JPL GPS Capabilities Overview

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JPL

GPS Capabilities in JPL's Tracking Systems and Applications Section: Introduction

- JPL is managed by Caltech for NASA as a Federally Funded Research and Development Center (FFRDC)
  - Work is also performed for other non-NASA agencies and private sector
- Our Section is one of five in JPL's Telecommunications Science and Engineering Division
  - 128 employees in the Section, 108 with B.S. or higher (74 Ph.D.'s)
  - 11 Technical Groups
    - Five groups focused on GPS technology: two hardware groups and three analysis groups (~ 55 technical employees)
    - Two groups focused on precision Frequency/Timing systems and quantum technologies (~ 20 technical employees)
  - 4 Supervisors here today
    - Yoaz Bar-Sever (Orbiter and Radio Metric Systems)
    - Larry Young (GPS Systems)
    - Bob Tjoelker (Frequency and Timing Advanced Instrument Development)
    - Frank Webb (Satellite Geodesy and Geodynamics Systems)
    - Also here: Stephen Lichten (Manager) and Jim Zumberge (Deputy Manager)

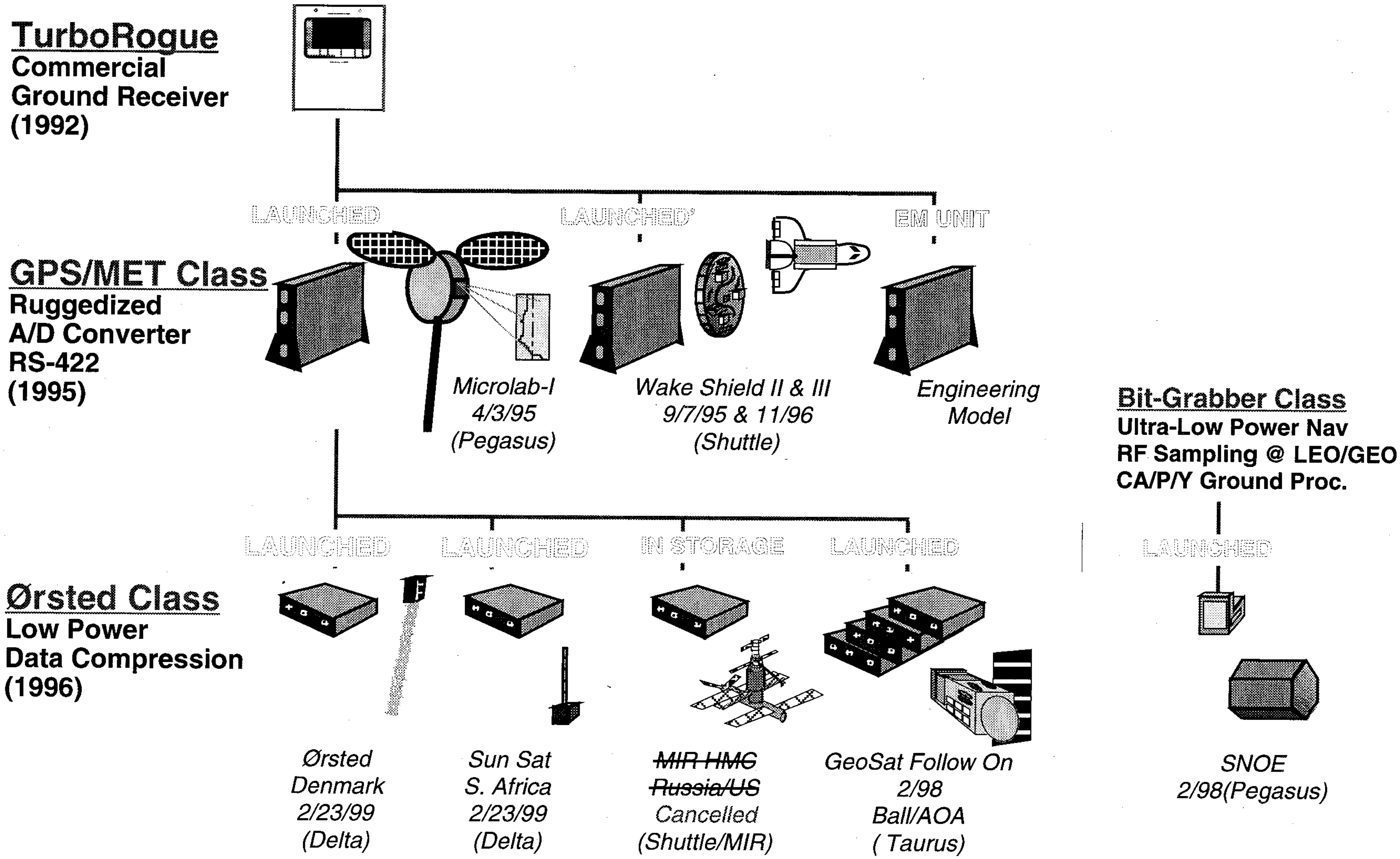
Introduction (cont.)

- **Diverse section with technologists, specialists, and scientists provides a "cradle to grave" capability in GPS-based systems and applications**
  - Signal structure expertise; in-receiver algorithms and software; performance trades
  - Innovative GPS receiver design (multiple patents)
  - GPS receiver/transceiver spaceborne experiments and deployments
  - Orbit/trajectory estimation and user positioning algorithms& software (multiple patents)
  - Precise spacecraft-spacecraft tracking systems
  - GPS ground networks and automated data acquisition systems for precision ground and orbiting applications (operating on 24/7 basis)
  - User applications: real-time and non-real-time; navigation/positioning; geolocation and time transfer; tropospheric and ionospheric science; gravity science; geophysics
- **Frequency and Timing unique core expertise**
  - Responsible for 24/7 operation of mission critical NASA/JPL frequency and timing subsystems in global Deep Space Network
  - Advanced atomic clock technology development; innovative oscillators and resonators; precision time and frequency measurements (multiple patents)
  - Underlying fields include: quantum electronics, laser cooling, quantum optics, fundamental physics
  - Presently building advanced space clocks for future GPS (Linear Ion Trap clock) and Space Station (Laser cooled clocks) deployments

Introduction (cont.)

- Other groups include specialists in: radio interferometry (ground and space); optical interferometry (space); antenna arraying; correlator systems; quantum science and technologies

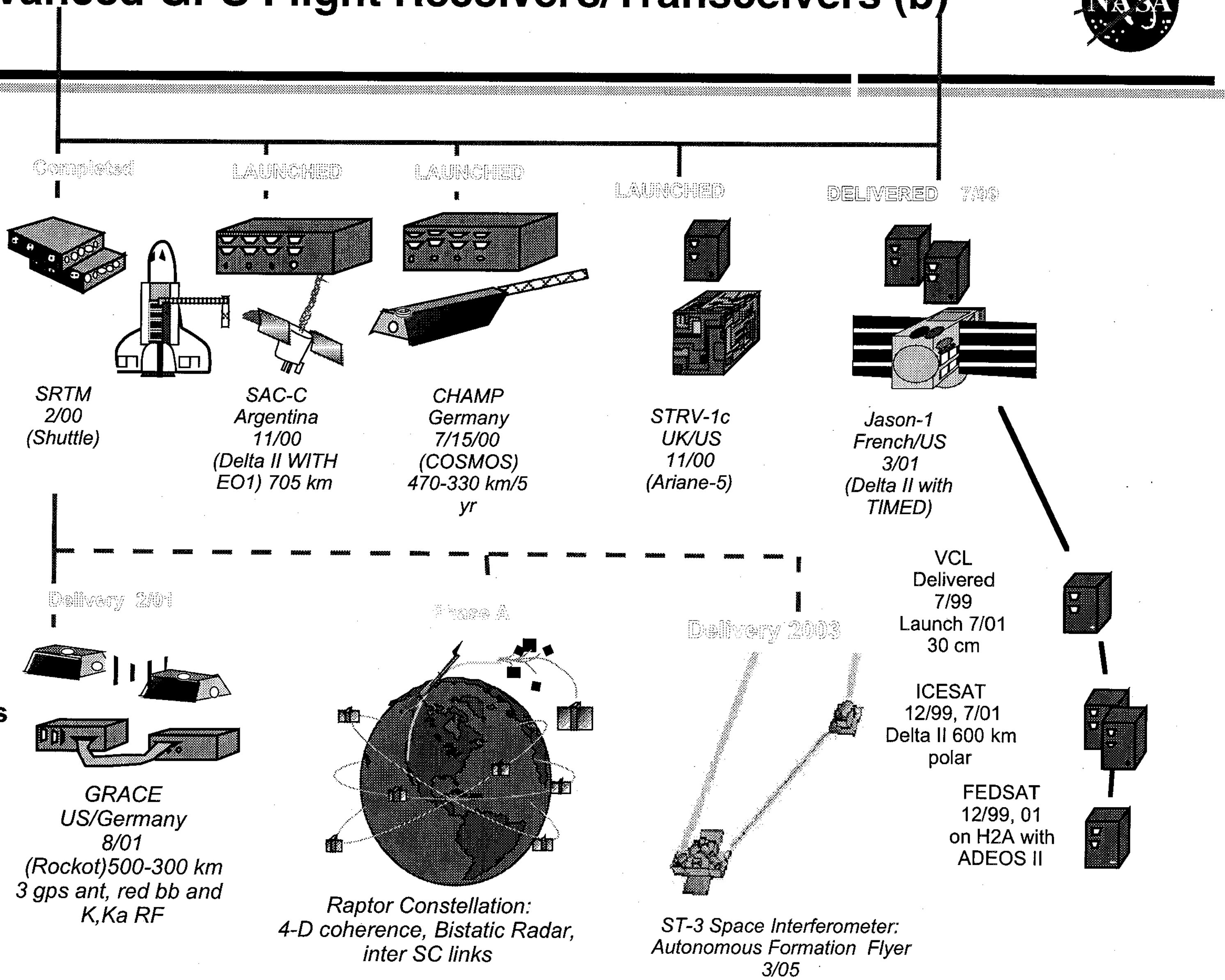
Advanced GPS Receiver Technology (a)



Advanced GPS Flight Receivers/Transceivers (b)

SAC-C Class

Hi- Performance PowerPC CPU
Lower Power
Multi-Antenna



Raptor Class

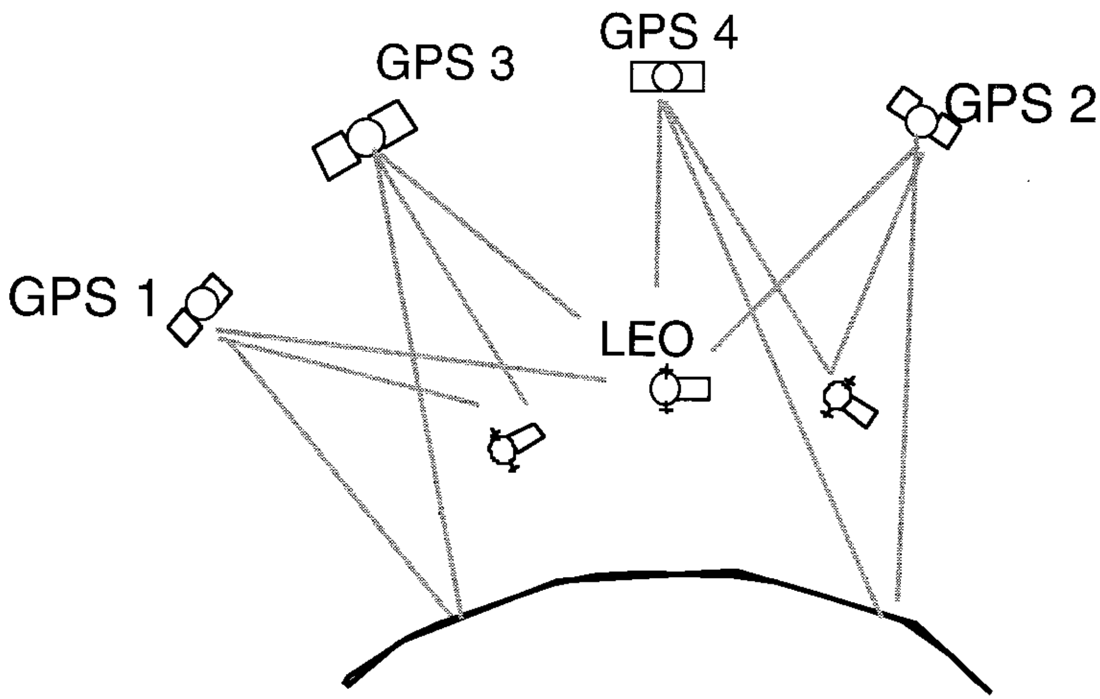
Additional Functions
Lower Power

And

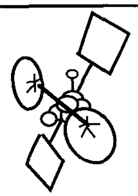
ST5
COSMIC 8 sats 1/03
LCAP, PARCS

Precision LEO Positioning and Timing

- GPS tracking maintains constant and precise knowledge of relative spacecraft positions & clocks

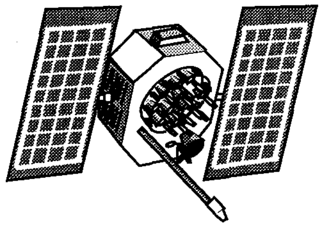


Demonstrated Orbit Accuracies



Geostationary
36000 km altitude
(TDRS, INMARSAT)

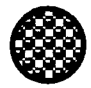
15 m
ground-based tracking



GPS

20000 km altitude

8 cm (< 40-cm real-time)
operational automated processing

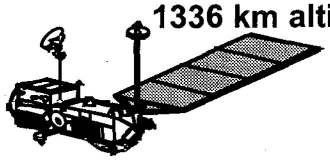


Lageos

6000 km altitude
<10 cm 2-way laser ranging

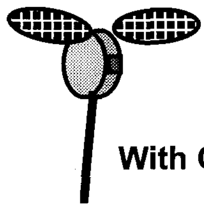
TOPEX/POSEIDON

1336 km altitude



With GPS: < 2 cm radial (AS off)
< 3 cm (AS on) radial

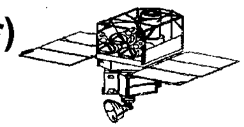
< 10 cm 3D RSS
operational automated processing



MicroLab/GPSMET
730 km altitude

With GPS L1/L2 < 10 cm

EUVE (Explorer)



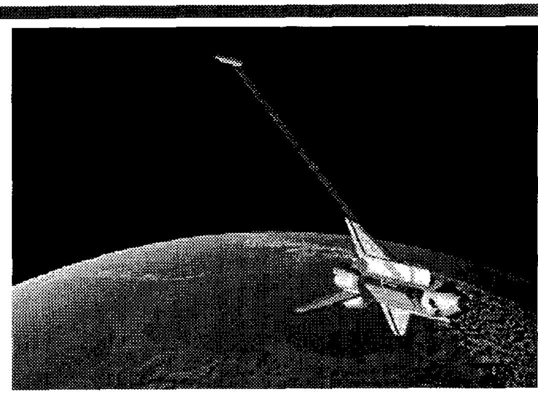
500 km altitude

2-3 m with GPS
L1 only

Shuttle Radar Topography Mission (SRTM): 230-km alt
45-cm orbit accuracy

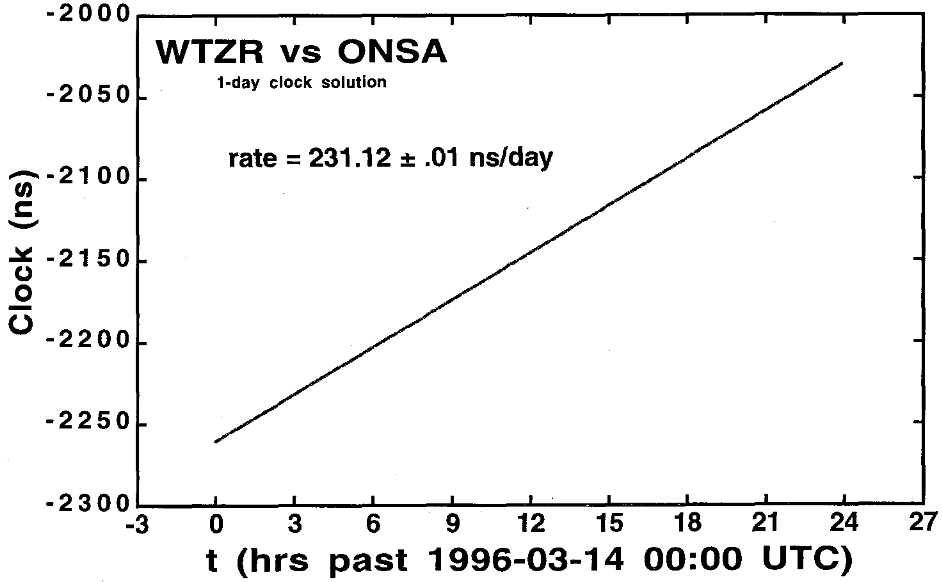
CHAMP: 470-km alt
< 10-cm orbit accuracy

