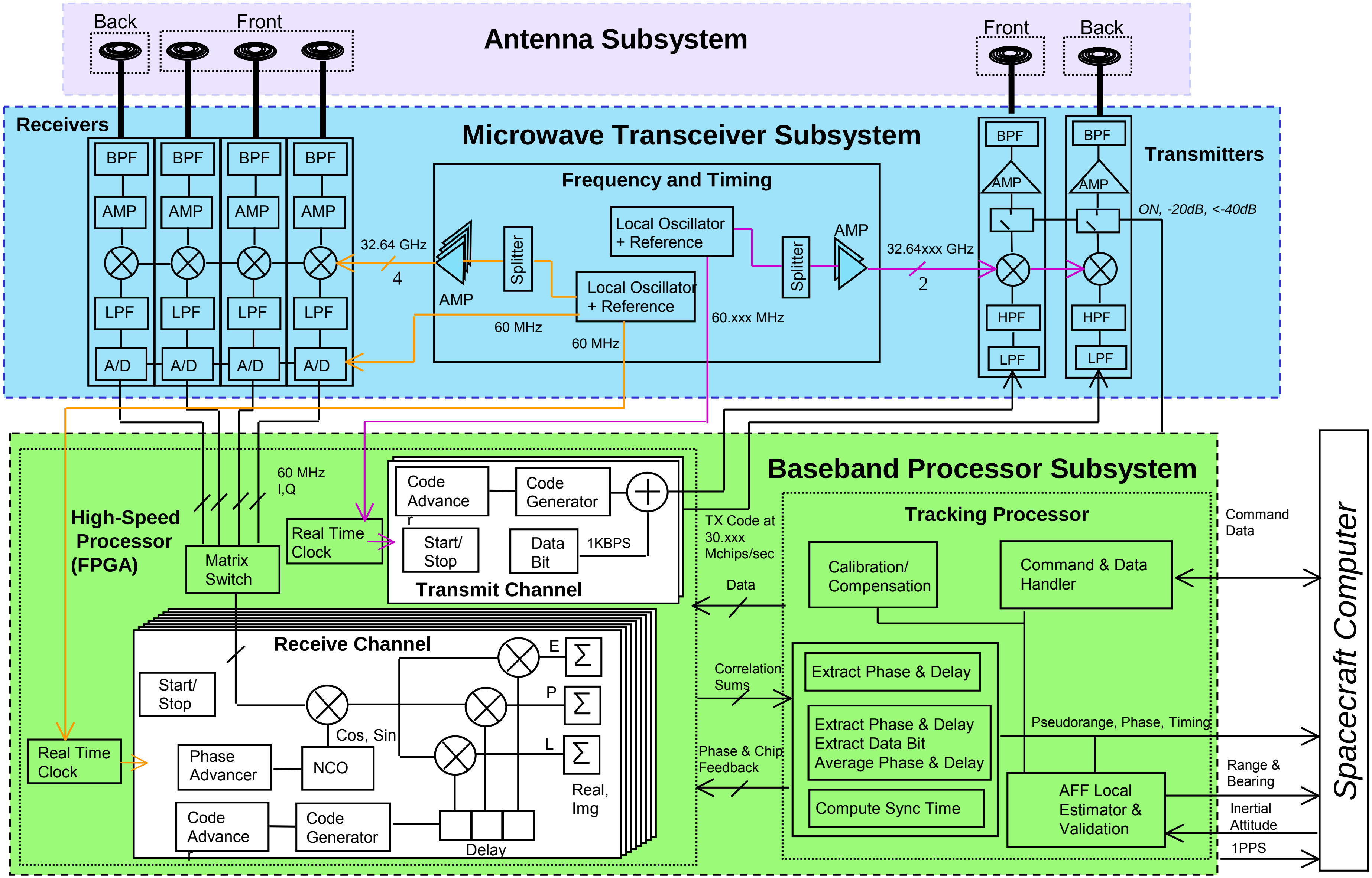


Design Description (Cont'd)

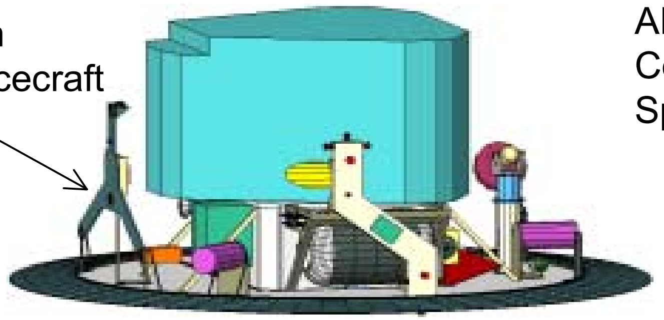
- Signal transmission and reception options
  - Simultaneously
  - Time-Division Duplexing (TDD)
    - Synchronously
    - Asynchronously

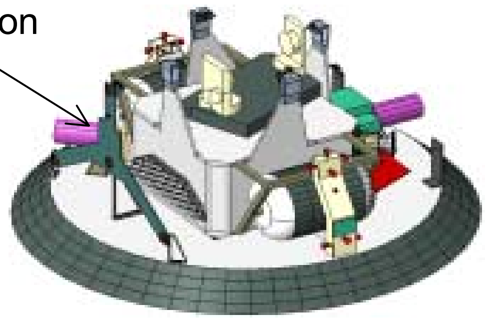


AFF Sensor Subsystems



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

Implementation Innovations

- Custom Antenna Design
  - To minimize multipath while keeping a wide field of view

- Ka-band implementation
  - Two closely spaced Ka-band references derived from a single (~10 MHz) reference source on each spacecraft
  - Coherence between RF signals with digital clocks

