# GPS in Space and the Vision for Space Exploration

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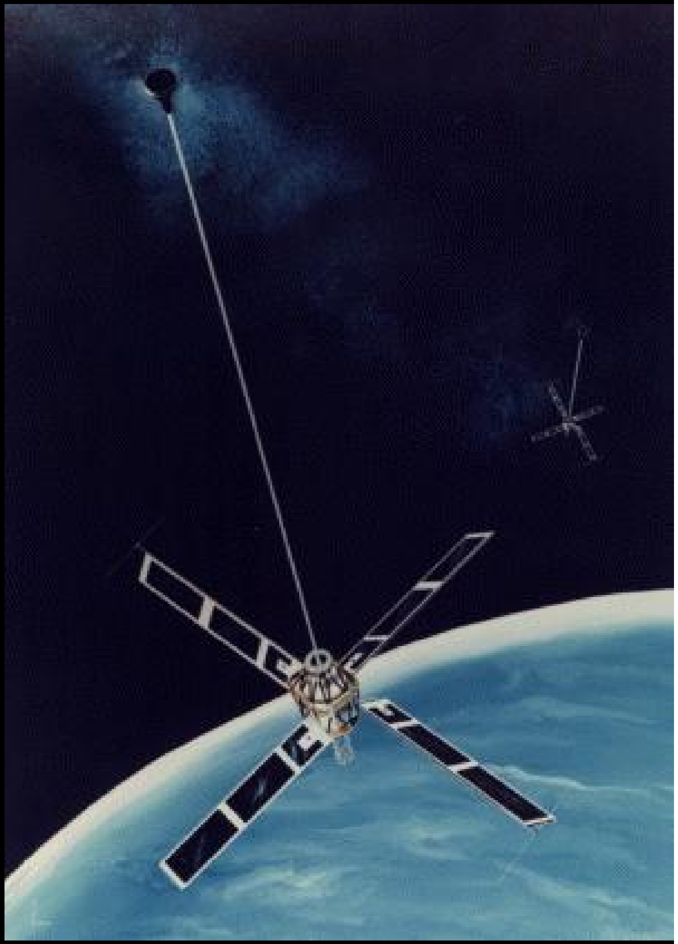
# Outline

- GPS Background
- NASA Science Applications of GPS
- NASA GPS Monitoring
  - GPS L2C Monitoring
  - GNSS Monitoring
- NASA Use of GPS in Space
  - Science Receivers
  - High Earth Orbit
  - Human Missions
  - Integrated Navigation and Communications
  - TASS
- The Vision for Space Exploration
- India - US Cooperation

# GPS History: In the beginning there was…

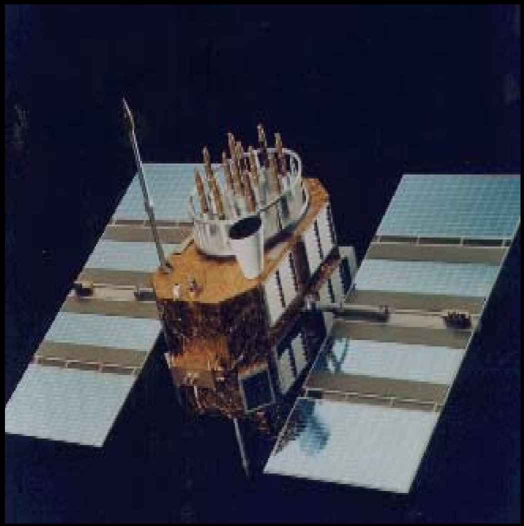
- **1962-1996: Navy Navigation Satellite System (NNSS), also known as Transit**
  - **Few hundred meter accuracy**
  - **Required knowing altitude and velocity, not very useful for air applications**
  - **Limited coverage and 35-100 min periods of unavailability**
- **1972: Naval Research Laboratory's Timation Satellites**
  - **Provide precise time and time transfer**
  - **Could provide navigation information through side-tone ranging**
  - **3rd satellite used as technology demonstrator for GPS**
- **1972: U.S. Air Force Project 621B**
  - **Demonstrated operation of satellite-ranging signal based on pseudorandom noise (PRN)**