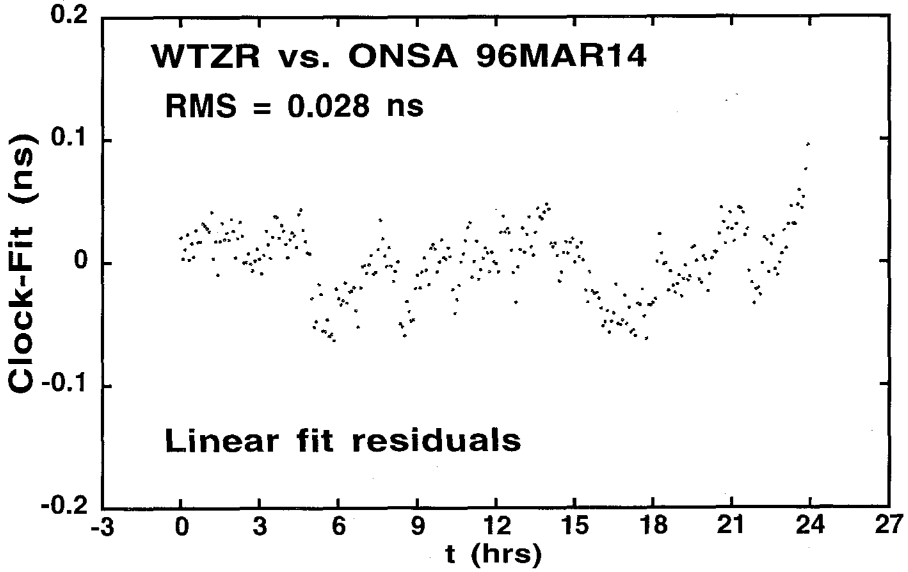
SAC-C: 705-km alt
< 10-cm orbit accuracy



FUTURE GOAL: < 1-cm Orbit Accuracy for LEOs

Ultra-Precise Time Transfer with GPS

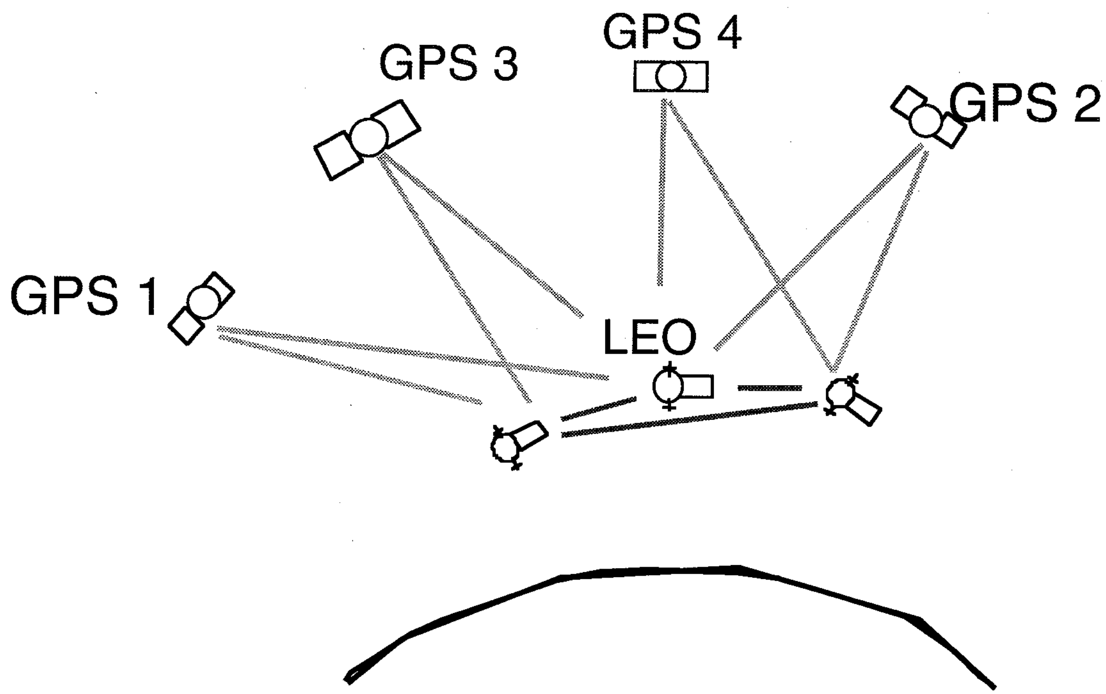




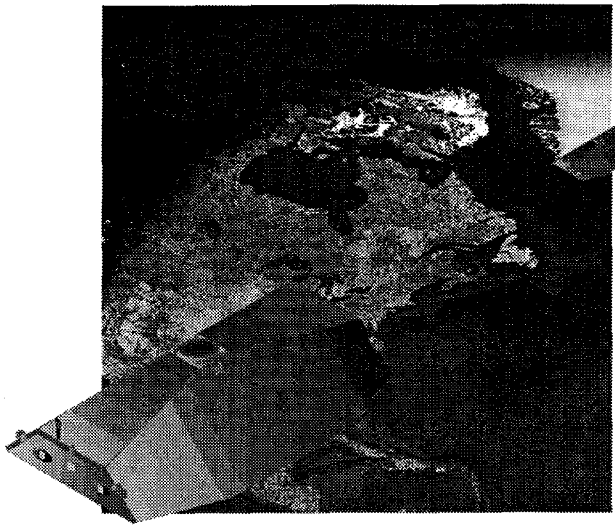
Linear fits to GPS-based clock estimates for pairs of masers worldwide (some separated by 1000's of km) show rms scatter of better than 30 picosec

Precision Spacecraft Positioning and Timing

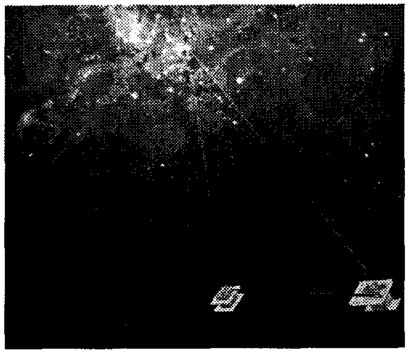
- GPS and/or LEO cross-link tracking maintain constant and precise knowledge of relative spacecraft positions & clocks



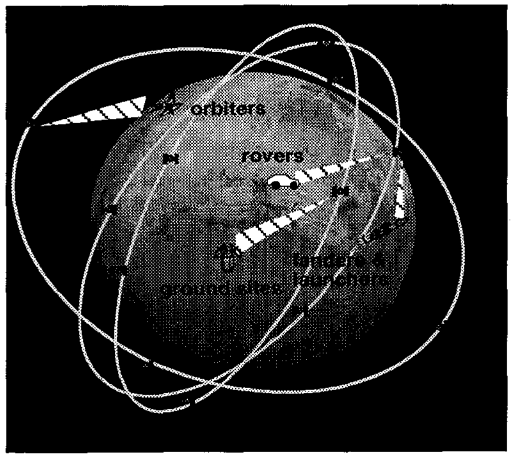
Spacecraft Cross-Link Sensors Under Development for Space Deployments



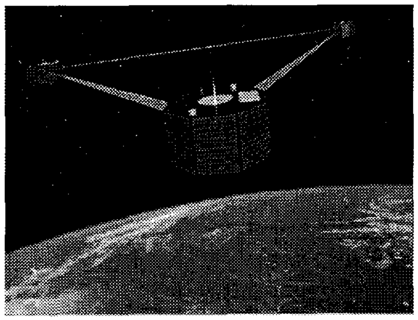
GRACE: JPL GPS Receiver with integrated camera and K-band spacecraft-spacecraft tracking, to provide 1-micron accuracy measurement of range change to improve knowledge of the Earth's gravity field <u>by several orders of magnitude</u>



ST-3: Precision (1-cm) formation flying



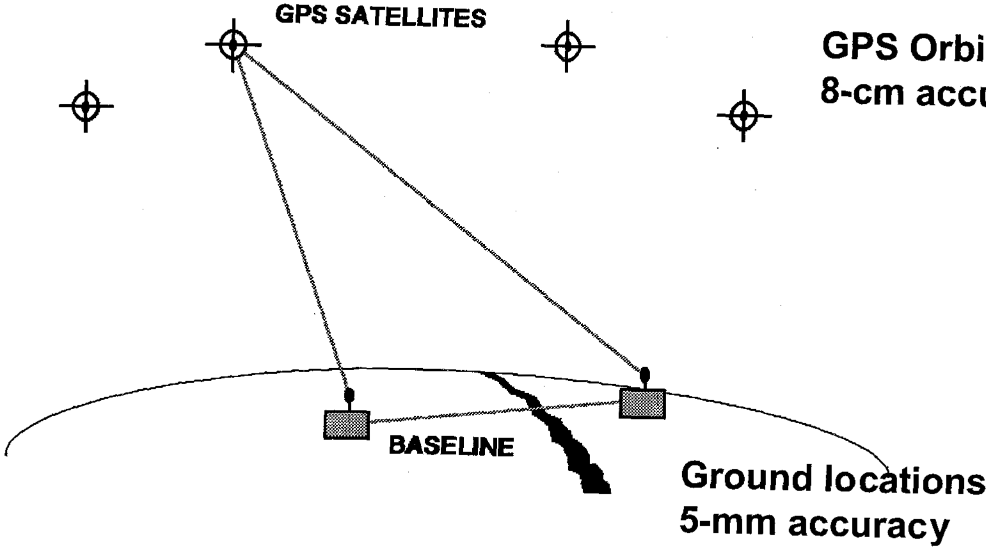
Mars Network Node: Integrated Navigation and Telecommunications



ST-5: Constellation Communications and Navigation Transceiver (CCNT) for meter-level cross-link ranging and inter-spacecraft telecom in constellation of three spacecraft in GEO-transfer elliptical Earth orbit

Global Positioning System (GPS) Measurements Applied to Geophysics and Natural Hazards

- NASA contributes about one-quarter of the ≈ 200 GPS tracking stations in the International GPS Service (IGS) global network
- Analyses of their data is interpreted in terms of tectonic plate motions and geodynamics
- High density deployment of GPS sites contributes to the assessment of earthquake hazards (southern California map)

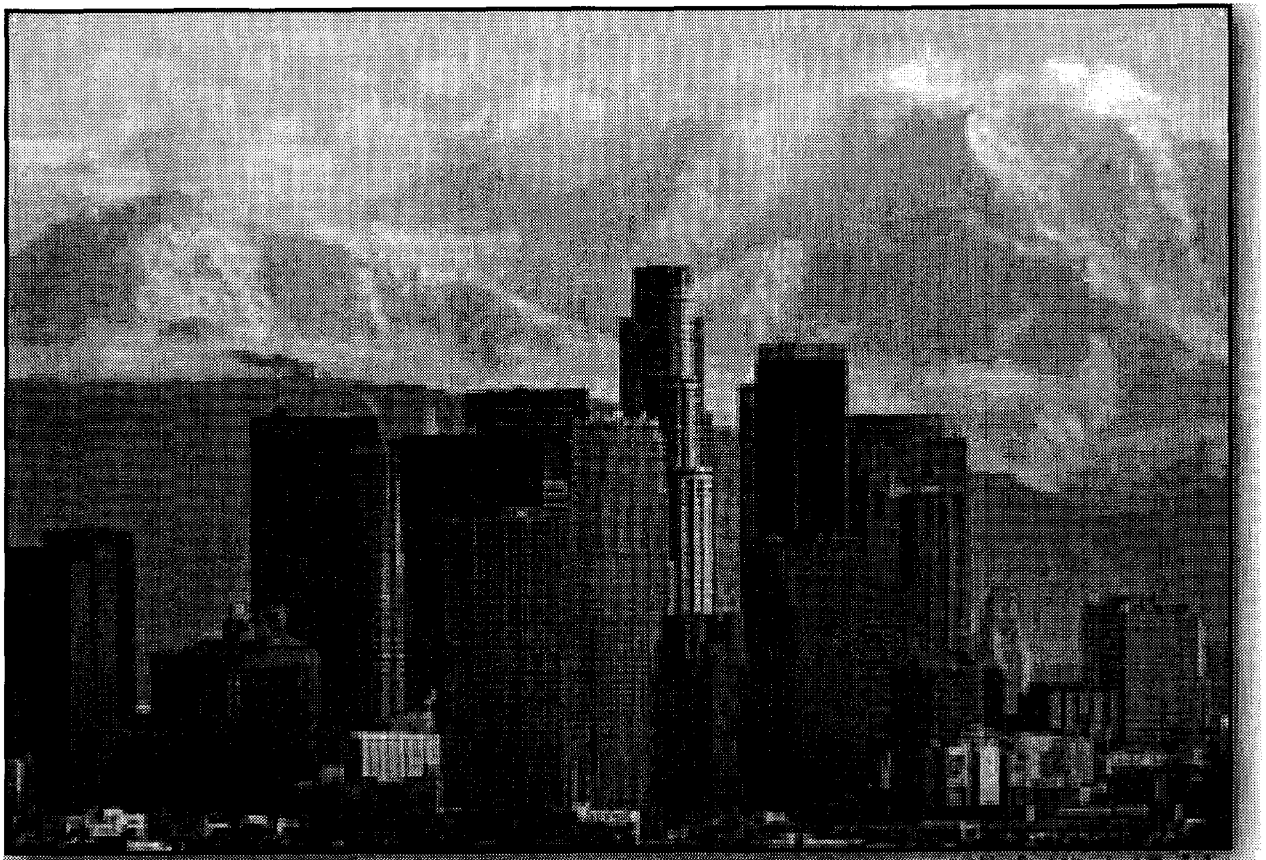


IGS Global Network

TV News

NBC NIGHTLY NEWS WITH TOM BROKAW

Los Angeles is moving, literally



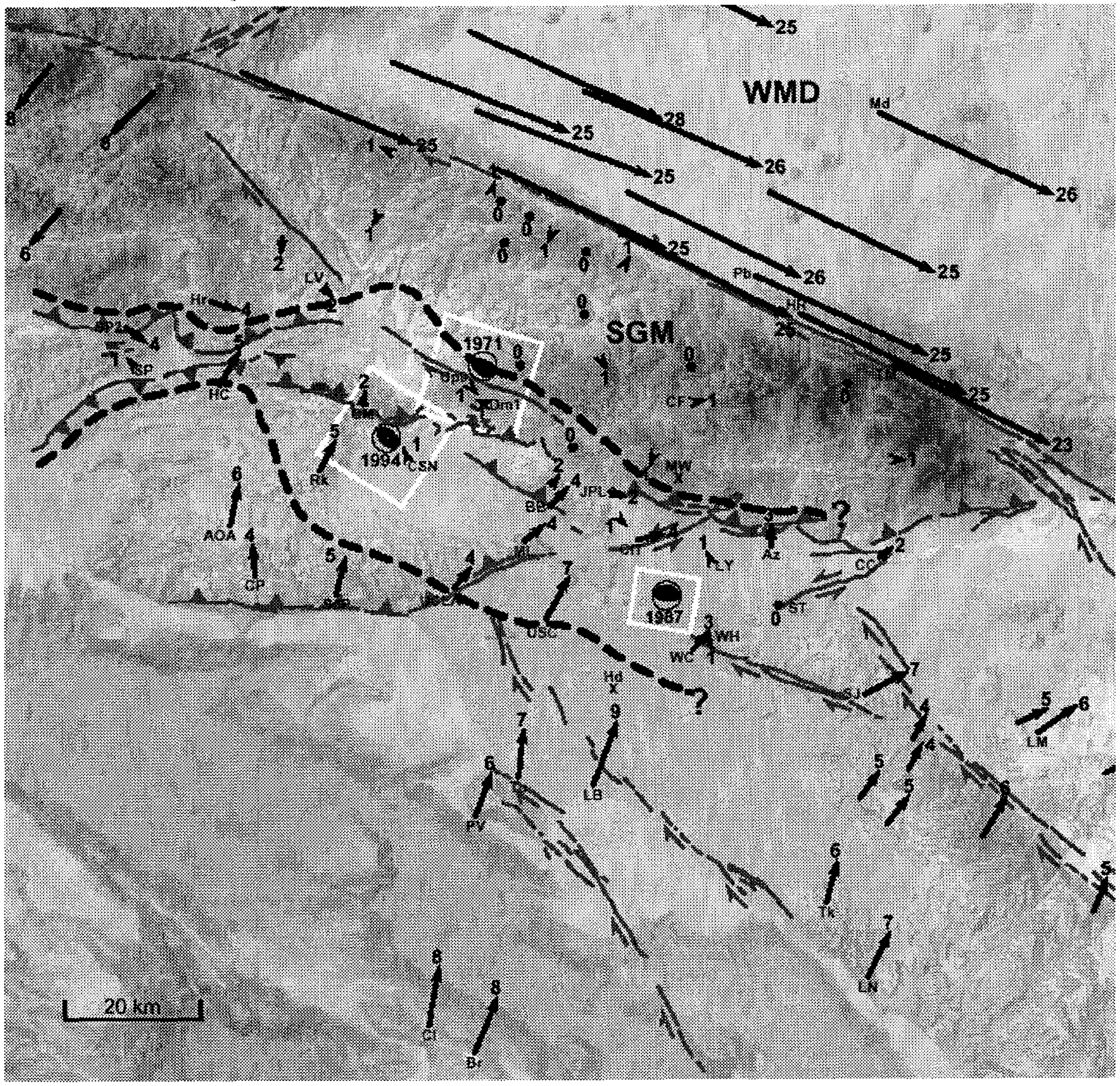
Nick Ut / AP file

LOS ANGELES, August 4 — Scientists at the Jet Propulsion Lab in Pasadena, Calif., have made measurements that suggest that downtown Los Angeles is moving toward the San Gabriel Mountains, and that a new mountain range is being formed beneath Hollywood.