- Digital Signal Processing
  - Continuous, instantaneous, self-calibration scheme
    - Operates across distributed system
    - Removes clock offsets, instrumental variations
  - Carrier-aided smoothing algorithm to improve range estimates
    - Coherence of generated code with the RF signals

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

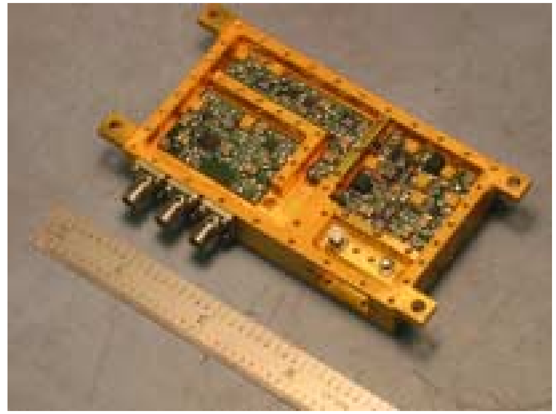
Outdoor Antenna Isolation Testbed

Indoor AFF Sensor Testbed

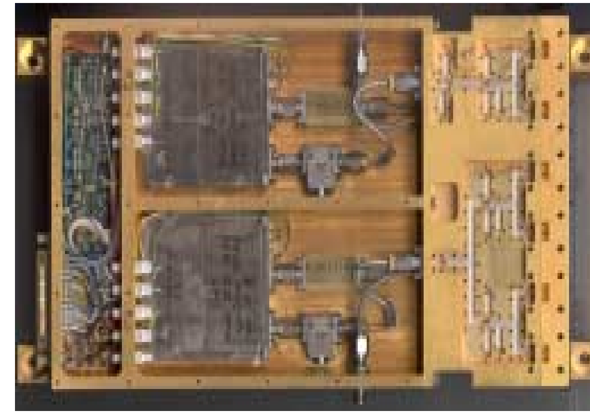
358-meter Range Outdoor Radiated Testbed

Prototype Hardware

Prototype Ka-band antenna with choke rings

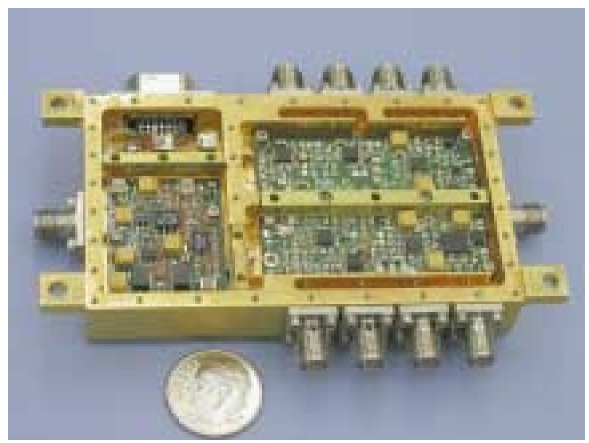


Ka-band Transmitter:
Output: 32.64 GHz RF signal at 13 dBm



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

Prototype Baseband Processor – modified GRACE baseband processor (IPU)



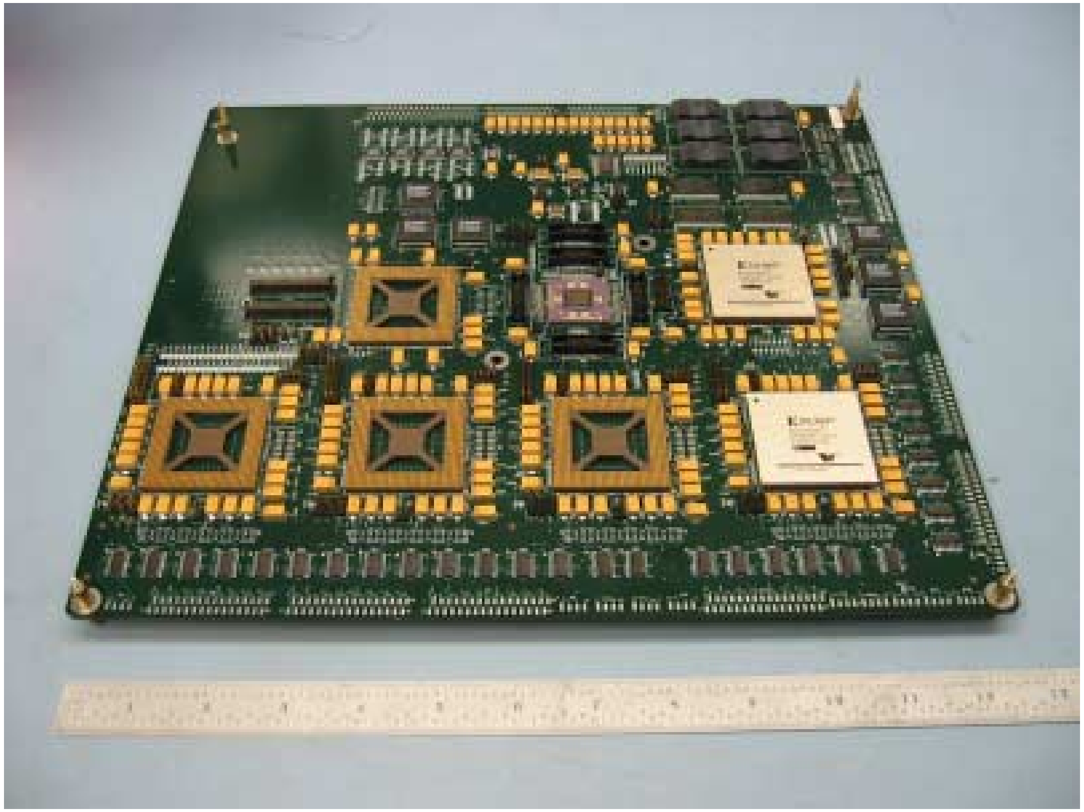
Ka-band Receiver:
Input 32.64 GHz,
Output: 60 MHz 1-bit I and Q samples

Reference oscillator:
120 MHz

60 MHz Baseband Processor

A 60 MHz Baseband Processor will be completed in Q1 FY-03.