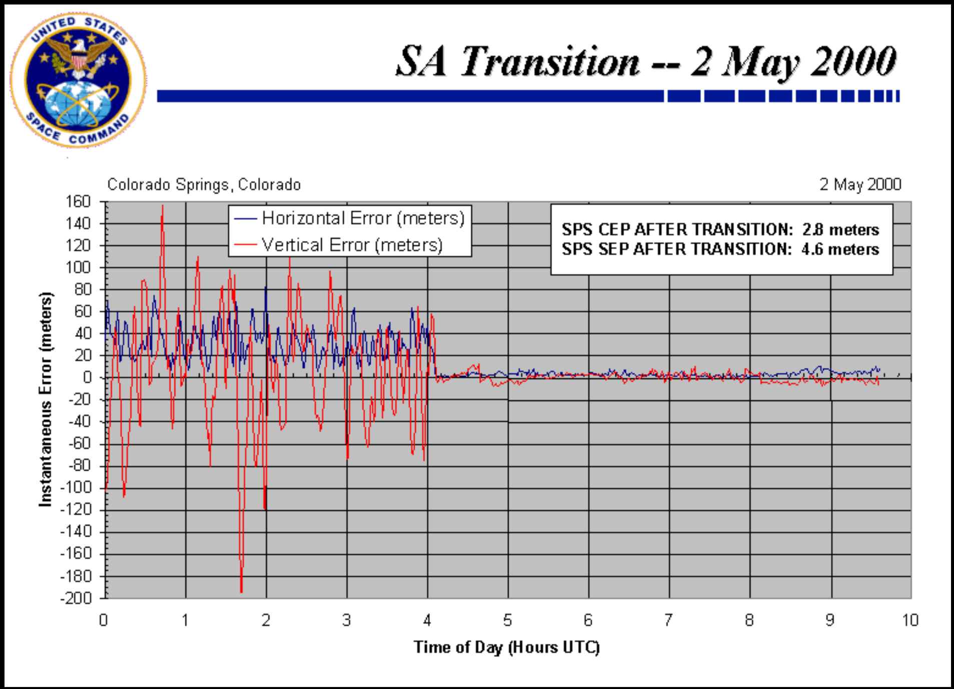


Transit

# GPS Milestones 1973- to date

- 1973: Joint Program Office (JPO) formed
- 1978: First GPS satellite launched
- 1984: Presidential decision to make available to civilian community
- 1998: Announcement that 2 new civilian signals would be provided by GPS
- May 2000: Selective Availability turned to zero by Presidential order
- January 2006: L2C signal declared operational





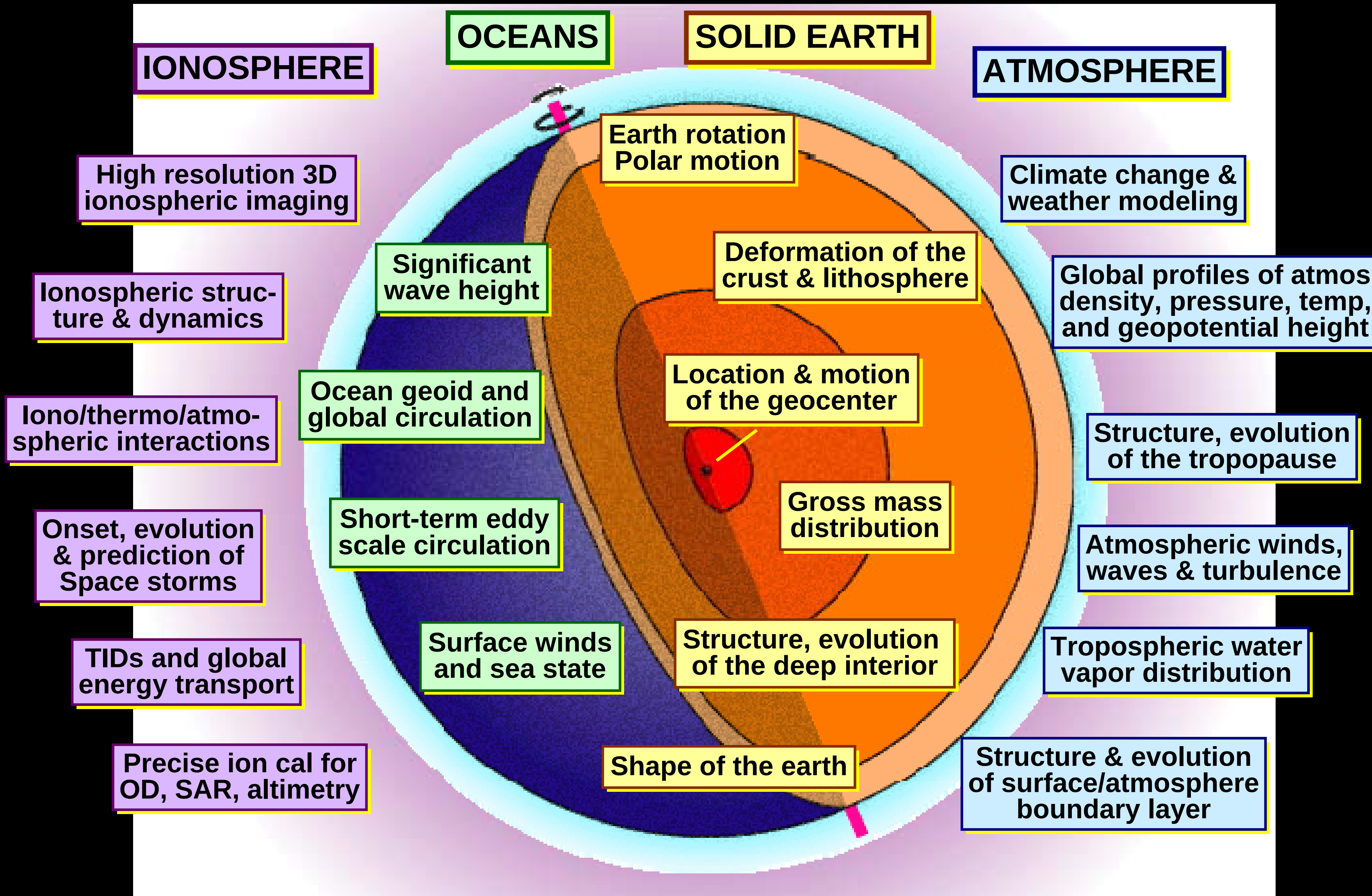

# Current GPS

## 24 satellite nominal constellation

- **15 Block II/IIA satellites operational**
- **12 Block IIR satellites operational**
  - **12 of 21 Block IIR satellites on orbit**
  - **Launch failure on IIR-1**
  - **Modernizing remaining 8 Block IIR satellites, known as IIR-M, to include two new military signals and a second civilian signal (L2C)**
- **1 Block IIR-M satellite operational**
- **Latest Launches:**
  - **6 Nov 04 (GPS IIR-13)**
  - **25 Sep 05 (GPS IIR-14(M))**
- **Continuously assessing constellation health to determine launch need**
- **Global civil service performance commitment continuously met since December 1993**