Shortening and Thickening of Metropolitan Los Angeles

residual velocity field

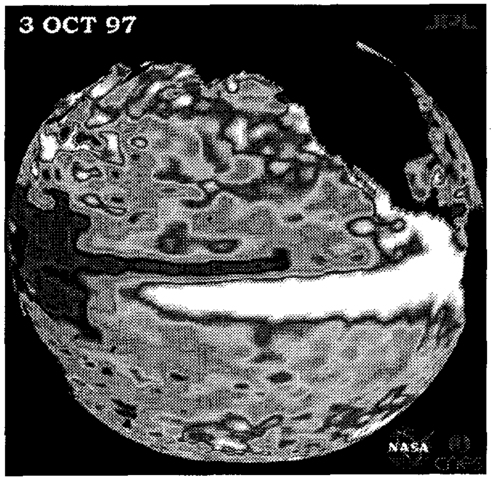
SGM fixed

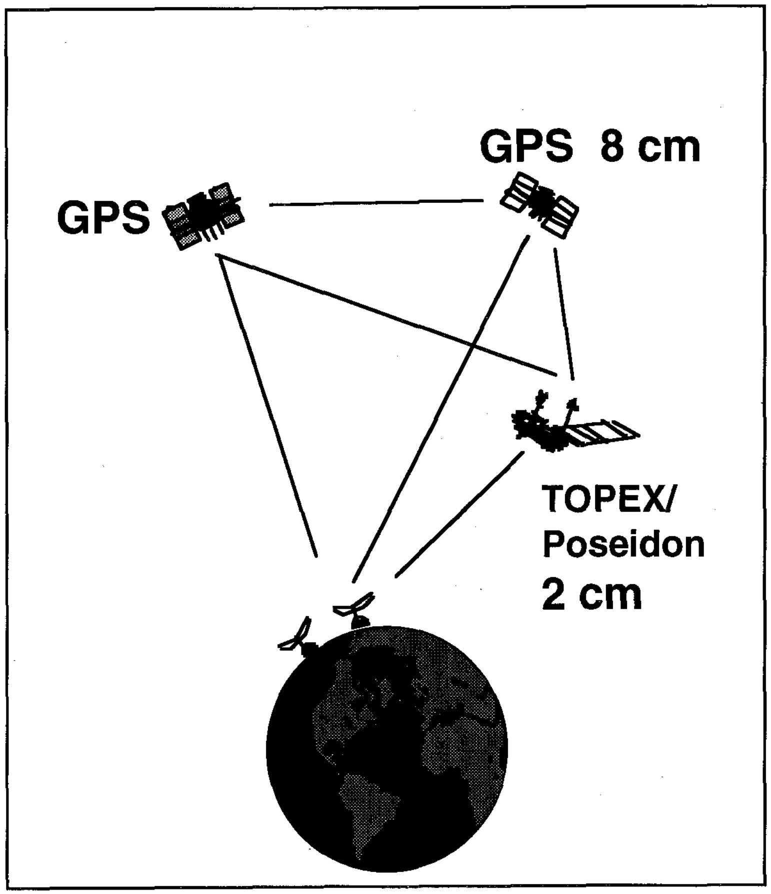


Mojave segment, San Andreas F.
best 25 mm/yr 20 km

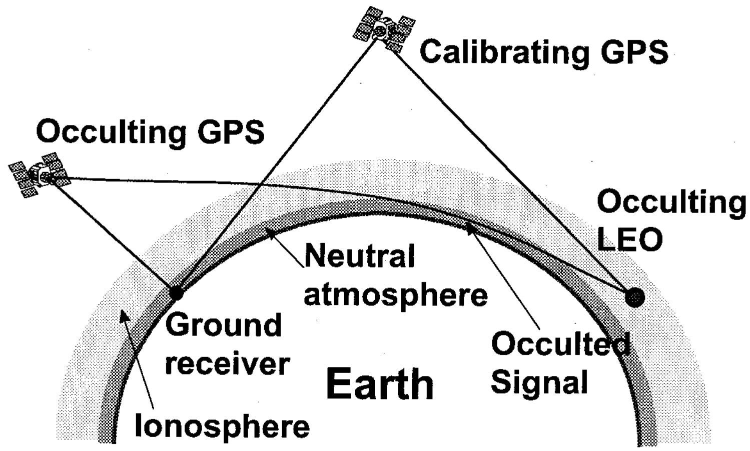
Using Satellite Technology to Help Track Global Change Such As El Niño

- JPL receives daily GPS satellite tracking data and automatically determines TOPEX/Poseidon orbit "next-day" accurate to a few centimeters
- Calibrated TOPEX/Poseidon altimeter data provide accurate information on sea level changes
- Scientists infer ocean temperatures and determine that an El Nino event is occurring based on sea level rise in Pacific Ocean
- Advance preparations can save lives and property

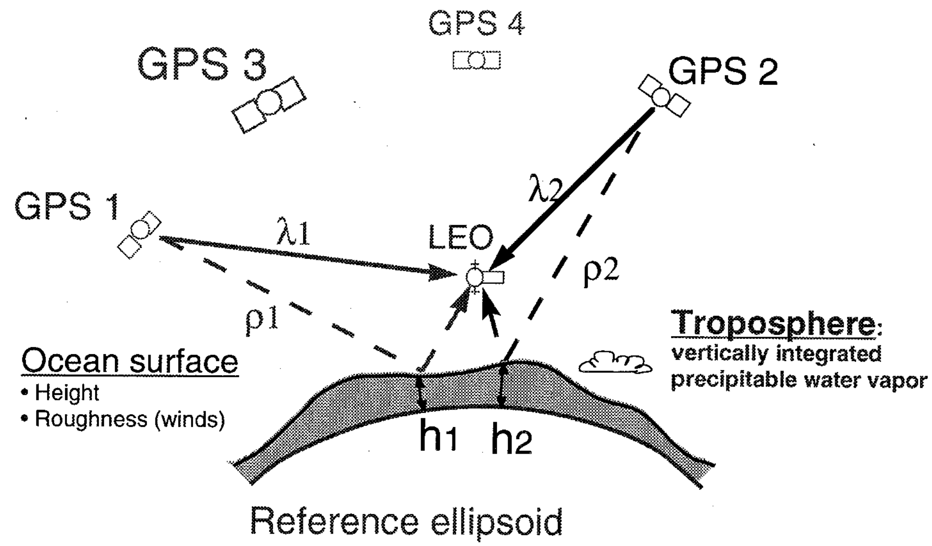




Novel Science Applications

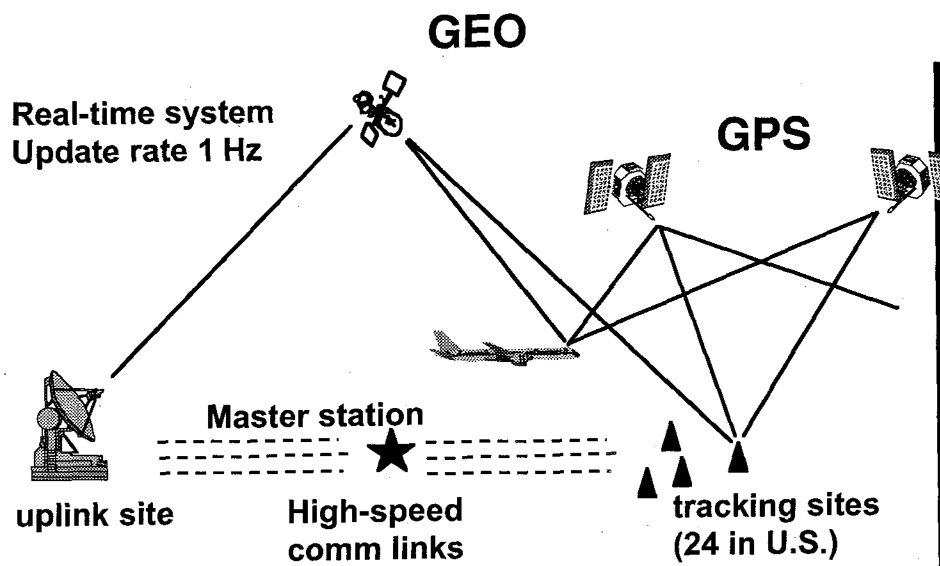


Atmospheric and Ionospheric Remote Sensing and Science



Bi-Static Ocean Reflectometry

Task: GPS Wide Area Augmentation System (WAAS) Implementation



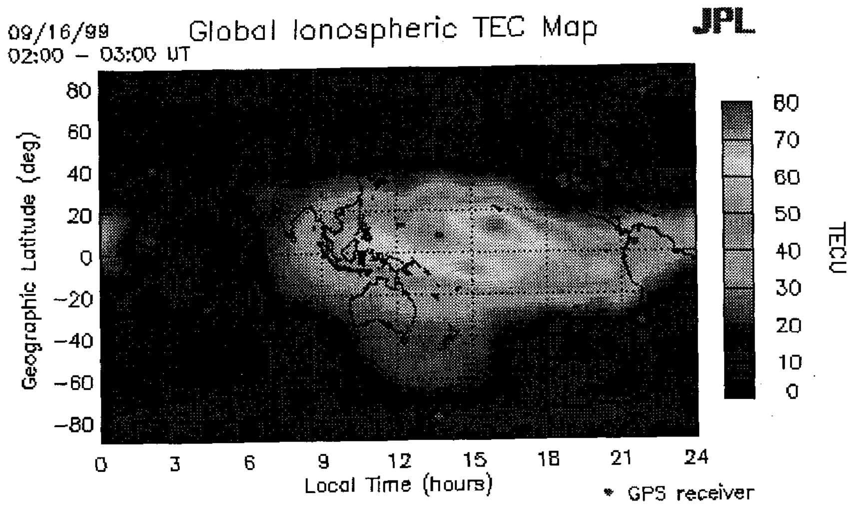
Task Purpose/Objectives:

- Deliver working prototype of real-time software for DOT/FAA's new GPS-based precision navigation system (WAAS) for aviation. Support its implementation and develop future enhancements.

Major Products and Deliverables:

- Real-Time GIPSY (RTG) software
- Real-time WAAS Ionospheric Software (WIS)
- New GPS and safety algorithms

Sponsor: DOT/FAA



Customer Relevance:

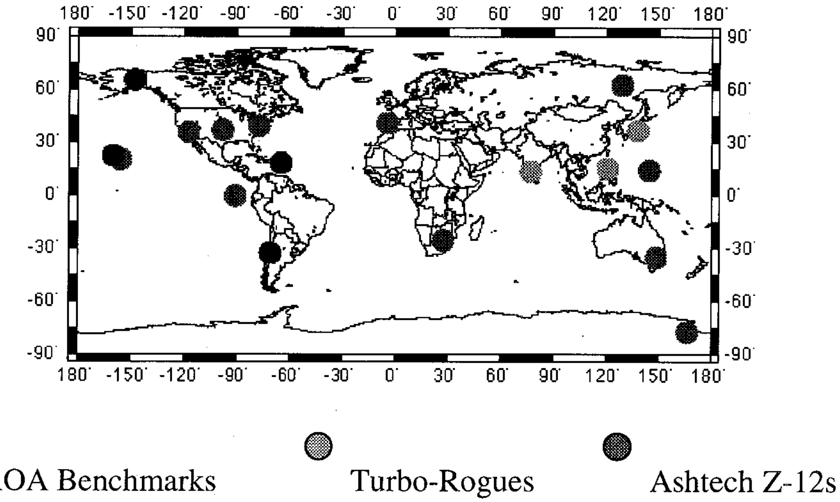
- Improve airline navigation accuracy by orders of magnitude; enhance aviation safety in U.S.
- Save $12B+ in next decade in fuel and airport costs

NASA Relevance:

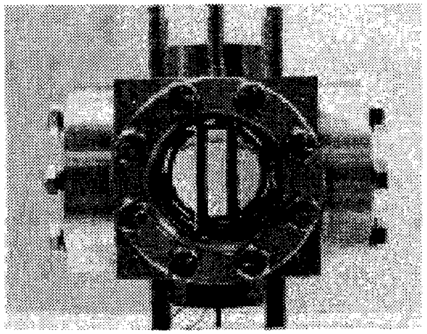
- Real-time, autonomous space navigation
- Onboard science data product generation
- Real-time natural hazard monitoring
- Pathfinder for the Mars Network Infrastructure.

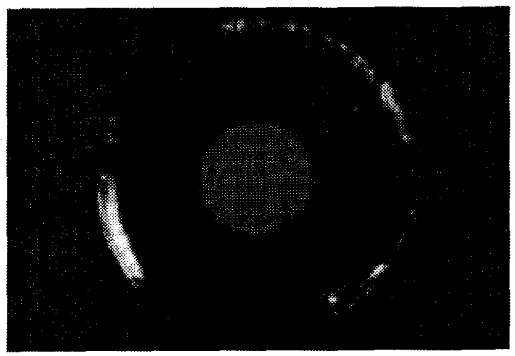
Precise Real-Time Global Differential GPS Navigation

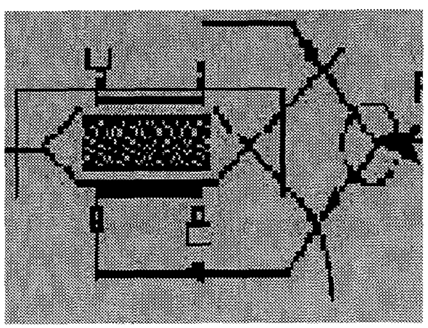
- **Established a global, real-time, differential GPS ground network**
  - **Real-time user accuracies: 8 cms RMS horizontal, 20 cms RMS**
    - **~ 10 times better than best available commercial and military systems**
  - **State-space method => no need to be near reference station (global availability)**
  - **30-40 cms 3D (RSS) global GPS orbits, in real-time**
  - **NASA, DoD and commercial applications being studied, including:**
    - **X33/RLV navigation (X33 flight demo planned)**
    - **Automated LEO navigation and onboard science data product generation**



Frequency and Timing Research







- **Linear Ion Trap frequency Standards (LITS): world's best for measuring times over ~ hours to weeks**
  - New generation of atomic frequency standards was developed at JPL and is now being installed in NASA ground stations. Small size, high reliability also make it a natural choice to advance spacecraft capabilities to ultra-high stability levels (10^{-15} or better).
  - Project underway to deploy LIT on a GPS satellite
- **Projects underway to fly laser-cooled clocks on the Space Station**
- **Photonic research**
  - Provide new capabilities for distribution, conversion & generation of ultra-stable RF & microwave signals.
  - These capabilities are essential to NASA's worldwide deep space antenna/communications system
  - Optical fiber with low thermal variability
  - Photonic frequency conversion that can entirely eliminate the need for an external downconverter.
  - OptoElectronic Oscillator: ultra-high stability in a small, room-temp package

Applications of JPL Technologies With Potential Interest for GPS III

- Studies of GPS signals & performance (propagation, jamming, codes ...)
- User equipment directed studies and research
- GPS system performance improvement (global network, 10-cm real-time user accuracy ...)
- "Truth systems" to validate operational performance
- Evaluation of GPS augmentations (space and/or ground)
- Prototypes (algorithms, software, hardware) for operational GPS enhancements (OCS, users ...)
- Precision clocks for long-term use in operational environments on ground or onboard GPS satellites

- ***JPL routinely contracts directly with non-NASA agencies and/or with private companies, and licenses its technologies (through Caltech).***

JPL's GPS Receiver Technology

Larry Young,

Dec 8, 2000

GPS System Building Blocks
(Today, Tomorrow)

- Satellites
  - Lc, second civil link
  - Ls, science link
  - POD-friendly design (phase center, rad. Models)
- Digital receivers
  - Sub mm precision
  - On-board multipath mitigation
  - Lower power/mass/cost
  - Additional capabilities (active ant array,...)
- Global tracking network
  - Data from >200 digital receivers
  - Automated 15-cm GPS orbits
  - Realtime 30-cm GPS orbits

JPL's GPS Receivers Characteristics

- Developed to provide the highest accuracy observables
- Designed in consultation with users of science data
- Flexible design (software radio)
  - All tracking loops closed in software
  - Next receiver replaces ASICs with FPGAs to allow dynamic hardware reconfiguration

JPL's GPS Receivers Development

- Design hardware and algorithms
- Predict performance analytically
- Simulate receiver performance at the sample level, with 10^{-8} cycle precision
- Do bench testing to measure performance vs analysis
  - Ex. C/A measured range vs SNR varies according to analysis. An SNR-based correction was added to the C/A pseudorange.