- Will provide more capability, flexibility and re-programmability for further investigation of the AFF Sensor.



AFF Sensor antennas mounted with mock-ups of the mounting plate and sunshade in the JPL 60-foot anechoic chamber

Objective:

Evaluate degradation of the delay and phase patterns of the transmitting and receiving antennas due to spacecraft multipath sources.

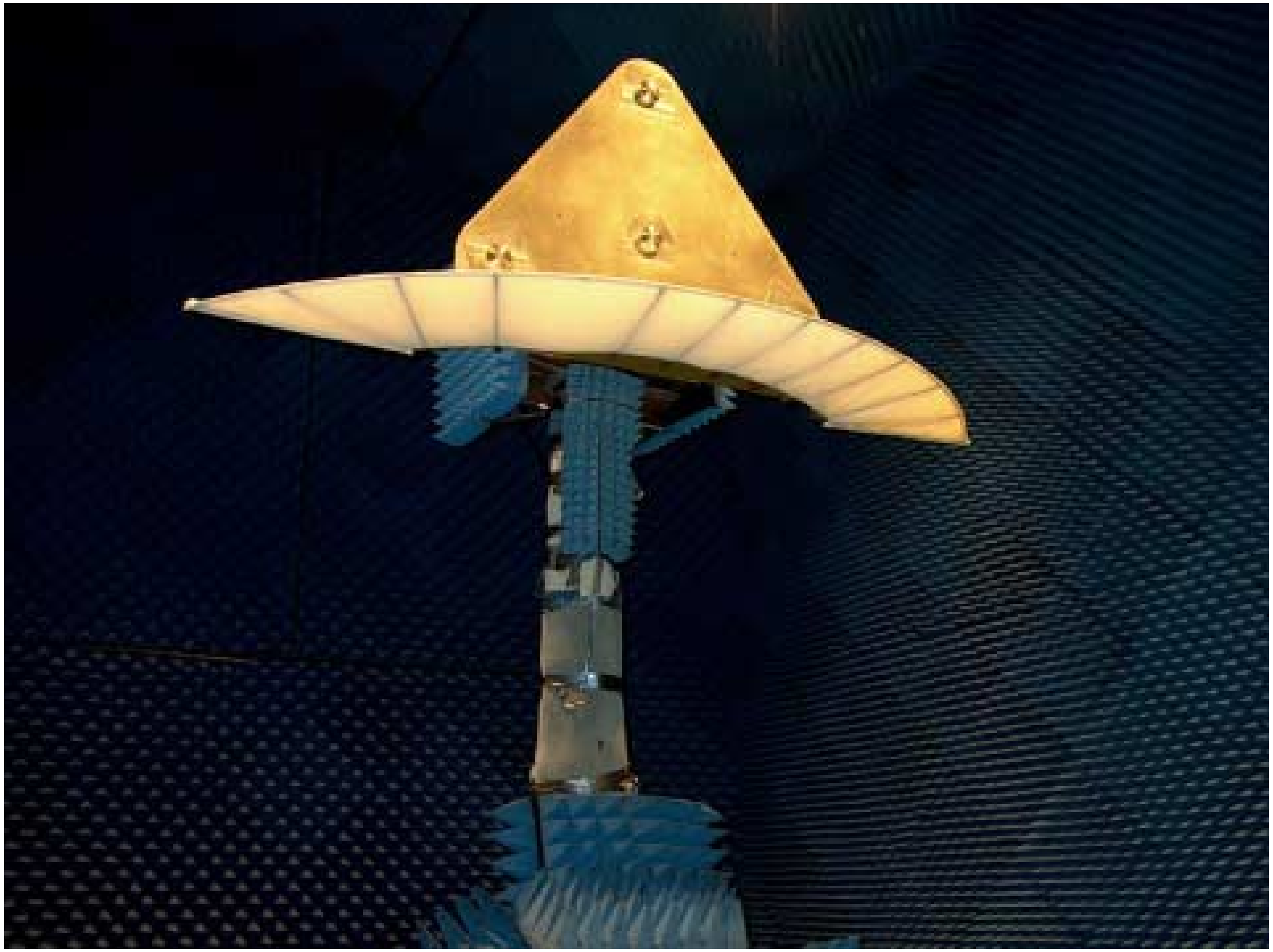
Approach:

- Construct mockups of the AFF mounting plate and sunshades.
- Measure the gain and phase patterns of the antennas in the mocked-up flight environment.
- Compare measured antenna pattern deviations due to structural environment with the allocation within the end-to-end error budget.