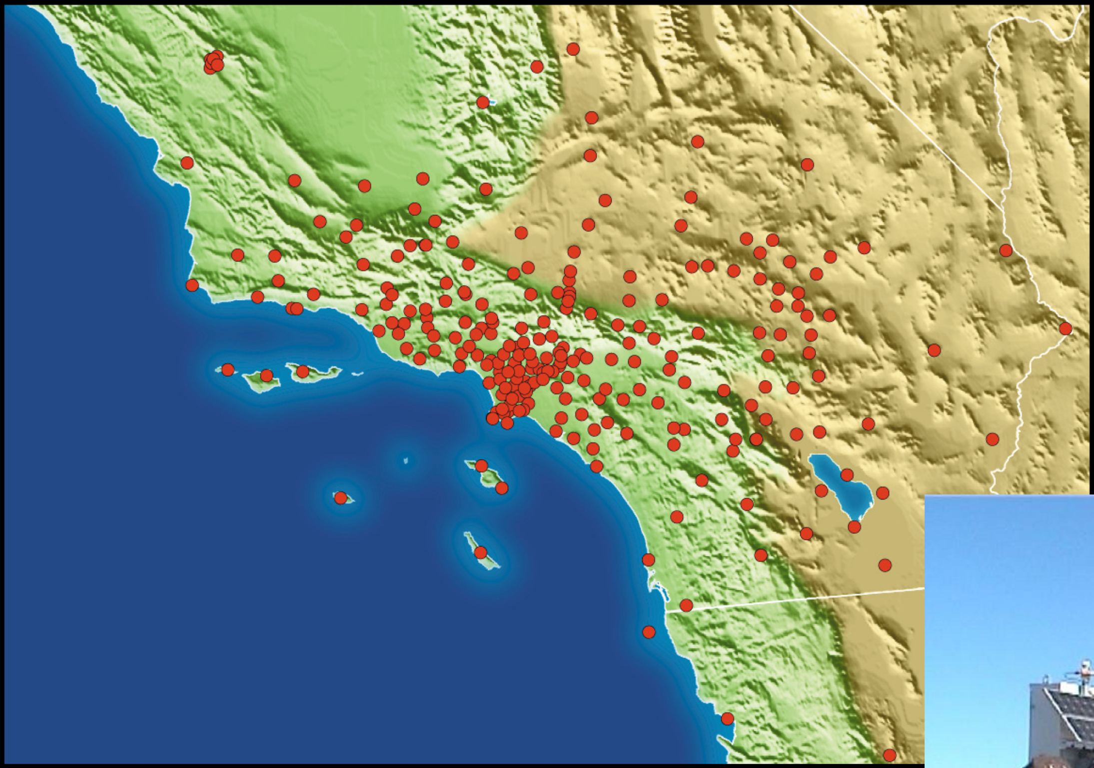
Launch of GPS IIR-14(M)

# Science Applications of GPS: Probing the Earth



# Science Applications of GPS: Southern California Integrated GPS Network (SCIGN)

- **SCIGN is operated and maintained by NASA, SOPAC (Scripps Orbit And Permanent Array Center) , and USGS (U.S. Geological Survey)**