JPL GPS Receiver History

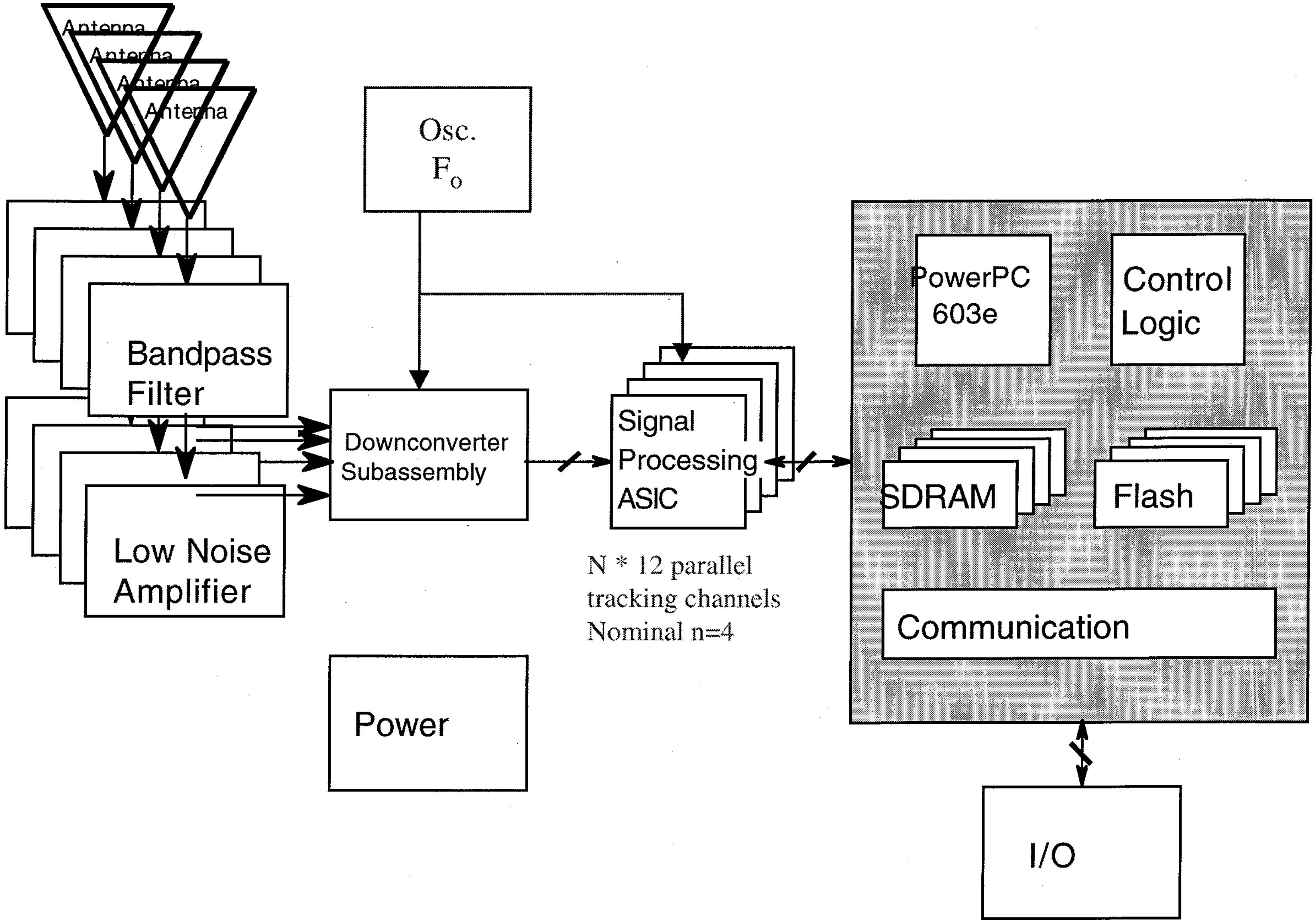
- Ground GPS receiver development at JPL (*tectonic deformation, clk. sync., ion maps, ships/planes)*
  - 1979 SERIES (codeless pseudorange, directional), cm precision, sub-ns clk synch
  - 1986 Rogue + 1992 TurboRogue (code and codeless pseudorange and carrier), 0.1 mm precision, 0.01 ns clock-synch precision

JPL GPS Receiver History (contd)

- Flight GPS receiver development at JPL (*Precise Orbit Determination, gravity, atmospheric occultation, bistatic radar, attitude, ...)*
  - 1995 TRSR on GPS/MET, Wake Shield, Ørsted, SunSat,
  - 1998 BitGrabber on SNOE, STRV-1C
  - 2000 BlackJack on SRTM, CHAMP, SAC-C, JASON, GRACE, ICESat, FedSat, VCL, ST5
- **Constellation flying**
  - SAC-C, GRACE, ST3, ST5, Mars infrastructure

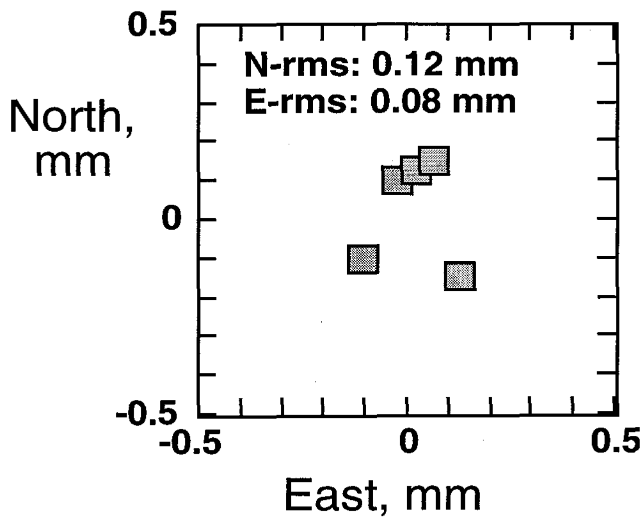
Architecture

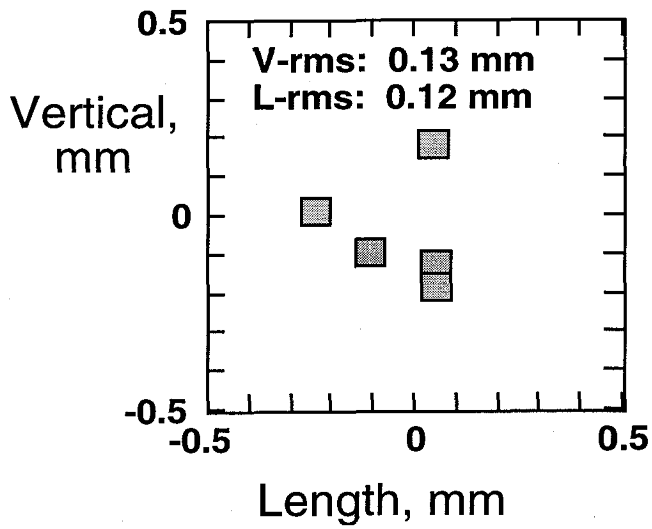
Block Diagram TRSR Subsystem



JPL-Developed Digital Receiver Performance

- Limiting-Performance test results
  - 29-m baseline measured on JPL mesa





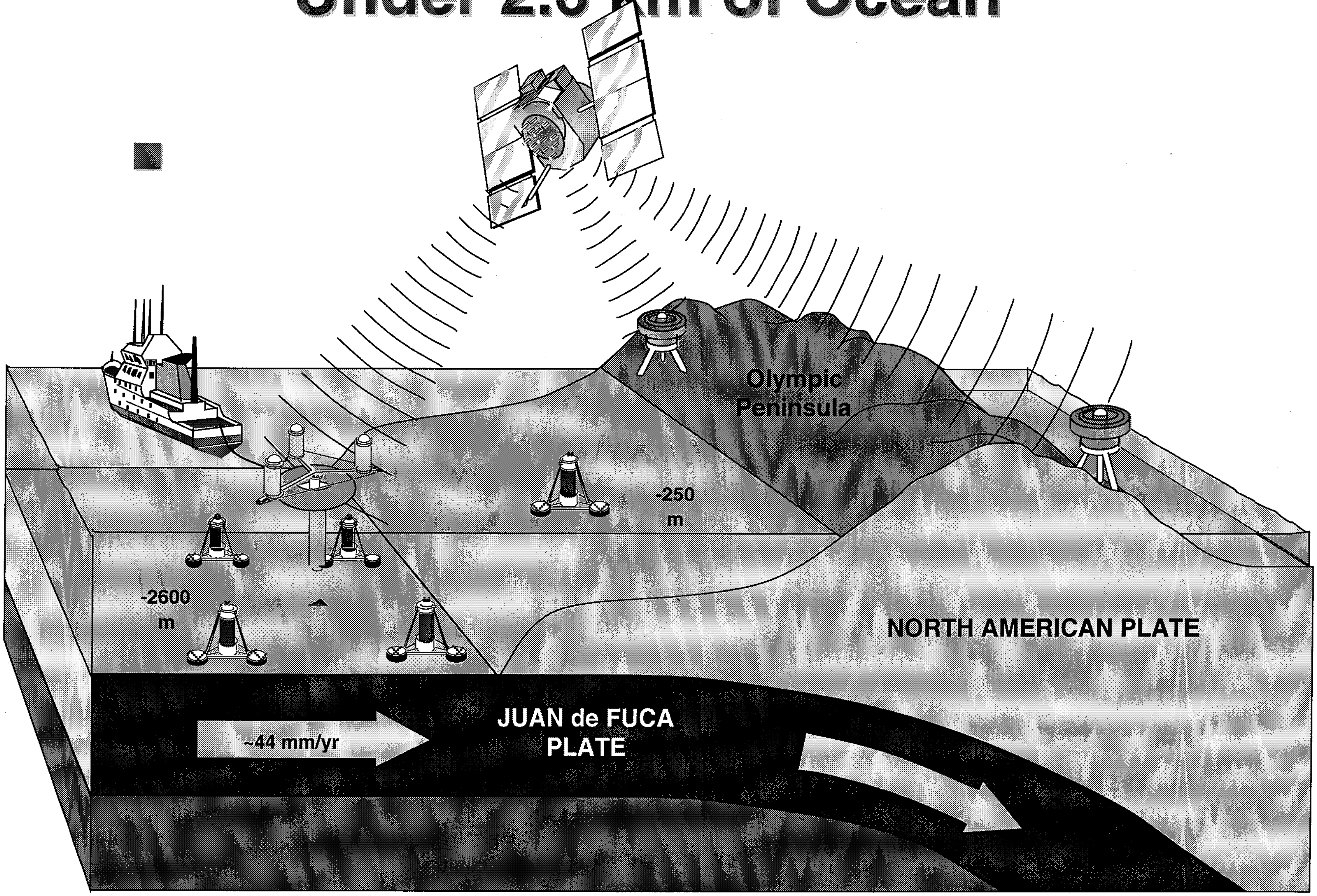
- Repeatability over 5 successive days is 0.1 mm (0.7 arc sec

Undersea Positioning

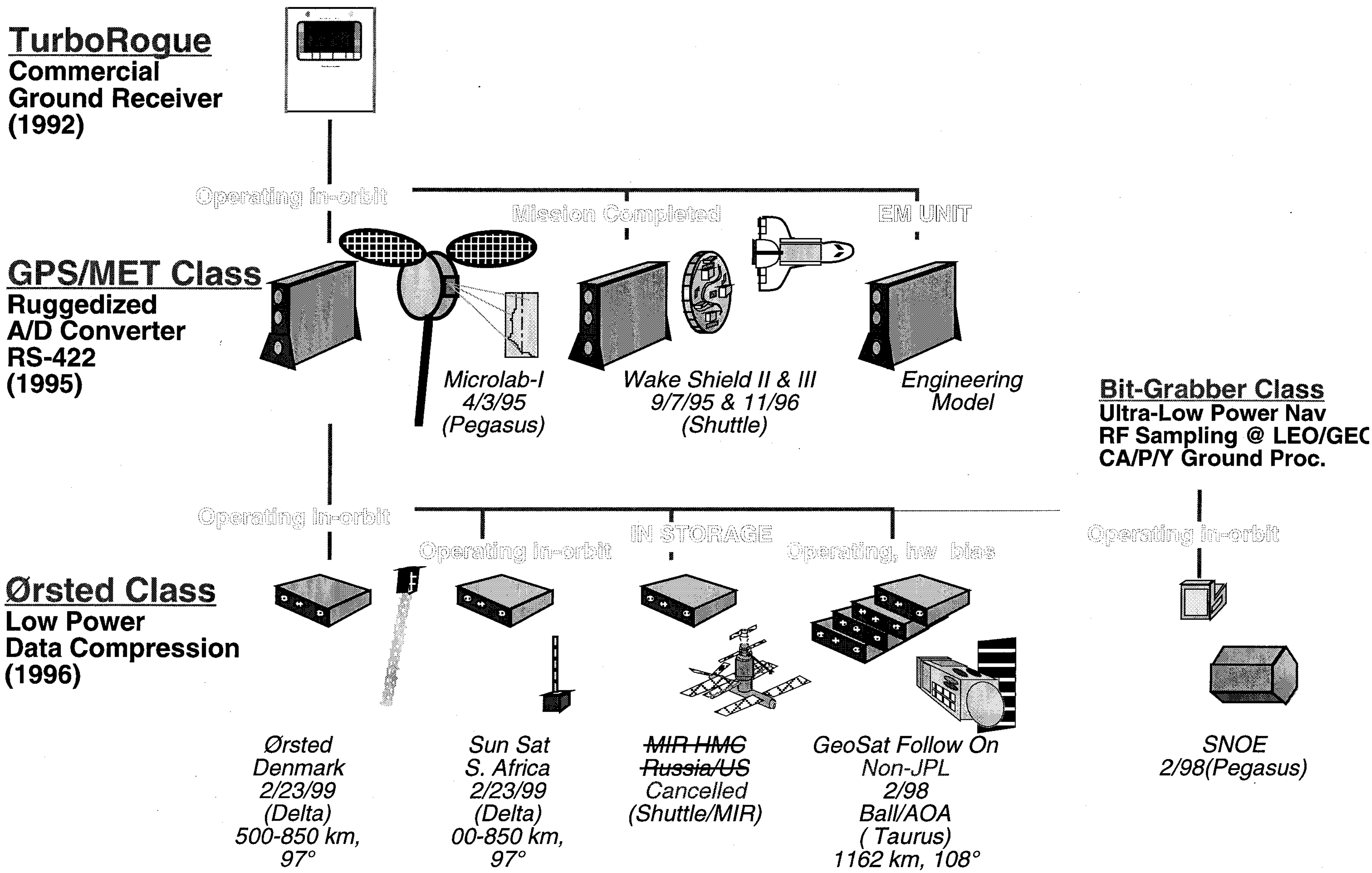
(Today, Tomorrow)

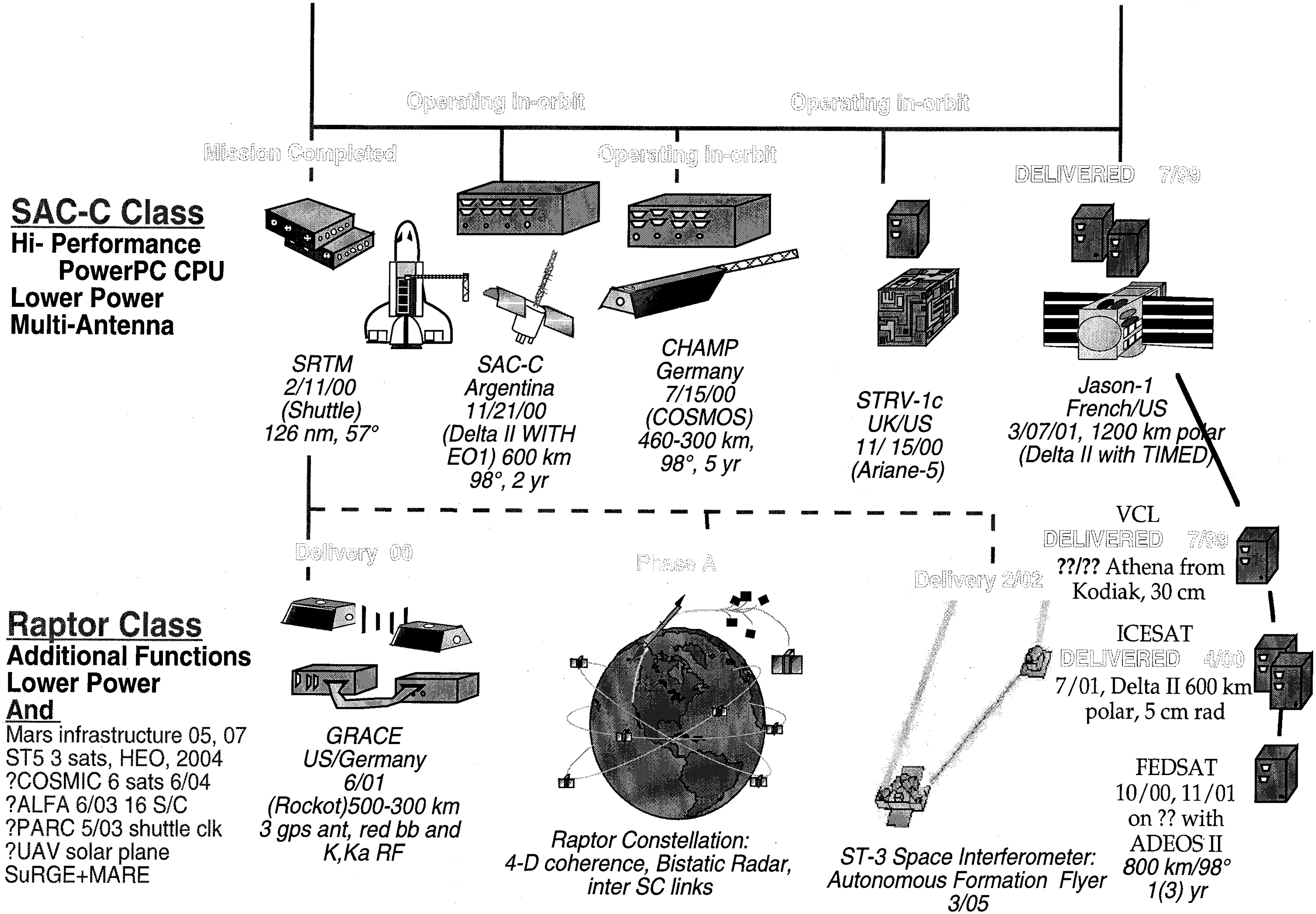
- GPS/acoustic buoy, multiple seafloor transponders
  - SIO/JPL demonstrated <10 cm repeatability for seafloor reference mark
  - Fixed site
  - Post-processed
- Multiple buoys to locate underwater vehicle
  - Develop algorithms to measure sound velocity
  - Produce sub-meter realtime kinematic positioning