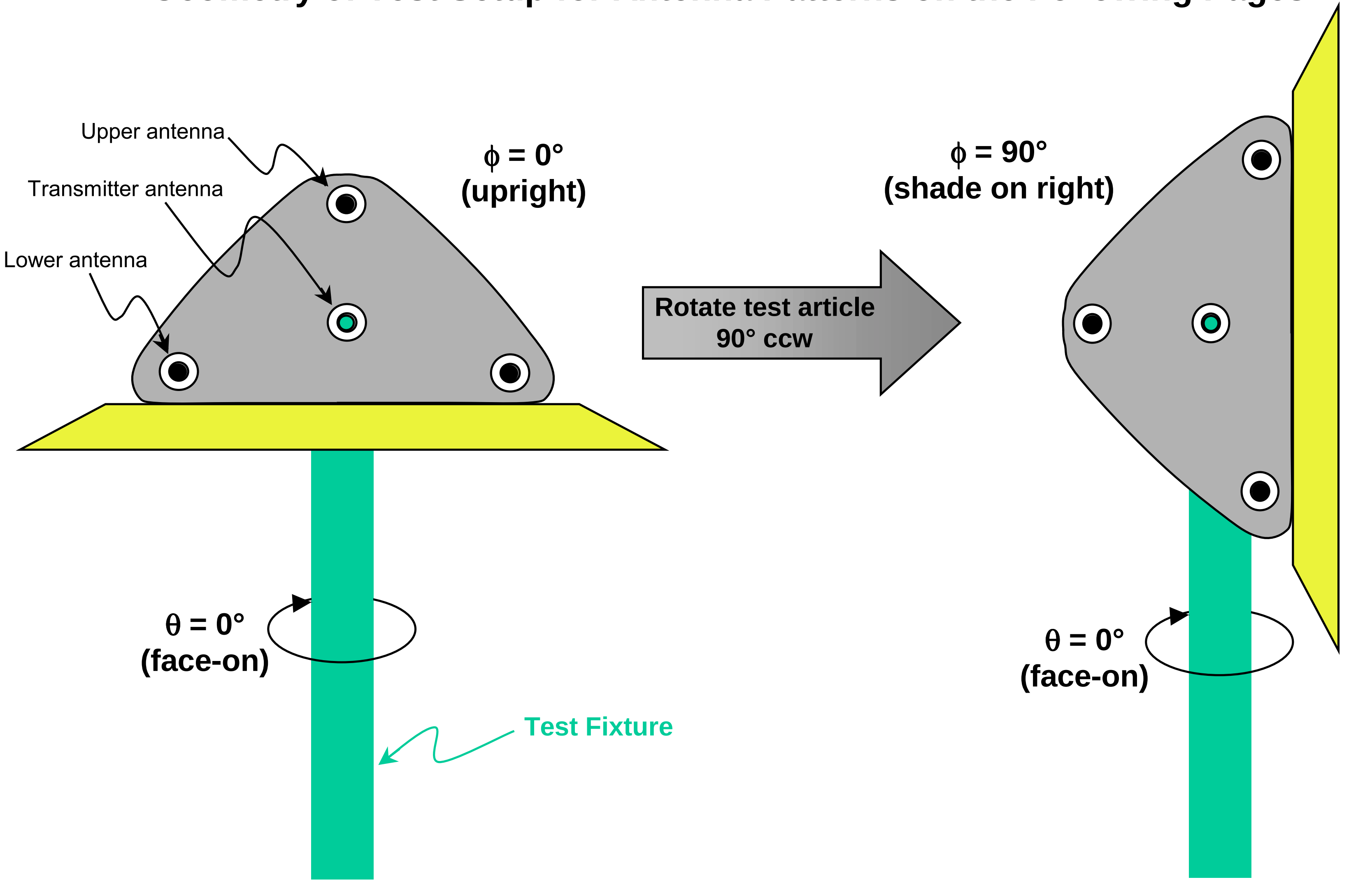
Antenna Pattern Testing (cont.) - Antenna Plate Baseline

Antenna Pattern Testing (cont.) – Collector Shade

Antenna Pattern Testing (cont.) – Combiner Shade

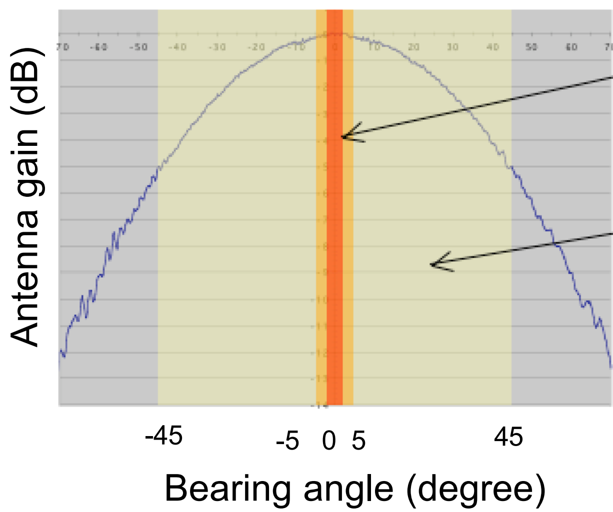


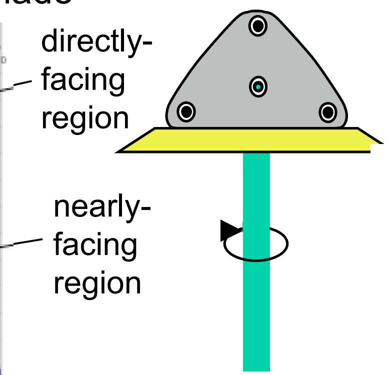
Geometry of Test Setup for Antenna Patterns on the Following Pages



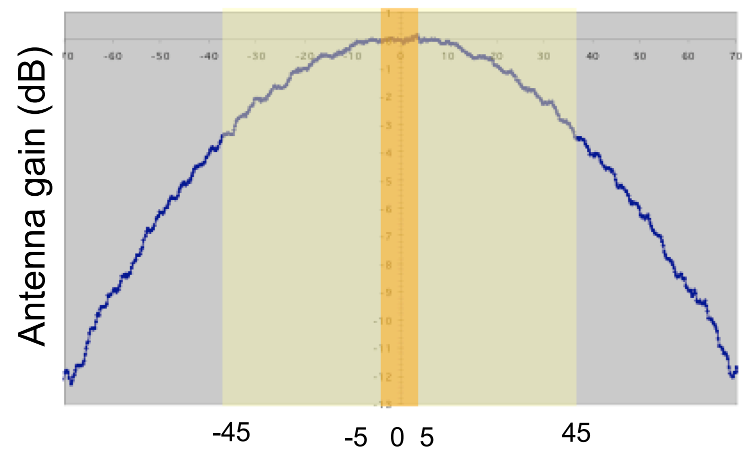
AFF Sensor Antenna Pattern Assessment Testbed (Cont'd)