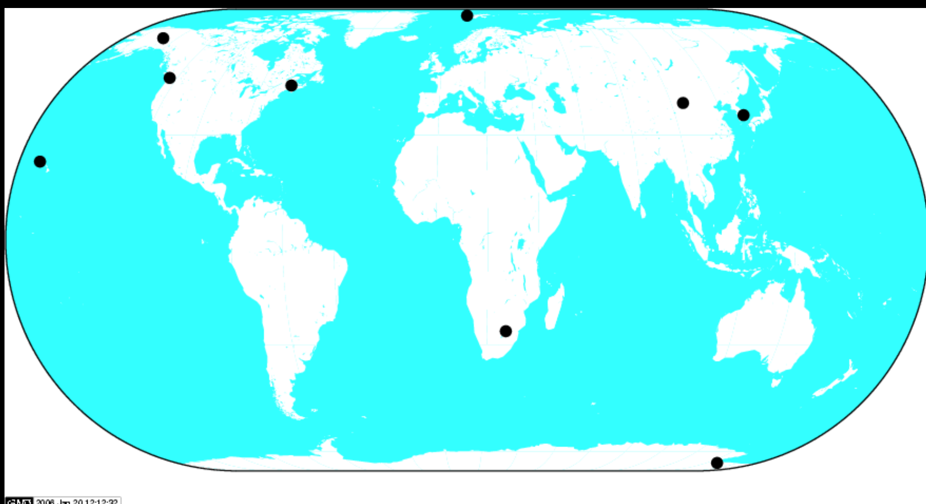


SCIGN Network Map

Station Photos

# GPS Monitoring: L2C Civil Tracking

**L2C Tracking Network**

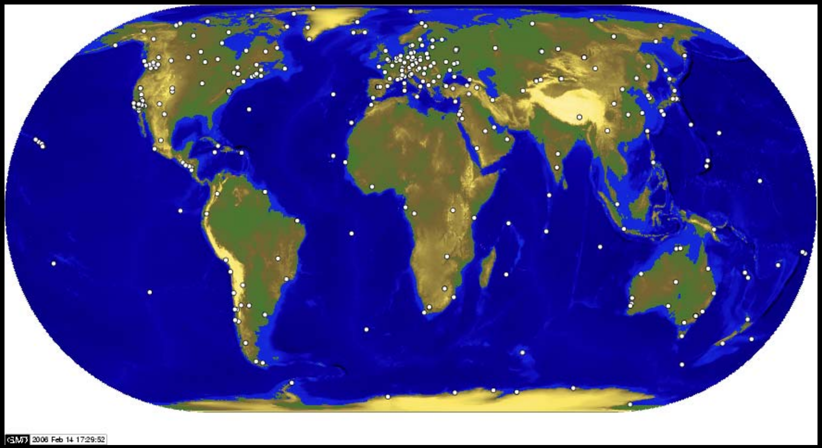


The first 2RM GPS satellite, PRN17, launched on September 26, 2005. The new civil signal, L2C, was first tracked by a JPL GPS Blackjack receiver at JPL on October 21, and a little later by a small global network of L2C-capable Trimble receivers that were deployed by JPL for this purpose.

- **NASA/JPL deployed a global network of L2C receivers with real-time communications**
- **Additional L2C-capable receivers were deployed by IGS partners**
- **Enables a robust assessment of the civilian performance of the new L2C capability**
- **Current status:**
  - ➢ **Real time L2C signal performance monitoring by GDGPS System**
  - ➢ **Data archiving**
  - ➢ **Characterizing transmitter code biases for this new signal**
  - ➢ **Signal is tracked in space by JPL's BlackJack GPS receiver on the SAC-C spacecraft**

# GNSS Monitoring: IGS

- The IGS is a voluntary federation of more than 200 worldwide agencies that pool resources and permanent GNSS station data to generate precise GNSS products.
- Over 350 permanent geodetic GNSS stations operated by more than 100 agencies worldwide comprise the IGS network. Currently the IGS supports two GNSS: GPS and GLONASS.
- NASA funds two centers, JPL and GSFC, to support IGS:
  - Day-to-day management and coordination by the IGS Central bureau.
  - Responsibility and management of NASA's global GPS network that contributes to the IGS Network.
  - An Analysis Center (one of eight) for GPS orbits, clocks, and reference frame products.
  - An IGS Global Data Center where full access to data and products is provided.