Sub Decimeter Positioning Under 2.6 km of Ocean



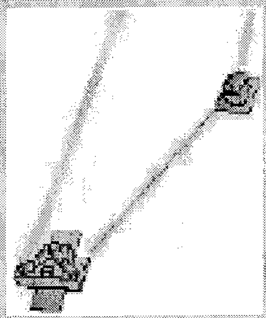
GPS Systems Group: TRSR Family Tree




Operating in-orbit
Operating in-orbit
Mission Completed
Operating in-orbit
DELIVERED 7/99
SAC-C Class
Hi- Performance
PowerPC CPU
Lower Power
Multi-Antenna
SRTM
2/11/00
(Shuttle)
126 nm, 57°
SAC-C
Argentina
11/21/00
(Delta II WITH
EO1) 600 km
98°, 2 yr
CHAMP
Germany
7/15/00
(COSMOS)
460-300 km,
98°, 5 yr
STRV-1c
UK/US
11/ 15/00
(Ariane-5)
Jason-1
French/US
3/07/01, 1200 km polar
(Delta II with TIMED)
VCL
DELIVERED 7/99
??/?? Athena from
Kodiak, 30 cm
Delivery 00
Phase A
Delivery 2/02
ICESAT
DELIVERED 4/00
7/01, Delta II 600 km
polar, 5 cm rad
Raptor Class
Additional Functions
Lower Power
And
Mars infrastructure 05, 07
ST5 3 sats, HEO, 2004
?COSMIC 6 sats 6/04
?ALFA 6/03 16 S/C
?PARC 5/03 shuttle clk
?UAV solar plane
SuRGE+MARE
GRACE
US/Germany
6/01
(Rockot)500-300 km
3 gps ant, red bb and
K,Ka RF
Raptor Constellation:
4-D coherence, Bistatic Radar,
inter SC links
ST-3 Space Interferometer:
Autonomous Formation Flyer
3/05
FEDSAT
10/00, 11/01
on ?? with
ADEOS II
800 km/98°
1(3) yr

BlackJack Derived Comm/Nav Transceivers

Delivery 7/04

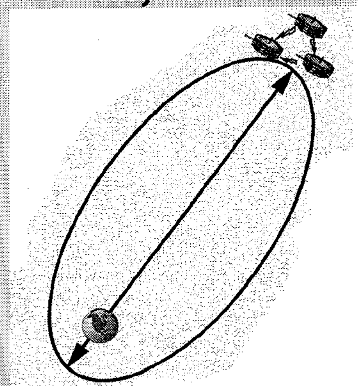


ST-3 Space Interferometer : Autonomous Formation Flyer (AFF)

AFF Class

- Ka-band
- S/C to S/C Link
- no GPS (deep space)
- Nav + Comm
- Range + Bearing Angle
- Extreme Performance
- 1 kbps (no coding)
- 6 month mission

Delivery 12/02

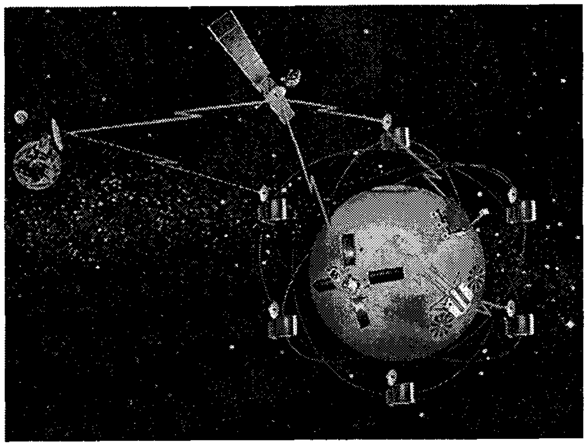


ST-5 NanoSat Constellation Trailblazer : Constellation Communication and Navigation Transceiver (CCNT)

CCNT Class

- S-band
- S/C to S/C Link
- “BitGrabber” GPS
- Nav + Comm
- Range
- Lower Performance
- 1 kbps + coding
- 6 month mission

Delivery 3/04



Mars Network Project (Infrastructure) : Mars Network Node (MNN)

MNN Class

- UHF + X-band
- S/C to many S/C Links
- no GPS (@ Mars)
- Nav + Comm
- Range + Doppler
- High Performance
- 2 Mbps + coding
- 5- 7 year mission

GRACE Mission

PROJECT OVERVIEW

SALIENT FEATURE

Launched from Plesetsk to a near-polar 500-km orbit:

- Separation is maintained to 220 km ± 50 km

The twin satellites are the instrument

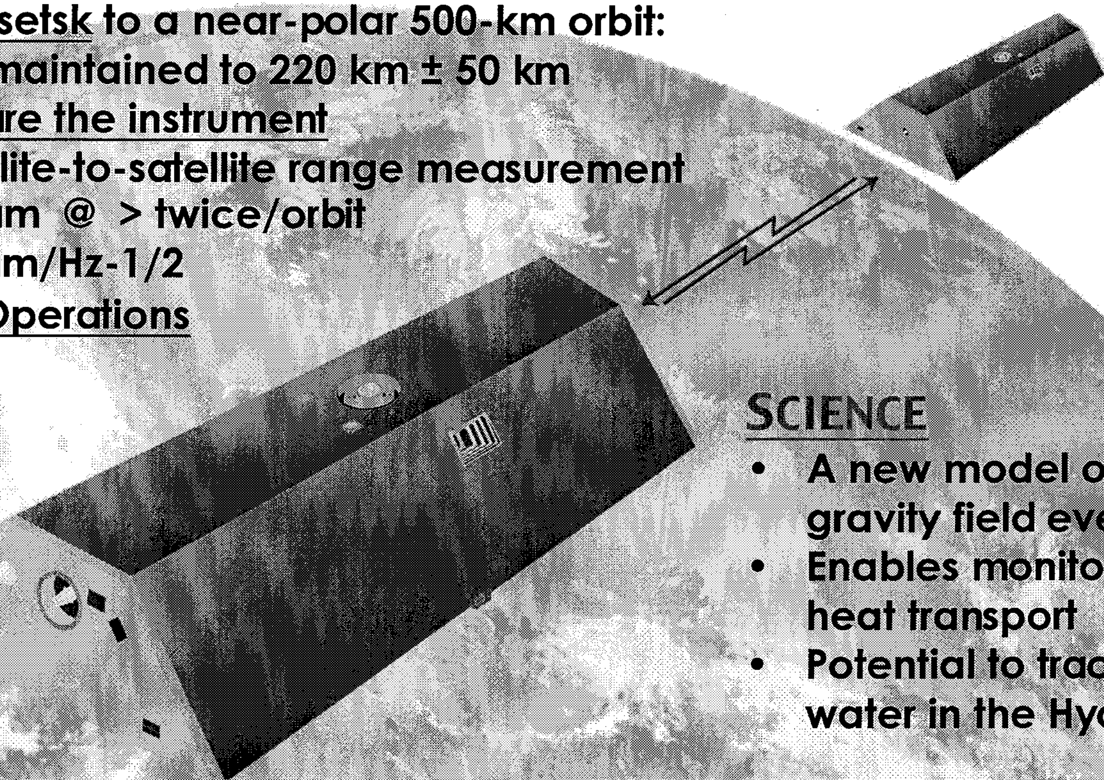
- Accurate satellite-to-satellite range measurement
  - Tones: $\leq 4\mu m$ @ > twice/orbit
  - Noise: $\leq 1\mu m/Hz^{-1/2}$

Launch & Mission Operations

- By Germany

Launch Date

- Fall 2001



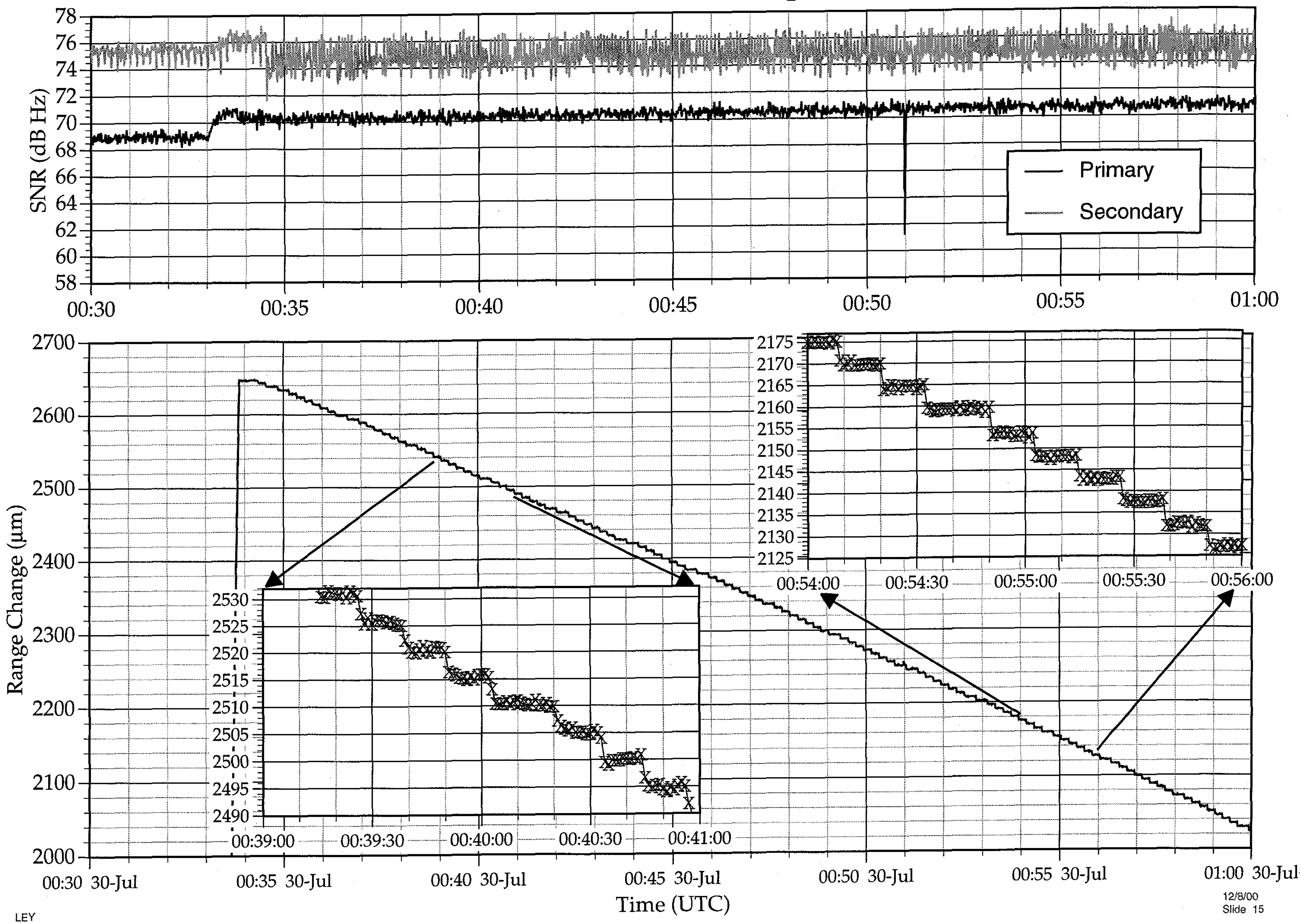
SCIENCE

- A new model of the Earth's gravity field every 30 days
- Enables monitoring of ocean heat transport
- Potential to track the storage of water in the Hydrologic Cycle

PERFORMANCE

- Minimum Science Mission – Geoid error < 10,000 microns for spatial scales of 285 km
- Expected performance – Geoid error < 350 microns for spatial scales of 285 km
- Expect to improve the knowledge by a factor of 1000 for spatial scales of 1000 km

Ka-Band; 5 µm Steps



LEY

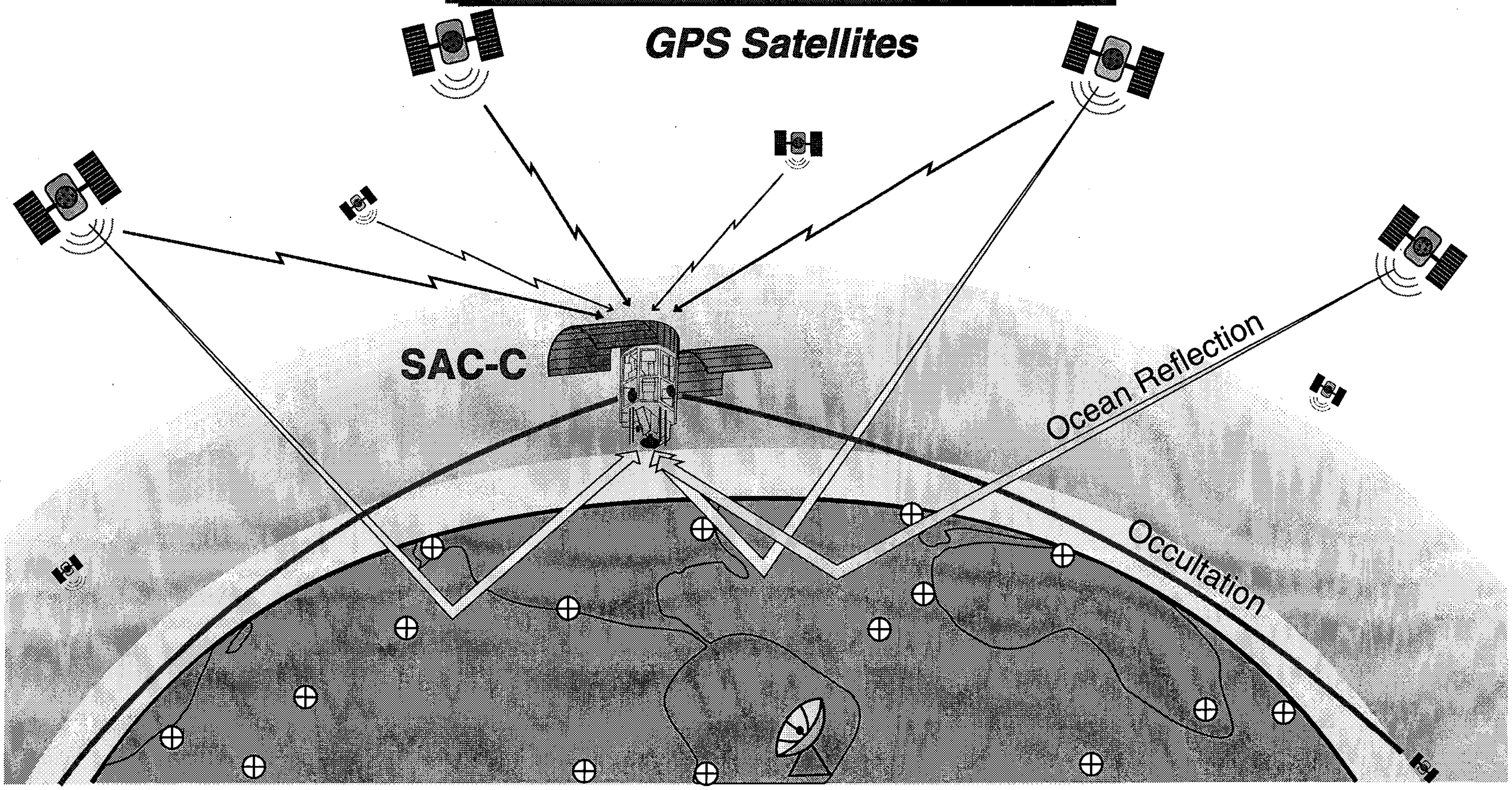
Altimetry + Scatterometry; Ocean Reflections of GPS