Antenna gain pattern with no sunshade



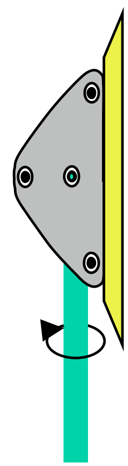


Upper antenna with sunshade , □ = 0°

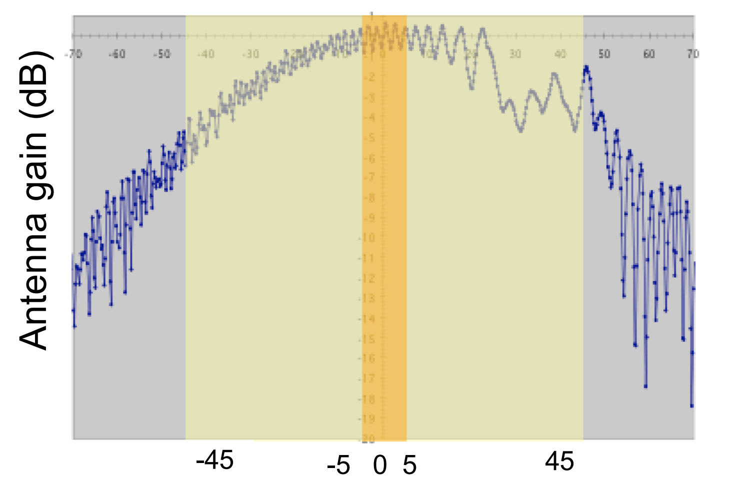


Conclusion

- Antenna pattern is degraded by the sunshade.
- Deviations from the nominal pattern (uncalibrated errors) fed into error trees show that the AFF Sensor can still meet the (2 cm, 1 arc-min) requirement
  - Degrades slower than requirement relaxation away from boresight.



Lower Antenna gain pattern with sunshade, □ = 90°



AFF Sensor Outdoor Antenna Isolation Testbed

Objective:

Determine whether isolation between the transmitting and receiving antennas on the same spacecraft is sufficient and stable.

Approach:

- Construct mockups of the mounting plate and sun shades.
- Measure isolation between the antennas with and without mocked-up flight environment.

With no sunshade

With Collector s/c sunshade

With Combiner s/c sunshade

AFF Sensor Outdoor Antenna Isolation Testbed

Conclusion:

- Without the sunshade, the measured levels of isolation matched predicted levels.
  - Antenna mounting plate did not introduce any unpredictable effects.
- Sunshade degraded isolation levels.
  - Level of degradation varied with the shape of the sunshade and with changes in location of the sunshade.
  - Repeatibility is poor due to effects at the small Ka-band wavelengths.
  - Multipath sources are localized.
- Possible to control isolation levels by placement of absorber at strategic locations.
- Consider Time-division duplexing (TDD) scheme on individual mission basis.

AFF Sensor Indoor Testbed (138-116 Laboratory)

Objective:

Verify fundamental algorithms distributed across multiple spacecraft.

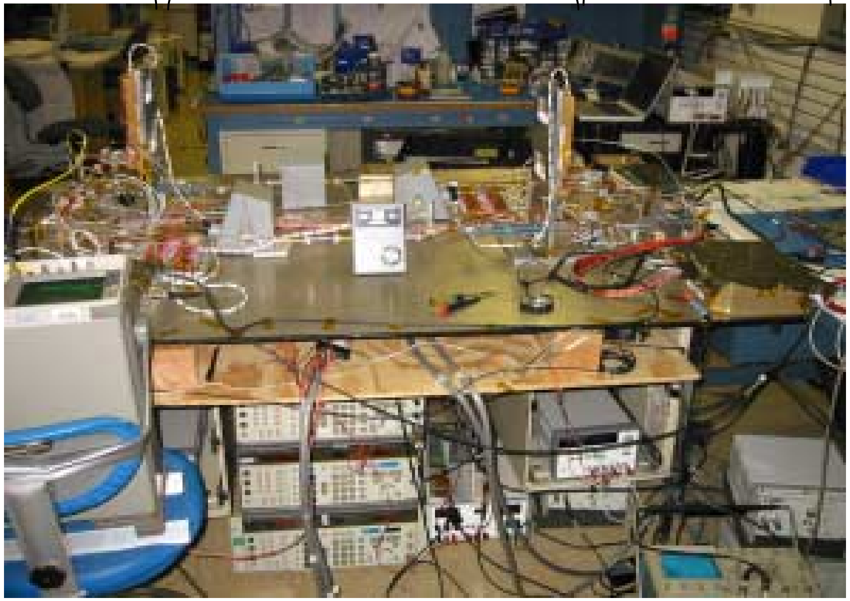
Approach:

- 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

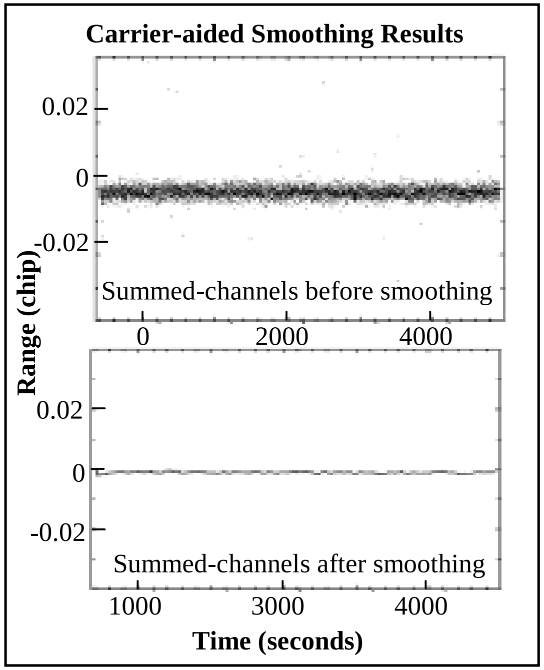
representative space-loss

AFF Sensor on Spacecraft # 2

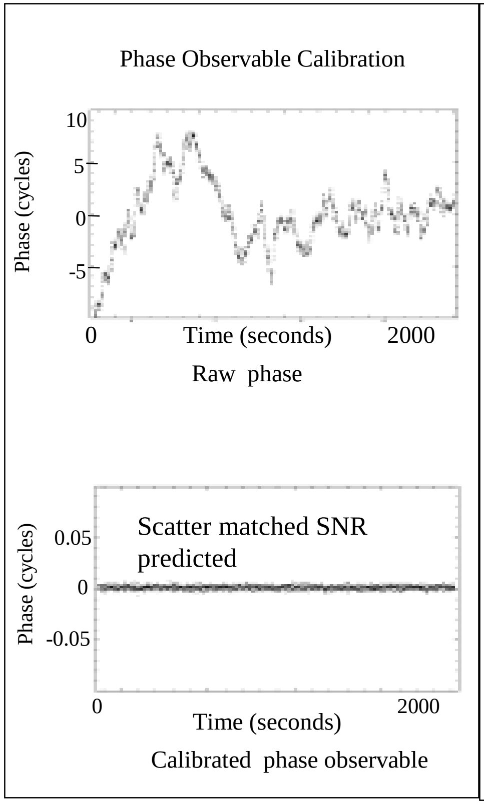


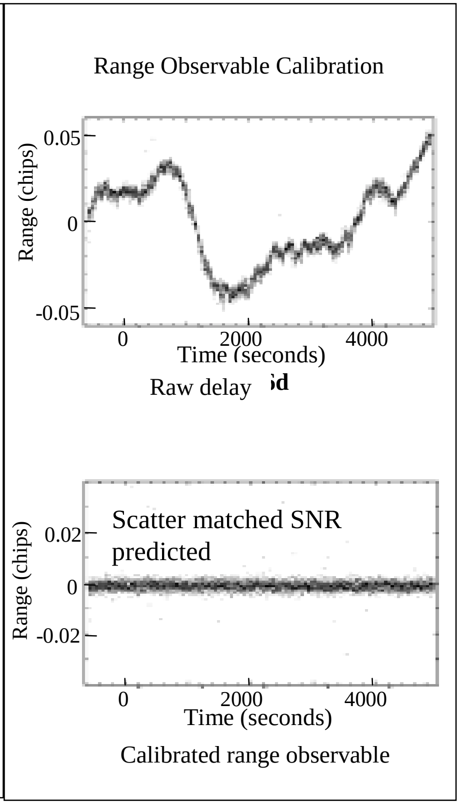
AFF Sensor Indoor Testbed (Cont'd)

- Fundamental, distributed Sensor algorithms have been verified.
  - Distributed operation
  - Ka-band scheme
- Carrier-aided smoothing algorithm was verified.

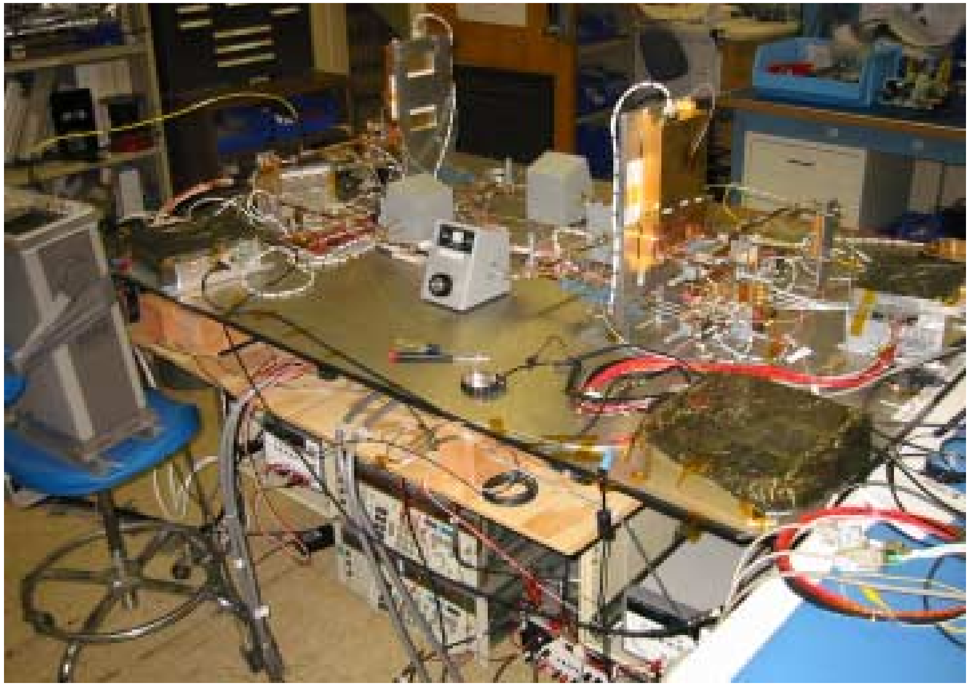


- Continuous self-calibration across two halves was verified.
  - Phase observable
  - Range observable





AFF Sensor Indoor Testbed



Conclusion:

- The following key technologies were demonstrated in the distributed environment:
    - Fundamental AFF Sensor scheme
    - Continuous self-calibration algorithm operating across two independent halves
    - Carrier-aided smoothing algorithm requiring sustained coherence across each spacecraft
    - Basic Ka-band scheme supporting the Sensor design
    - Time-Division Duplexing (TDD) scheme

End-to-End Functionality Field Test across a 1200-foot Outdoor Range

Objective:

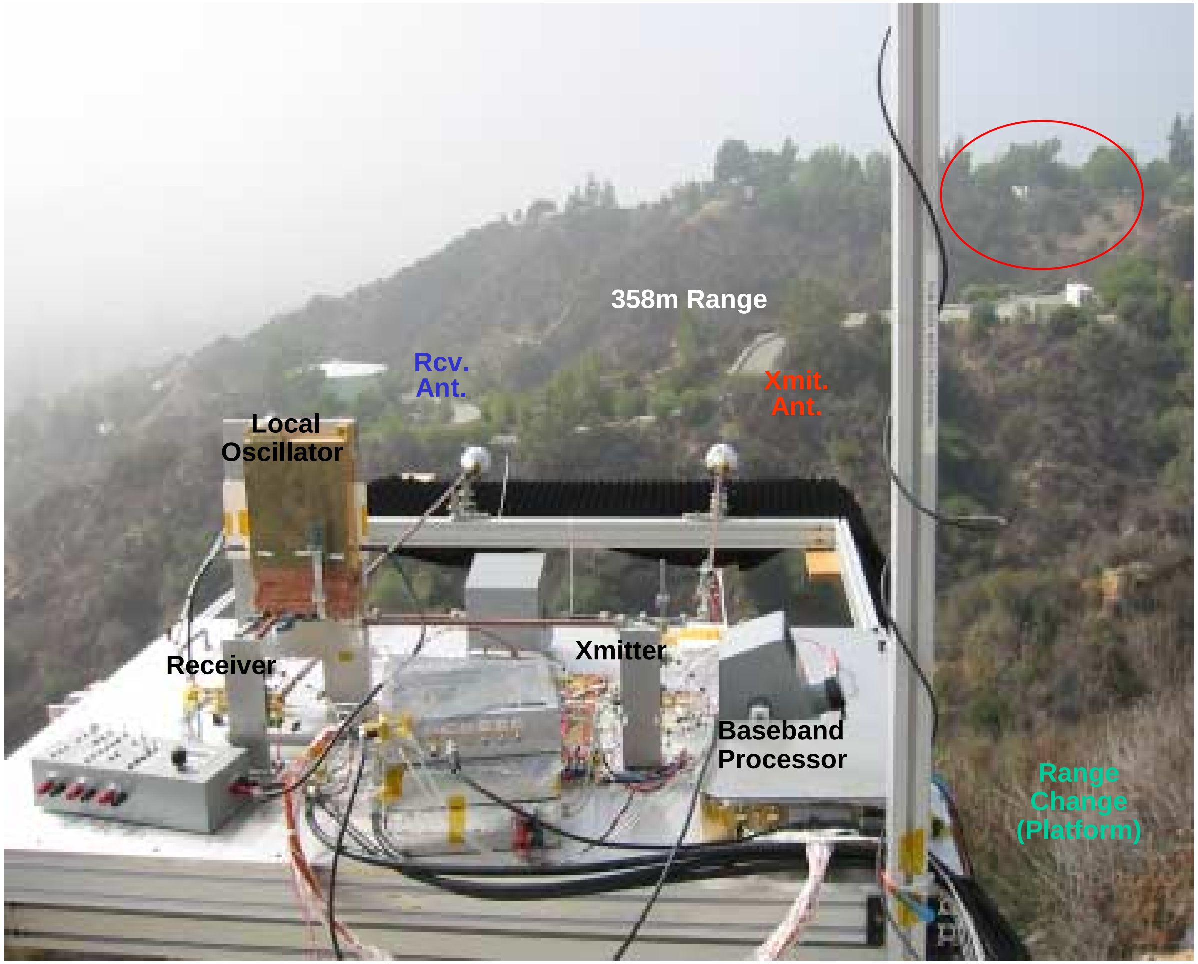
• Verify end-to-end functionality of the complete AFF Sensor. (Full performance is not expected in the presence of uncontrolled multipath sources in the outdoor environment.)

Approach:

• Operate the prototype AFF Sensor distributed over two halves across a 1200-foot outdoor range.
• Introduce changes in ranges and bearing angles.
• Derive estimates of the range and bearing angle from observables measured during end-to-end operation.

End-to-End Functionality Field Test across a 1200’ Outdoor Range (Cont’d)

East End



End-to-End Functionality Field Test across a 358-m Outdoor Range (Cont'd)

West End

End-to-End Functionality Field Test across a 358-m Outdoor Range (Cont'd)

Conclusion:

- End-to-end functionality of the AFF Sensor has been verified by successful operation across the 1200-foot range.
    - Range, range-change and bearing angle were determined successfully.
        - Measured ranges matched the GPS-surveyed "truth" ranges (within the accuracy expected in the presence of uncontrolled multipath)
        - Range-change and bearing angle estimates matched the "truths" in the experiment.
    - Full end-to-end performance needs to be determined by operation across a large (>30 m) range with space-like conditions.

Conclusion

- A prototype of the AFF Sensor is fully functional.

- Fundamental algorithms have been verified for operation in a distributed spacecraft environment.

- Performance dependence upon the spacecraft architecture is understood.

- Results show that AFF Sensor can meet the StarLight requirements.