IGS World Tracking Network

Fairbanks, Alaska, USA

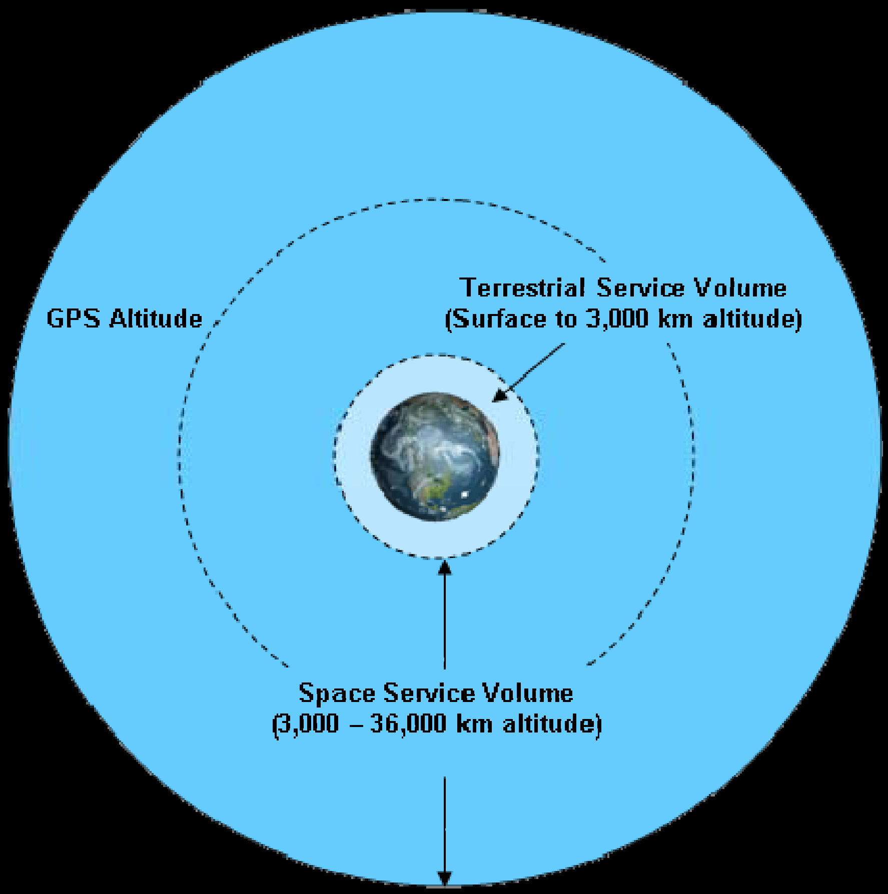
Hyderabad, India

Robledo de Chavela, Spain

# Use of GPS in Space

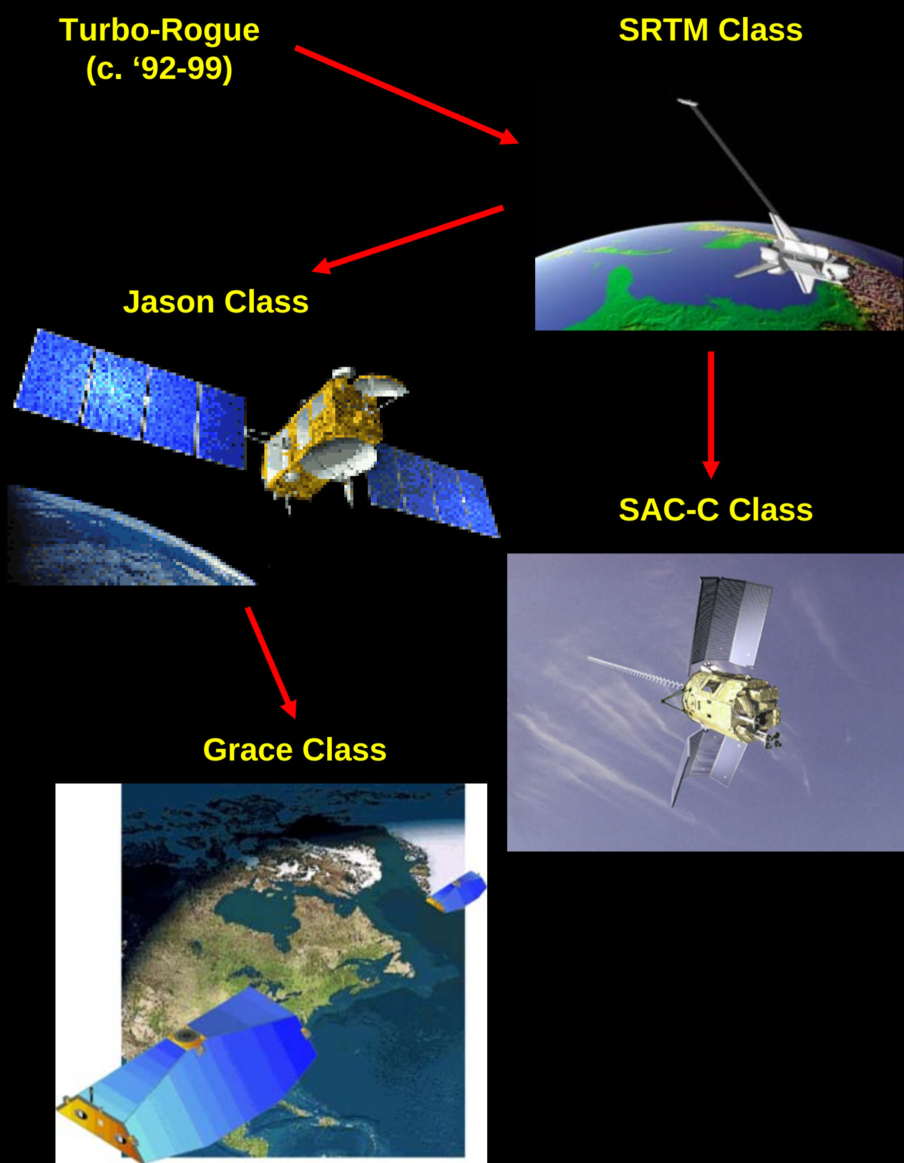
- Many current applications in Low Earth Orbit within the GPS Terrestrial Service (up to 3000 km)
- Many emerging space users of GPS beyond Low Earth Orbit
  - Geostationary Orbits
  - High Earth Orbits (Apogee above GEO altitude)
- Space users in the Space Service Volume (beyond 3000 km altitude) share unique GPS signal challenges
- GPS space flight experiments in high orbits have shown that existing signal availability becomes more limited due to:
  - Geometry between the SV and the space user
  - Vast signal strength changes due to signal path length variations (near/far problem)
- Robust GPS signals in the Space Service Volume:
  - Needed to support future civil and military space requirements
  - Will open unprecedented science opportunities for 21st century space vehicles

GPS Service Volumes



# Space Applications of GPS: Blackjack Science Receivers

## Blackjack Family ('99 to present)




## Features:

- Developed at JPL and available in multiple configurations
- Tracks GPS occultations in both open-loop and closed-loop modes
- Tracks simultaneously from multiple antennas

## Missions:

SRTM Feb 2000, CHAMP Jul 2000, SAC-C Nov 2000, JASON-1 Dec 2001, GRACEs 1 and 2 Mar 2002, FedSat Dec 2002, ICESat Jan 2003, COSMICs 1 through 6 Mar 2006, CnoFS Apr 2006, Terrasar-X Jul 2006, OSTM 2008