(Today, Tomorrow)

- Ground and aircraft-based demos by JPL, Dassault, NASA-Langley, and U. of CO
- Two small satellite missions scheduled
  - TurboRogue receiver modifications to process data on-board
  - Receiver-controlled antenna array will be used
  - 100 MHz code on Ls will enable cm-level altimetry
  - 5 GHz Ls carrier will enhance scatterometry

GOLPE: GPS OccuLtation and Passive Reflection Experiment

- Precise Orbit Determination
- Long Wavelength Gravity Recovery
- Atmospheric & Ionospheric Imaging
- Ocean Altimetry & Scatterometry

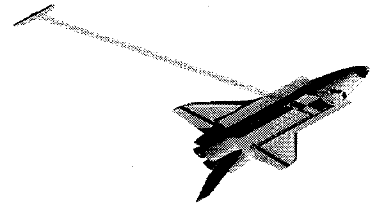


SIBLE SPACE-BORNE GPS REFLECTION DATA

Shuttle Radar Laboratory

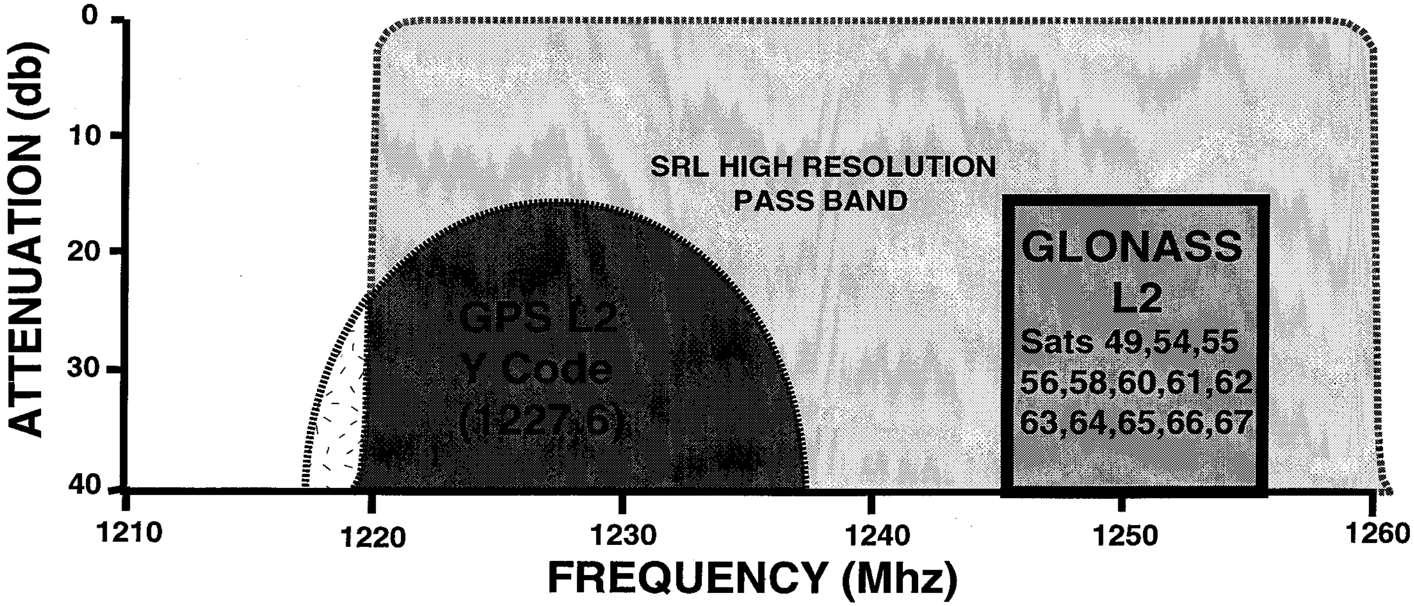
SIR-C/X-SAR

SHUTTLE RADAR LABORATORY DATA SET

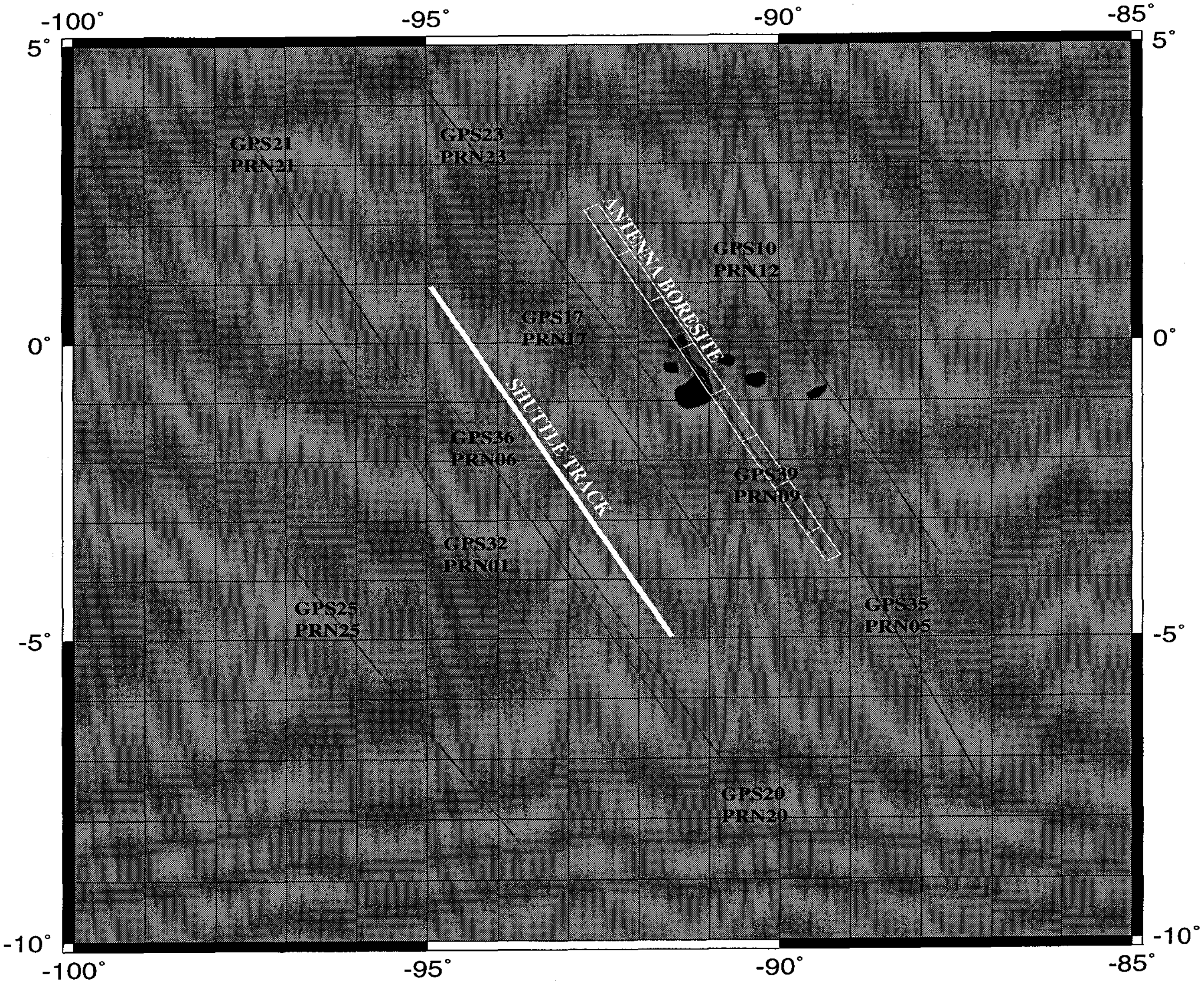


Some data were gathered in High Resolution mode during April and October, 1994 Shuttle Missions

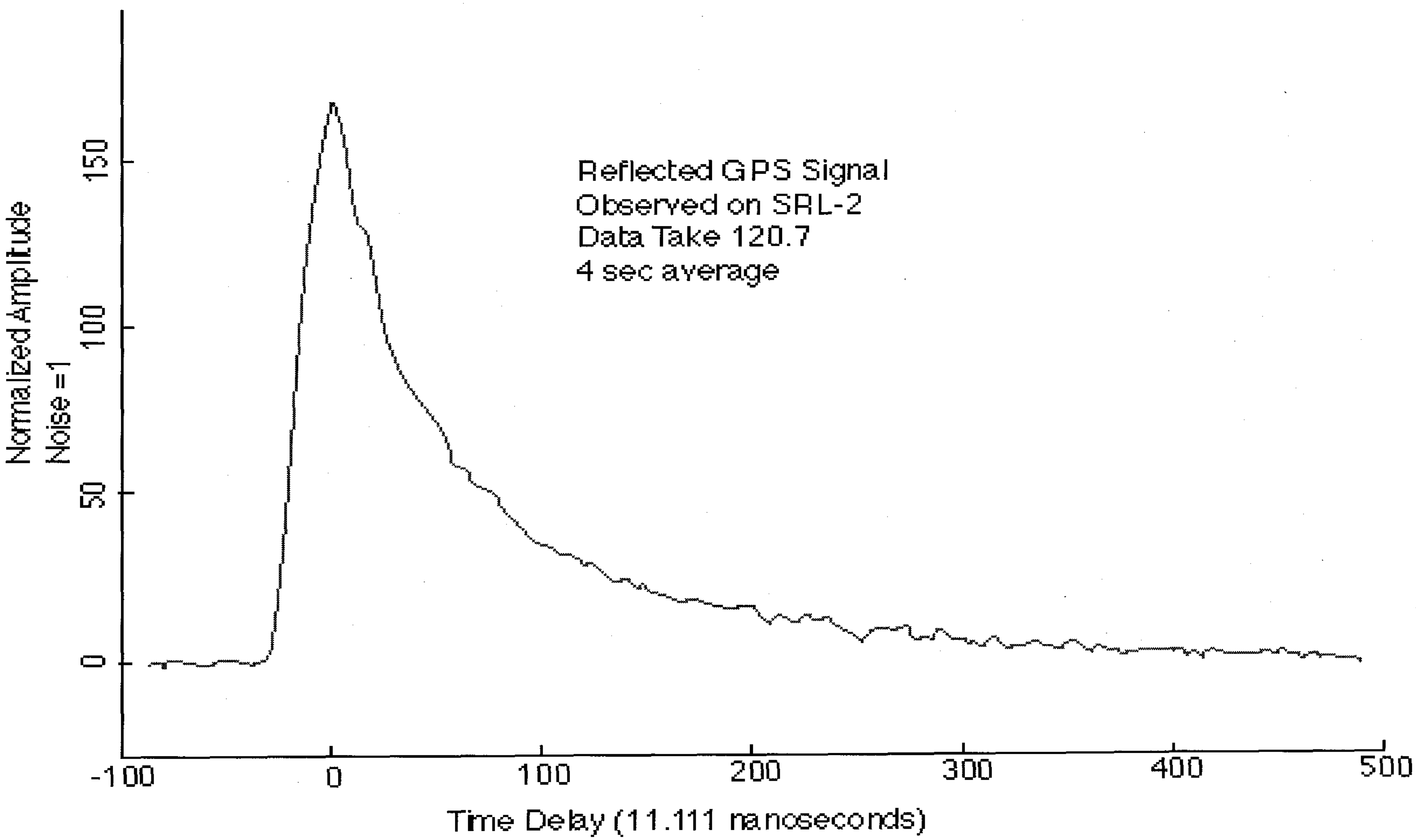
- Sampling Rate: 89.99424 Mb/sec (1 byte samples)
- Bandwidth: 40 Mhz (1220-1260 Mhz)
- Antenna Gain: 60 db with ~27 km Ground Swath Width
- Polarization: Vertical
- Two seconds before and after each data take were in a listen only mode



Specular Point Distribution for Data Take 120.7

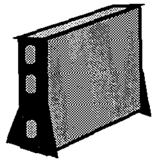


stimate of Bistatic Cross Section for Galapagos

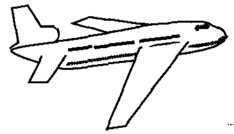


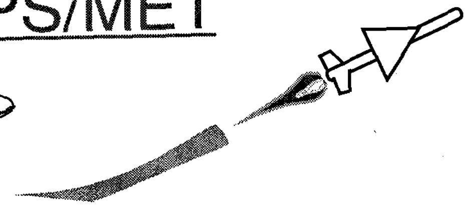
Climate/Weather from GPS
(Today, Tomorrow)

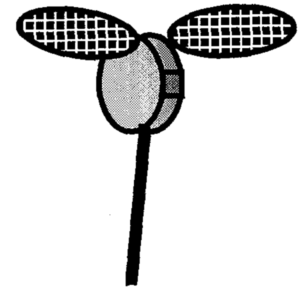
- GPS/MET
  - demonstration of 1 K accuracy temperature profile
  - about 200 profiles per day
- Constellation of 100 microsatellites
  - satellite hardware and operations costs low
  - about 50,000 globally distributed profiles/day



GPS/MET







Status

- Pegasus Launch 4/3/95
- About one software version per month
- Receiver remains healthy after 27 months

TurboRogue Firsts

- First Occultation Measurements of Earth's atmosphere
- First true cold start of GPS receiver in orbit(4/12/95).
- First Autonomous Scheduling of Science Observations
- First single antenna GPS attitude determination

Problems (through 1st year on orbit)

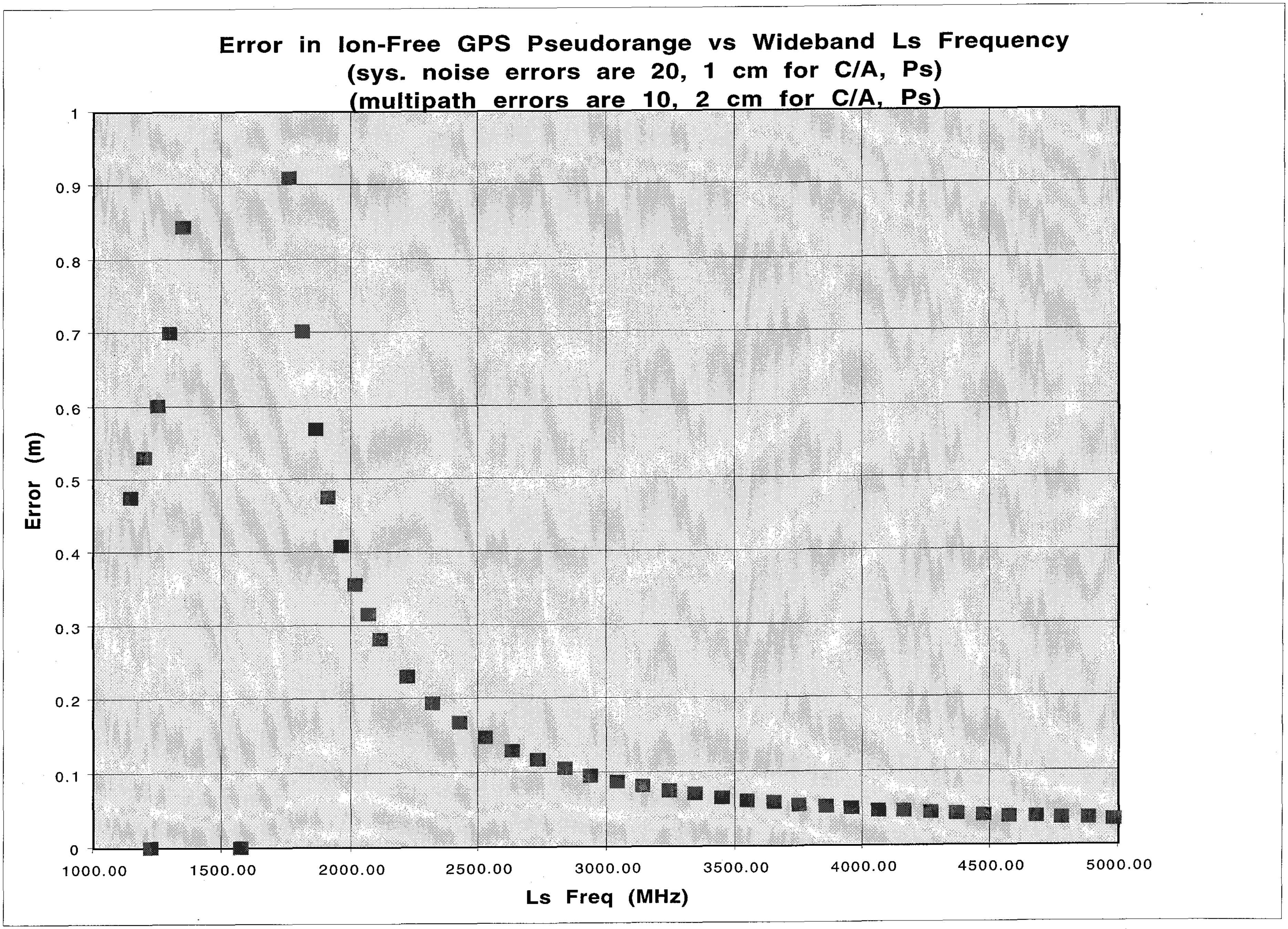
- AS
- Data Outages

Many	Space Craft Resets
Many	Space Craft Power Problems
Many	Receiver Resets (SEU's)
Many	Communication Errors
10-20	Space Craft attitude problems -Single Antenna Attitude Determination
6-7	Commanding Errors
7	Uploads (1 lasting 90 minutes)
2	Software Errors