- Is ready for adoption into future multiple spacecraft precision formation flying mission
  - Sensor providing coverage from lost-in-space to full performance at face-to-face spacecraft configuration
  - Real-time
  - Autonomous
  - Applicable in deep space, near-Earth or regions with no access to GPS
  - Flexible FPGA-based signal processing
  - Can be augmented with star-trackers, Global Positioning System receivers (for near-Earth application)
  - For each mission, optimize on individual basis by design trade-off among: spacecraft design, Sensor field of view, formation flying system, instrument design.

Conclusion (Cont'd)

Further Investigations for Application to TPF

- Extend for five-spacecraft sensor design
  - Simultaneous multiple links in a dynamic environment
  - Which spacecraft are sensing signal from which other spacecraft under what circumstances
  - Antenna configuration

- Requires instantaneous 4π steradian coverage

- Much tighter non-directly facing requirements
  - Multipath modeling and mitigation
  - Self-Jamming (evaluate TDD for five S/C)
  - Near-Far issue (jamming from other S/C)

- New signal structure to avoid spacecraft rotation maneuver to resolve bearing angle ambiguities

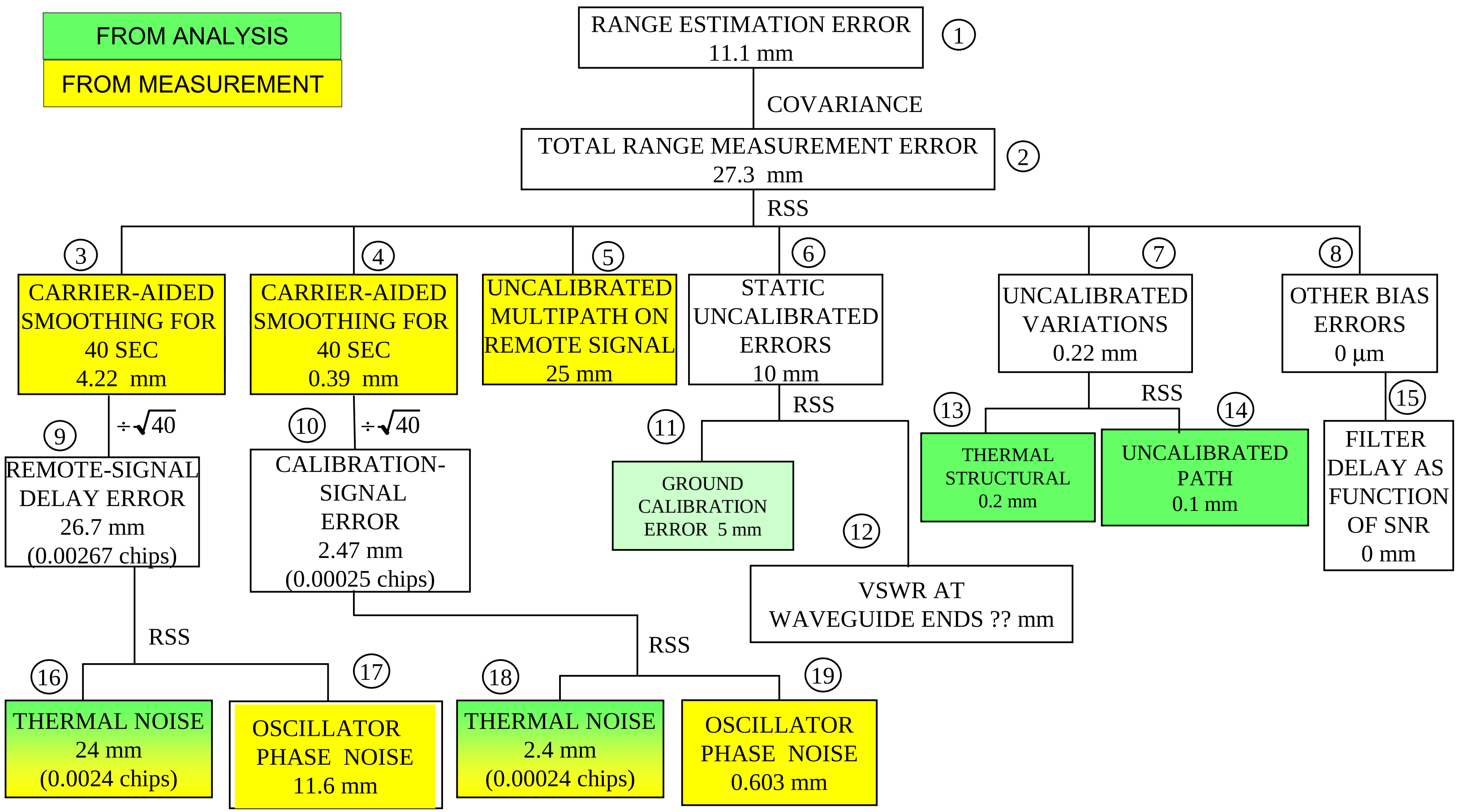
- Integrated inter-spacecraft communications

Back-up

Key Parameters

PARAMETER	VALUE
RF carrier frequency	32.64 GHz
Chip rate of the PRN ranging code	30 Mchips/s
Sample rate	60 Msamples/s
Transmitted power	20 mW (13 dBm)
Transmitting and receiving antenna gain, on axis	9.2 dBi
Polarization loss (transmitting linear, receiving circular)	3 dB
Sky background temperature	3 K
Receiver noise temperature	2030 K
Receiver noise bandwidth	80 MHz
Separation between spacecraft	30-1000 m

TIME DIVISION DUPLEXING RANGE ERROR BUDGET, ANY CALIBRATION STATE, range 1000 m, 1-second observables



SINGLE-SAMPLE SNR = –15 dB
CNR = –3 dB

Error Tree 7

TIME DIVISION DUPLEXING BEARING-ANGLE ERROR BUDGET, GROUND CALIBRATION + IN-ORBIT ROTATION CALIBRATION, range 1000 m, 1-second observables