## Results:

- Shuttle Radar Topography Mission (SRTM): 230-km alt / 45-cm orbit accuracy
- CHAMP: 470-km alt / < 5-cm orbit accuracy
- SAC-C: 705-km alt / < 5-cm orbit accuracy
- GRACE: 500-km alt (2 s/c) / 2-cm orbit accuracy, 10-psec relative timing, 1-micron K-band ranging, few arcsecond attitude accuracy with integrated star camera heads

# Space Applications of GPS: Space Shuttle and International Space Station Receivers

## Miniaturized Airborne GPS Receiver (MAGR-S)

- Modified DoD receiver to replace TACAN on-board the Space Shuttle
- Designed to accept inertial aiding and capable of using PPS
- Single-string system (retaining three-string TACAN) installed on OV-103 Discovery and OV-104 Atlantis, three-string system installed on OV-105 Endeavour (TACAN removed)
- GPS available during re-entry of STS-114 / OV-103 Discovery
- GPS now certified for orbit and entry navigation

**STS-114 Landing**

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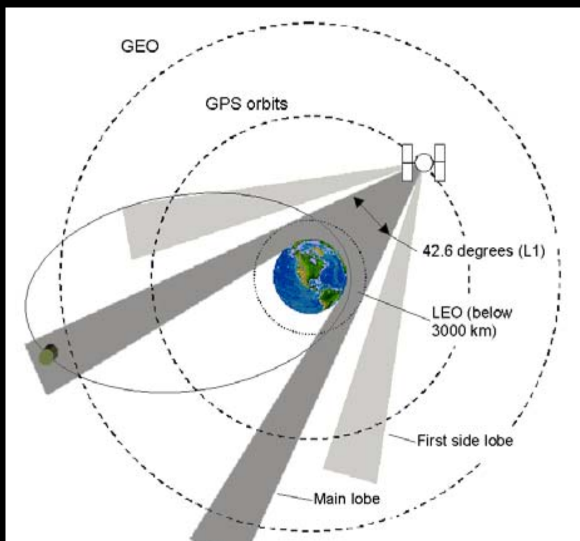
## Space Integrated INS/GPS (SIGI)

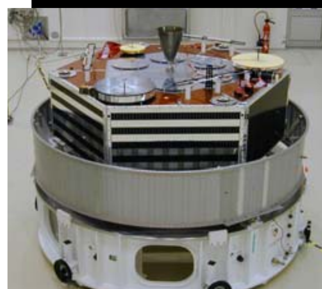
- Flight tests on the shuttle supported development
- The ISS provides an array of 4 antenna on the T1 truss assembly
- Currently in operation

# Space Applications of GPS: High Earth Orbit Receivers

## Expanding use of GPS well beyond LEO…

**AMSAT Flight Experiment –**
**Measurements of GPS Side-Lobes**

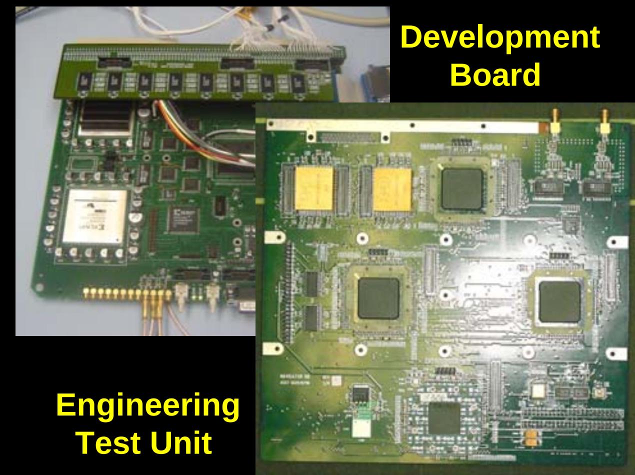


## GEONS Software

- Flight software package developed by NASA to provide onboard orbit determination
- Processes GPS data, one-way forward-link Doppler data from ground stations and TDRSS, optical measurements from attitude sensors, and inter-satellite crosslink data
- Simultaneously estimates absolute and relative orbital states for satellites and satellite formations
- Employs an extended Kalman filter (EKF) augmented with physically representative models for gravity, atmospheric drag, solar radiation pressure, clock bias and drift to provide accurate state estimation and a realistic state error covariance

## Navigator GPS Receiver



Development Board

Engineering Test Unit

- FFT-based signal acquisition engine provides extremely fast acquisition times
- Extending correlation interval to full 20ms data bandwidth provides acquisition and tracking below 25 dB-Hz
- Integrated GEONS navigation software
- Implemented in General Dynamics development board: Xilinx FPGAs with ColdFire microprocessor - hardware test results indicate 10 meter orbit determination accuracies achievable at GEO
- Space qualified design using Actel FPGAs, in development for relative navigation sensor experiment on HST Servicing Mission 4 flight (ETU available September 2006)
- Future flight opportunities: MMS, GOES