- 1 Latch-Up
  ~48 hour duration, affected only one channel,

Science Link, Ls
(Today, Tomorrow)

- Ls
  - Special session on Ls at American Geophysical Union mtg, Ls design presented @ AGU, Talk @ JPL seminar,
  - Desired attributes
    - Precise ion-free pseudorange
    - Tri-laning for robust carrier ambiguity resolution
    - Low multipath
  - Future appl.: altimetry, scatterometry, bistatic radar...
  - Strawman design for freq., range code, constant-amplitude modulation scheme



Error in Ion-Free GPS Pseudorange vs Wideband Ls Frequency
(sys. noise errors are 20, 1 cm for C/A, Ps)
(multipath errors are 10, 2 cm for C/A, Ps)
Error (m)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1000.00
1500.00
2000.00
2500.00
3000.00
3500.00
4000.00
4500.00
5000.00
Ls Freq (MHz)

Two Concepts for Enhancing GPS
(Today, Tomorrow)

➔ **Upgrade existing constellation to enable <50 cm (expect 20 cm) stand alone user positioning**

- Augment GPS constellation to improve robustness, availability, and add new C-band frequency signal
- Significantly enhance GPS cross-links with continuous phase and range to maintain precise time transfer across entire constellation
- Could support 10-cm real-time non-differential user accuracy while requiring global monitor network of only ~ 20 ground sites

Summary

- GPS receivers
- GPS antennas
- On-receiver data processing
- GPS signal design
- New applications for GPS

JPL's relevant expertise in GPS performance analysis and software

Presenter: Yoaz Bar-Sever

Contents:

Core capabilities and activities

Strategic software tools

Selected contribution to GPS performance

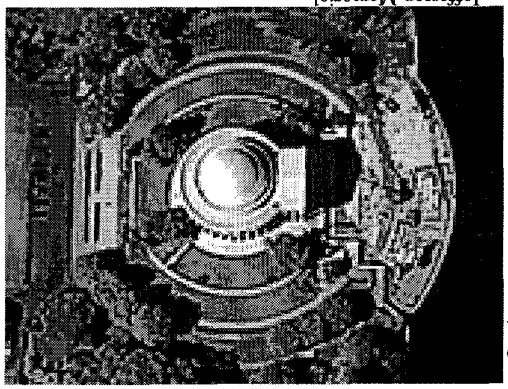
GPS III study topics

Core capabilities and activities - orbit determination

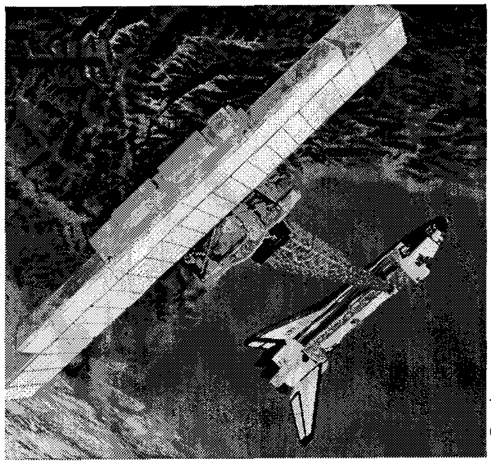
Precise orbit determination (scientific, military and commercial)

- GPS, Topex, SRTM, Ikonos, SAC-C, Jason, OV3, PARCS,...

An Ikonos image of...
Jefferson Memorial



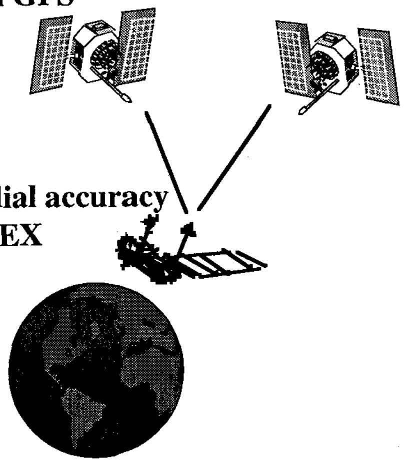
1 m orbit
Accuracy
on Ikonos



1 m orbit
Accuracy
on SRTM

10 cm 3D accuracy
on GPS

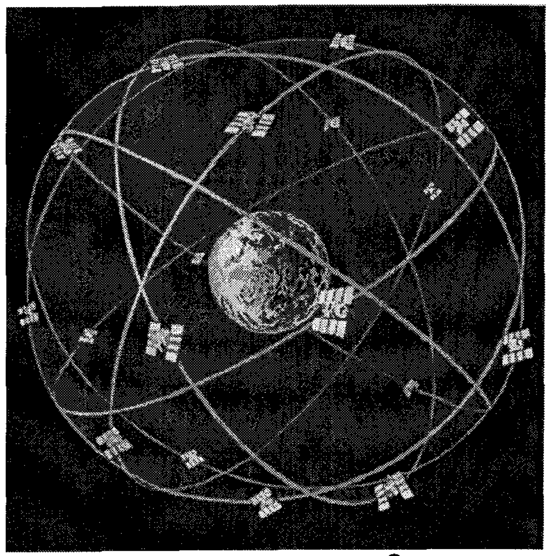
2 cm radial accuracy
on TOPEX



Routine and automatic GPS orbit determination processes

- Precise (better than 10 cm 3D RMS) with 3 day latency
- Rapid (20 cm 3D RMS) with 12 hours latency
- Real time (30 cm 3D RMS)
- 48 hour orbit prediction (50 cm median 3D error over last 24 hours)

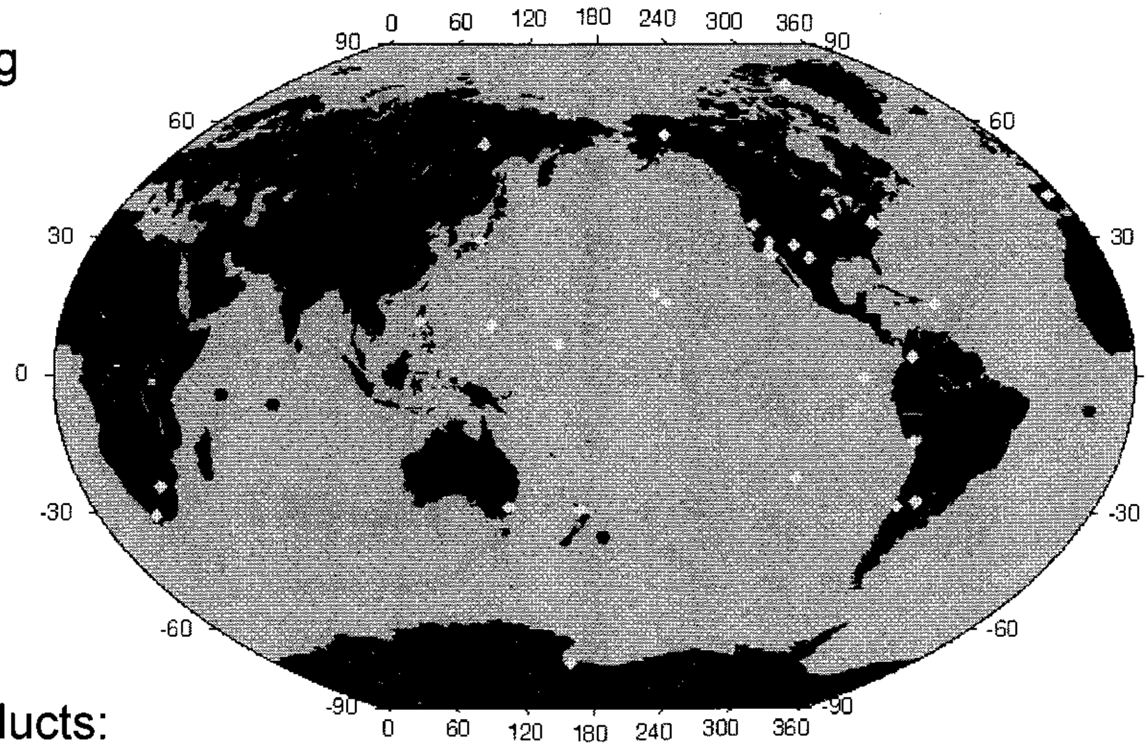
Routine and automatic daily orbit determination for Topex



Core capabilities and activities - reference networks

Operating and maintaining NASA's global GPS network (GGN)

- Dual frequency geodetic receivers
- Real time global sub-net
- Sub-cm routine daily positioning of hundreds of sites world wide



NASA's Global GPS Network

GPS orbit determination by-products:

- Earth orientation parameters
- Determination of terrestrial reference frame
- Global ionospheric maps

Core capabilities and activities - real time systems

1995 White Paper (WADGPS)
Real Time GIPSY (RTG)

1996 RTG is licensed to SATLOC
RTG is licensed to Raytheon (WAAS)
NASA-FAA Inter-Agency Agreement

1997

1998 2nd RTG license to Raytheon (MSAS-Japan)

1999 Internet-based Global Differential GPS (IGDG)

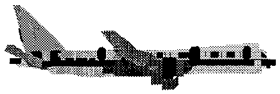
2000 Global Differential GPS with IGDG operational

IGDG wins NASA Software of the Year Award

Initial ground positioning
Demonstrated 50-cm (97)

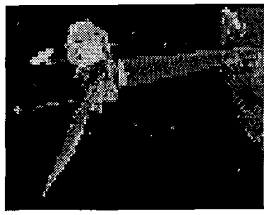
Automobile positioning
Demonstrated 80-cm (98)

Aircraft real-time Wide Area Differential navigation:
NASA SAR plane (98)
and FAA/WAAS (99)
Demonstrated 40-cm vertical 30-cm horizontal (98)



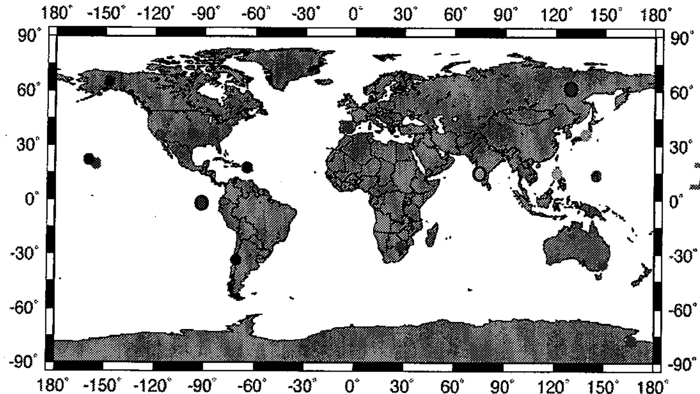
Internet-based Global Differential (IGDG) (00)
Real time ground positioning
Demonstrated 10 cm horizontal, 20 cm vertical accuracy

X-33/RLV IGDG real-time positioning demo (01)
Goal: sub-meter accuracy



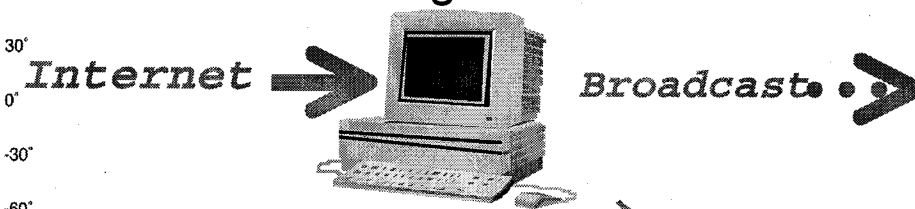
Real-time autonomous positioning and navigation for Earth orbiters (00-01)
Goal: sub-10-cm accuracy

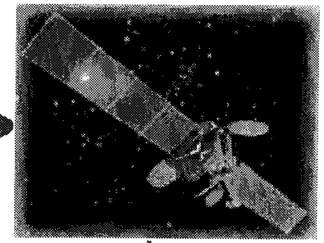
Core capabilities and activities - real time systems

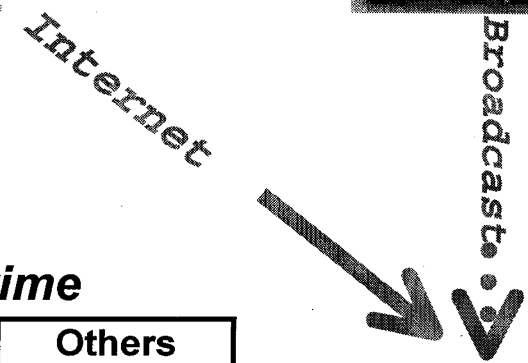


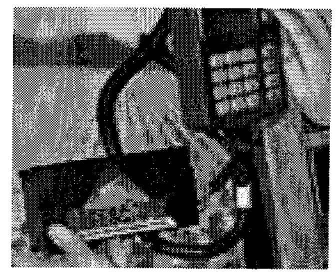
Network receivers running IGDG

JPL processing center running IGDG









Remote user running IGDG

Revolutionary new capability:
decimeter real time positioning, anywhere, anytime

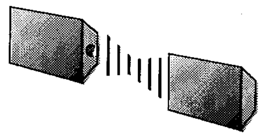
Capability		JPL's IGDG	Un-augmented GPS	Others (WADGPS services)
Coverage:	Global	Yes	Yes	No
	Seamless	Yes	Yes	No
	Usable in space	Yes	Yes	No
Accuracy:	Kinematic applications	0.1 m horizontal 0.2 m vertical	5 m	> 1 m
	Orbit determination	0.01 – 0.05 m (goal)	1 m	N/A
Dissemination method		Internet/broadcast	Broadcast	Broadcast
Targeted users		Dual-frequency	Dual-frequency	Single-freq.

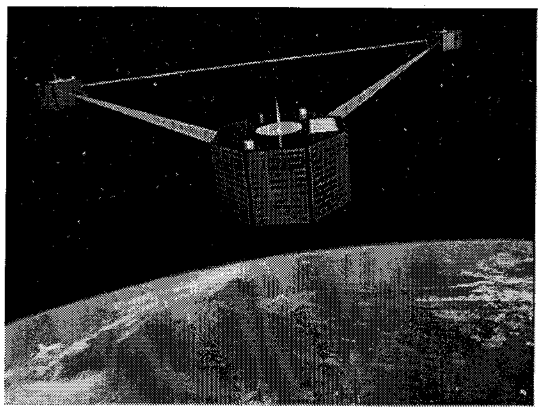
For more info:
http://gipsy.jpl.nasa.gov/igdg

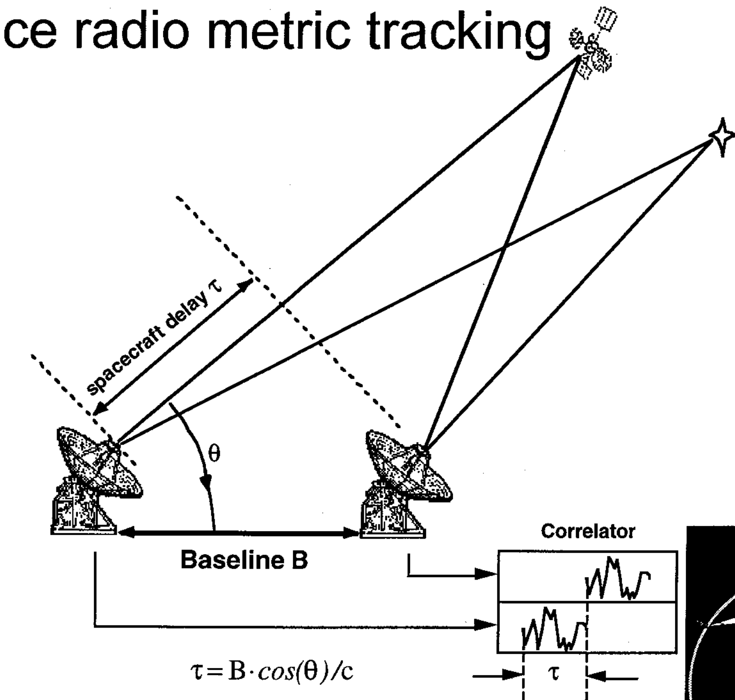
Core capabilities and activities - non-GPS tracking systems

Advanced tracking systems for spacecraft and constellations

- Next generation constellation tracking system (CETDP)
- GRACE (orbit determinations and gravity recovery)
- Constellation Communications and Navigation Transceiver (ST-5 CCNT)
- Interferometry-based deep space radio metric tracking