# Space Applications of GPS: LPT Receiver

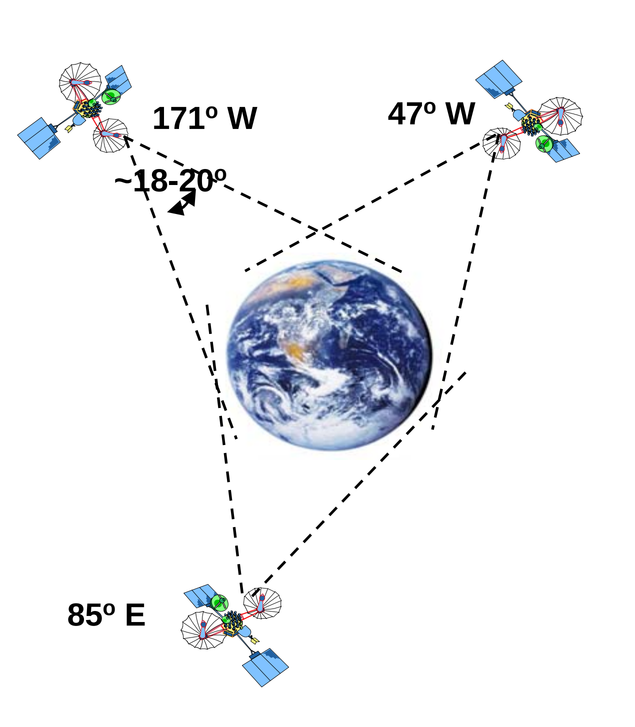
**The Low Power Transceiver (LPT) is a software radio that combines navigation and communication functions into a single unit**

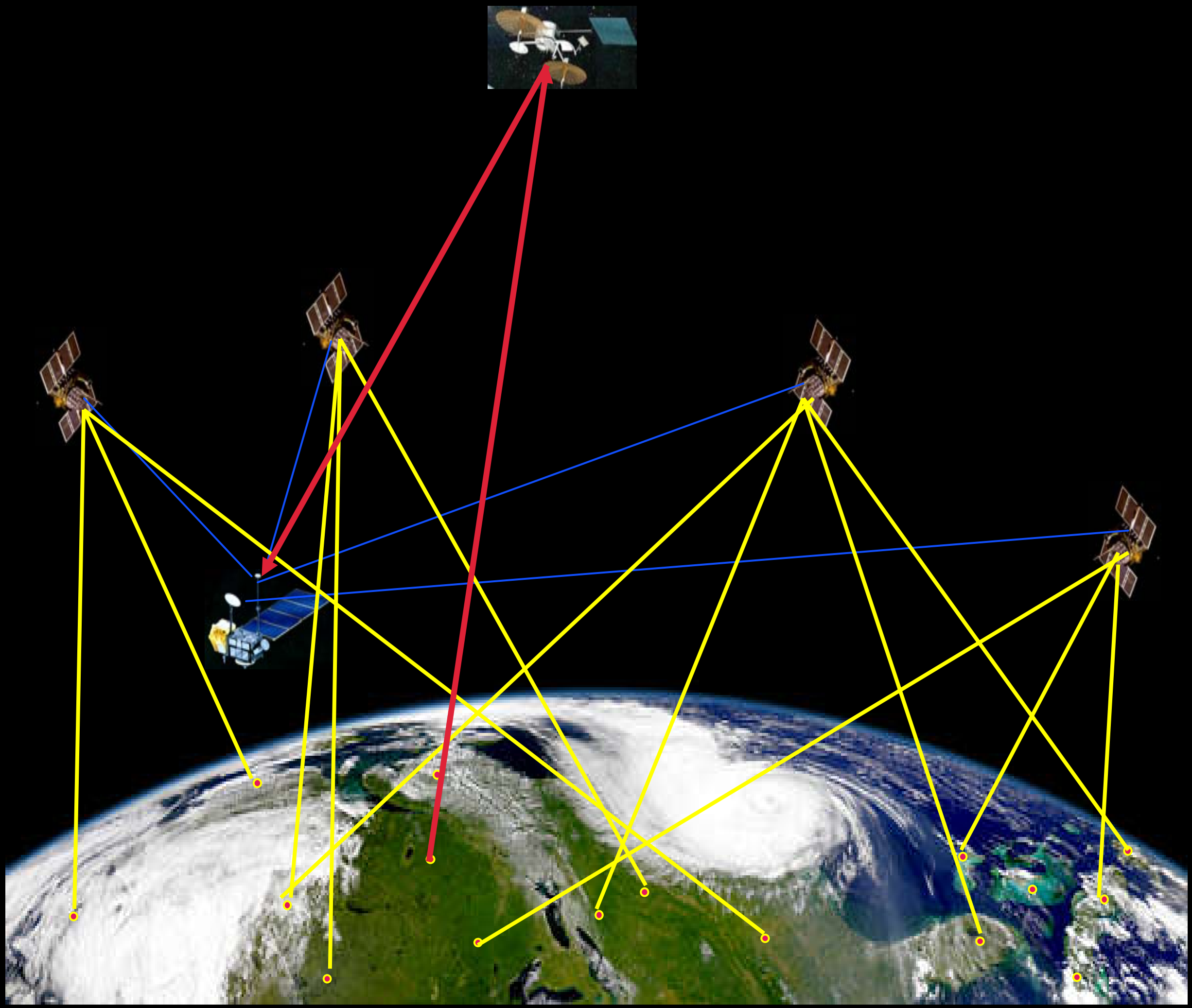
- **Developed by ITT Industries under NASA technology development sponsorships**
- **Communications capabilities include:**
  - **TDRSS SSA and MA**
  - **NASA GN/AFSCN S-band**
  - **LPT crosslink**
- **Navigation capabilities**
  - **Up to 32 channel L1/L2 GPS receiver**
  - **Real-time orbit determination using the <u>G</u>PS <u>E</u>nhanced <u>O</u>rbit <u>D</u>etermination <u>E</u>xperiment (GEODE) flight software**
    - **Software developed by NASA GSFC**