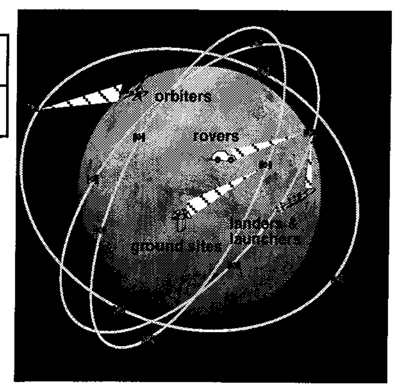




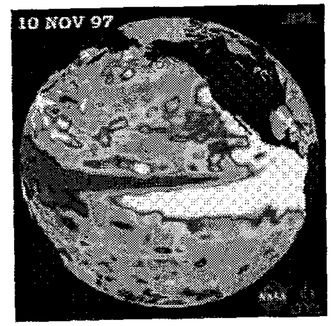


Constellation design

- Mars infrastructure network (comm. and navigation)
- Galileo
- Constellation design tools (visualization and analysis)

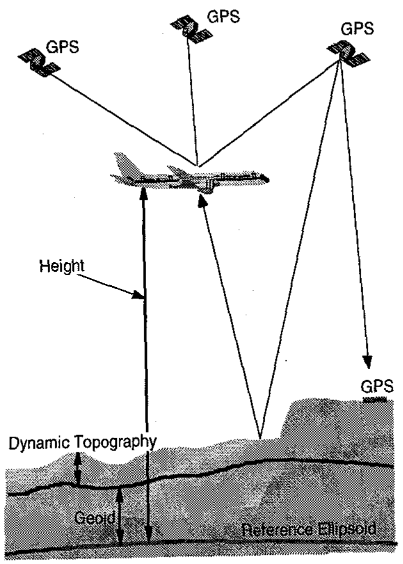


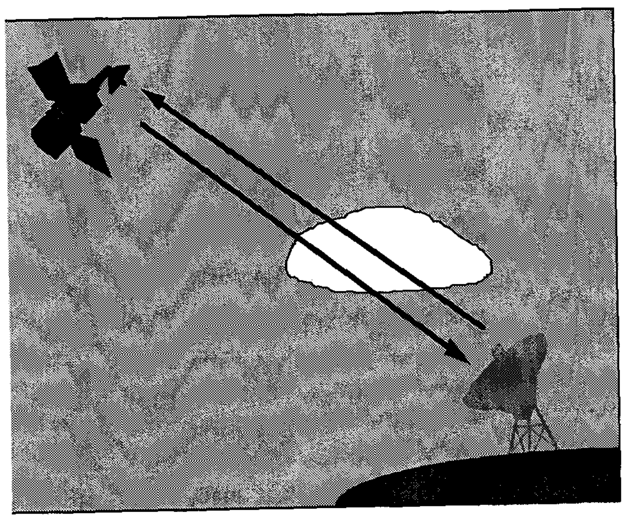
Core capabilities and activities - remote sensing



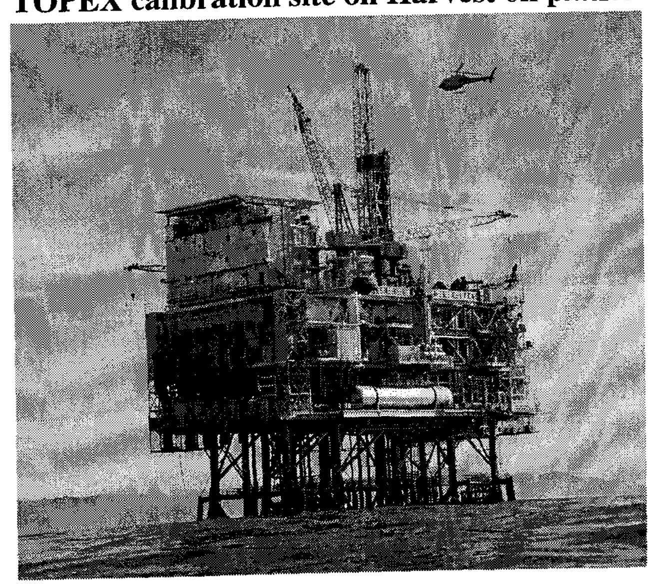
GPS-based remote sensing and science

- Altimetric missions calibration/validation
- Atmospheric sounding (ground-based and occultations)
- Global ionospheric maps
- Geodesy
- Earth orientation monitoring
- Bi-static ocean altimetry and scaterometry
- Radio science propagation calibration (Cassini)



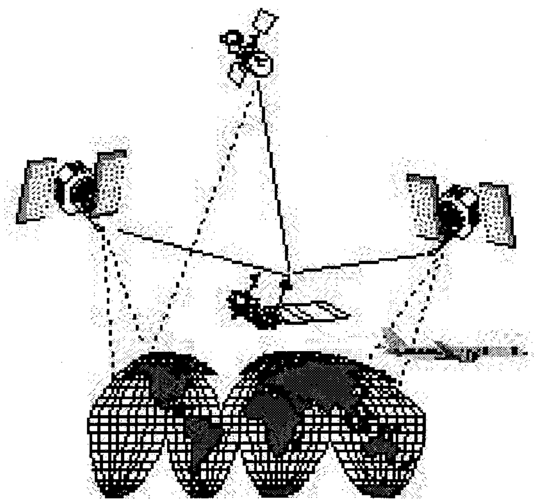


TOPEX calibration site on Harvest oil platform



GPS Inferred Positioning System/Orbit Analysis and Simulation Software

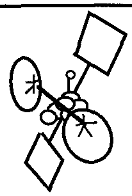
- General tracking systems analysis and orbit determination/positioning
- Uncompromised modeling accuracy: cm-level accuracy demonstrated (ground and space)
  - Earth/Sun/Moon/planets (and tidal) gravity perturbations, solar pressure, thermal radiation, drag, empirical models etc.
  - Earth orientation, tides, ocean loading, general relativity, plate motion, troposphere, etc.
  - Unique GPS kinematic and dynamic models developed in-house (yaw, solar pressure)



- Unparalleled flexibility: space-space and ground-space tracking, range, Doppler, phase, angles, GPS, DORIS, SLR, 1-way, 2-way, 3-way data types
- Unique filter/smoother is without equal in estimation capabilities and accuracy
- Hundreds of licensed government, industry, and academic users world wide

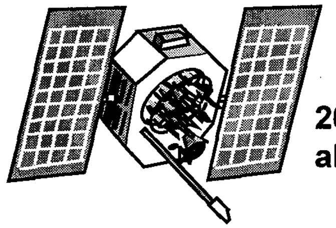
Strategic software tools - GIPSY-OASIS

A small sample of GIPSY's track record



Geostationary
36000 km altitude
(TDRS, INMARSAT)

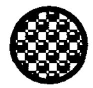
5-25 m
ground-based tracking



GPS

20000 km
altitude

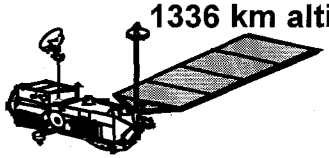
>10 cm
operational automated processing



Lageos

6000 km altitude
<10 cm 2-way laser ranging

TOPEX

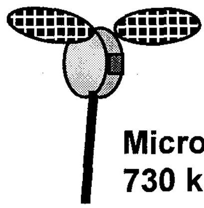


1336 km altitude

With GPS: **< 2 cm (AS off) radial**
< 3 cm (AS on) radial

< 10 cm 3D RSS (AS off)

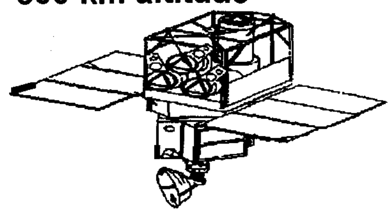
operational automated processing



MicroLab/GPSMET
730 km altitude

With GPS L1/L2 < 10 cm

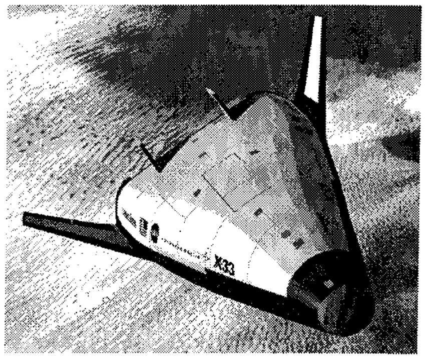
EUVE (Explorer)
500 km altitude



2-3 m with GPS
L1 only

Strategic software tools - Real Time GIPSY (RTG)

- Optimized for real-time, autonomous radio metric data processing, orbit determination, and user positioning
- Compact - currently 50,000 lines of ANSI C code
- Designed to run in personal computers, small workstations, or flight computers (including processors embedded in GPS receivers)
- Retain the precision of the venerable GIPSY-OASIS software
- Minimize load size (400 kbytes) with fast throughput for flight CPUs
- Widely portable
- Unparalleled track record: WAAS prototype, commercial differential system, used for orbit determination (on the ground) of SNOE (Student Nitric Oxide Experiment) spacecraft, 30 cm real time GPS orbit determination.
  - Scheduled to fly on SAC-C GPS receiver (2001)
  - Scheduled to fly on the RLV/X33
  - Scheduled to fly on ST-5 constellation (2003) and perform constellation state determination using **crosslinks and GPS**

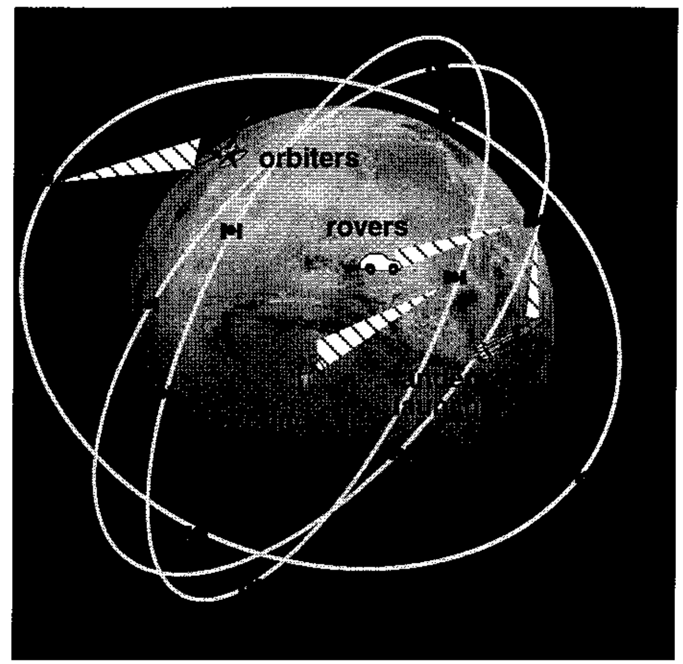


RLV/X33

Visualization and Analysis Package for ORbiting Systems

Powerful constellation design and analysis tool with unique capabilities:

- Analysis of navigation, communications and radio science performance
- Robust Monte-Carlo simulation capabilities
- Ground-space and space-space links
- Innovative and stunning visualization capabilities

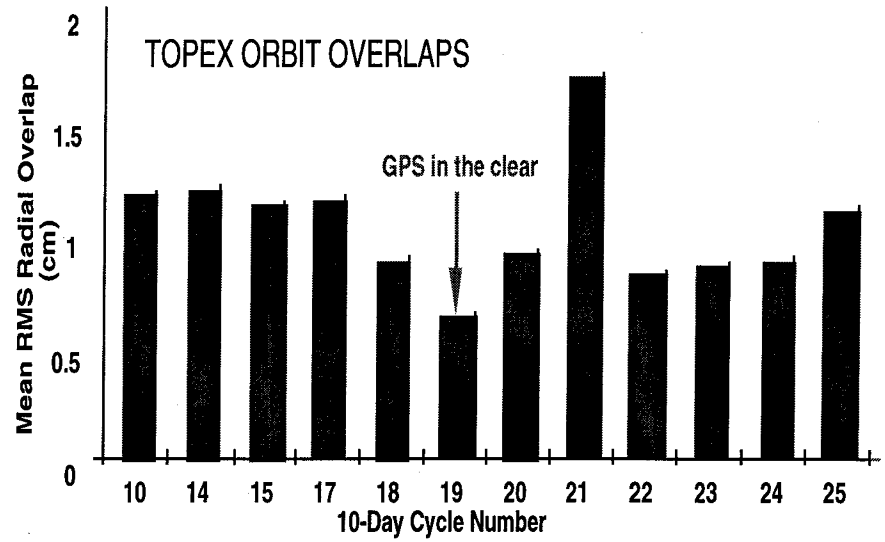


Primary tool for design and analysis of the Mars Network

Selected contributions to GPS operations/performance

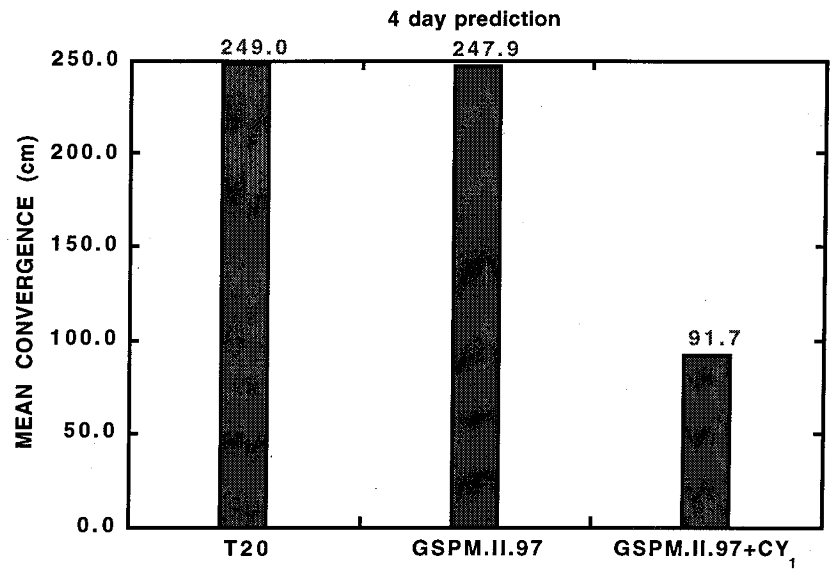
GPS yaw attitude (Bar-Sever et al., *Navigation*, 1995, Bar-Sever, *J. geodesy*, 1996)

- Explained unpredictable behavior of GPS satellites during eclipse season
- Efforts led to altering of GPS yaw attitude in orbit (1994)
- Developed and implemented in GIPSY a new model for GPS yaw attitude which directly contributed to improved GPS orbit determination.



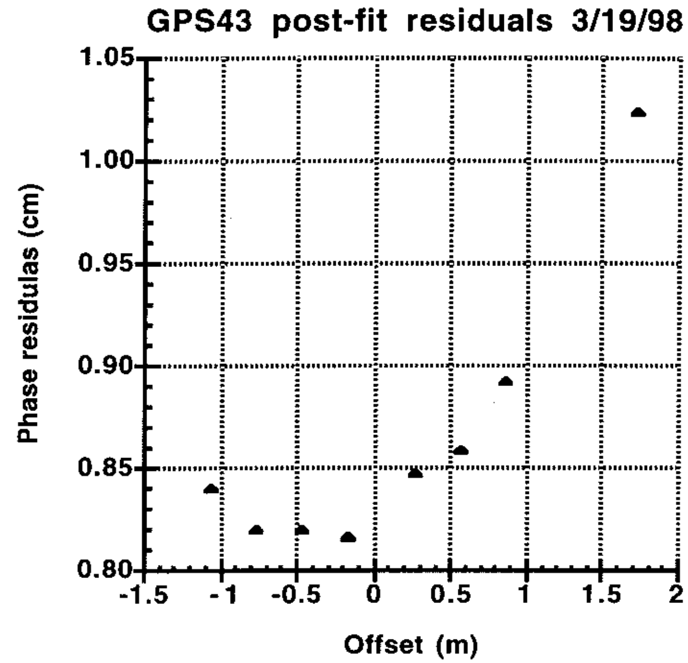
GPS solar pressure (Bar-Sever, *JPO/CZSF Report*, 1997)

- Developed methodology to estimate solar radiation pressure in orbit to account for *actual* s/c behavior
- Developed new GPS solar radiation model significantly improving on the ROCK/T20 model. Allows for continuous tuning as satellite age



GPS antenna phase center (Bar-Sever., *PAWG meeting*, 1999)

- Estimated GPS transmit antenna phase center offset using ground-based observations. Reveal significant non-nominal value, including 1.5 m off-nominal value for SVN 43 (Block IIR)
- Analysis efforts on-going.



Tgd estimation

- Identified inaccuracies in the broadcast Tgd value
- Estimated values were delivered to 2SOPS and implemented in the broadcast message (1999)

Potential GPS III studies

Autonomy

- On board navigation software
- Utilization of cross links for navigation and communications
  - Distributed onboard computing
- Limitation of orbit prediction capabilities
- Mitigation of Earth-fix orbit uncertainties

Improve navigation message

- New information for enhanced accuracy (eg attitude)
- Data compression schemes

Constellation design and coverage analysis

- Assess combination of LEO, MEO, GEO with VAPORS, GIPSY

System performance analysis and simulation

- GIPSY provides unique value to assess complex system

In orbit performance assessment

Potential GPS III studies

In orbit performance assessment
- Using ground network

In orbit model enhancement and tuning
- spacecraft never behave nominally. Successful approach demonstrated

Effective ground segment
- Achieve best accuracy, economy, and safety with new paradigm: IGDG++

End-user software
- Continuous phase smoothing
- Atmospheric modeling/estimation
- heading/windup