**3rd Generation LPT**

# Space Applications of GPS: GDGPS & TASS

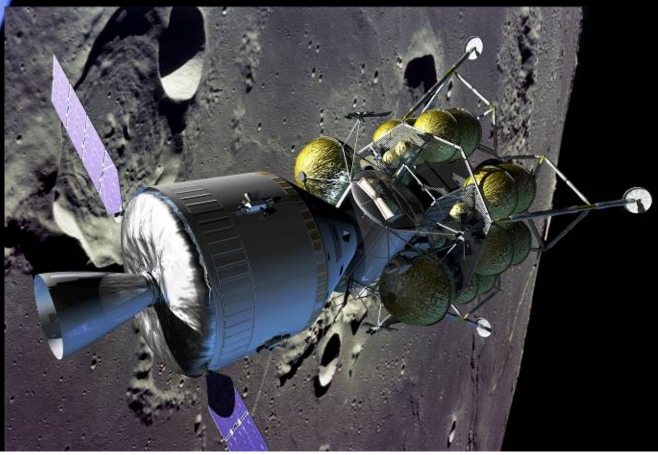
- TDRS Augmentation Service for Satellites (TASS) provides Global Differential GPS (GDGPS) corrections via TDRSS satellites
- Integrates NASA's Ground and Space Infrastructures
- Provides user navigational data needed to locate the orbit and position of NASA user satellites



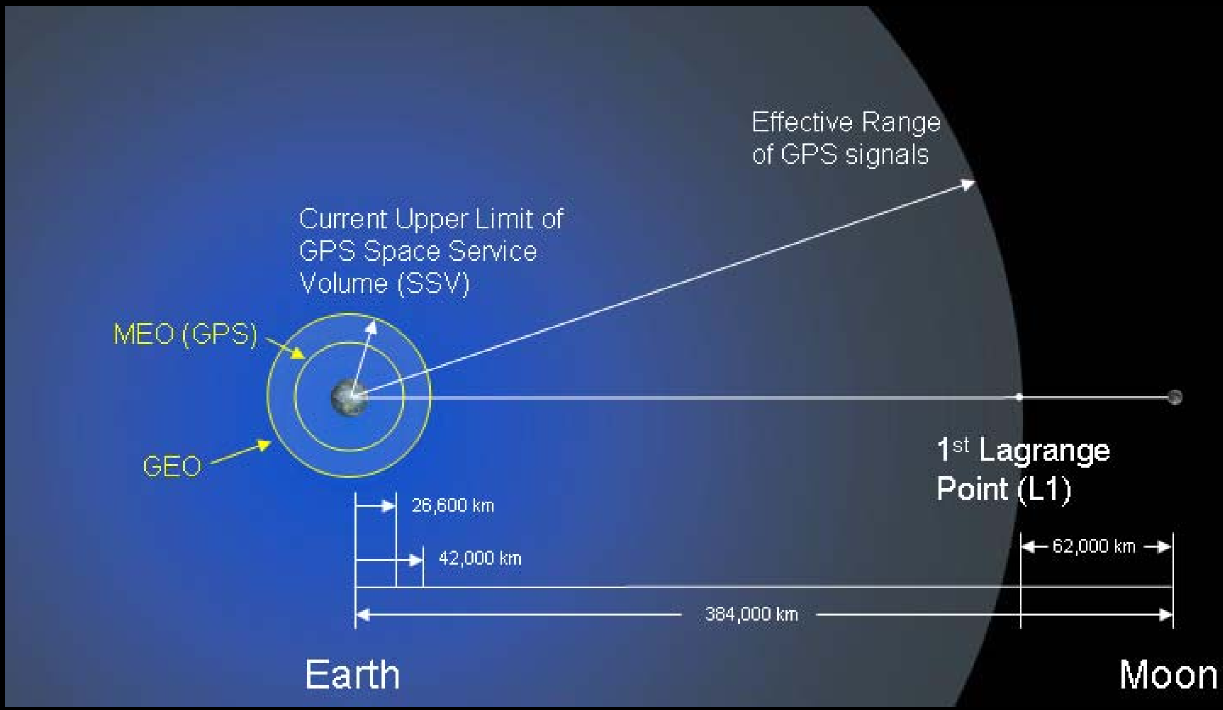
# The Vision for Space Exploration (VSE) : Mandate

- **On January 14, 2004 the US President announced a new vision for NASA to**
  - **Implement a sustained and affordable human and robotic program to explore the solar system and beyond;**
  - **Extend human presence across the solar system, starting with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations;**
  - **Develop the innovative technologies, knowledge, and infrastructures both to explore and to support decisions about the destinations for human exploration; and**
  - **Promote international and commercial participation in exploration to further U.S. scientific, security, and economic interests.**



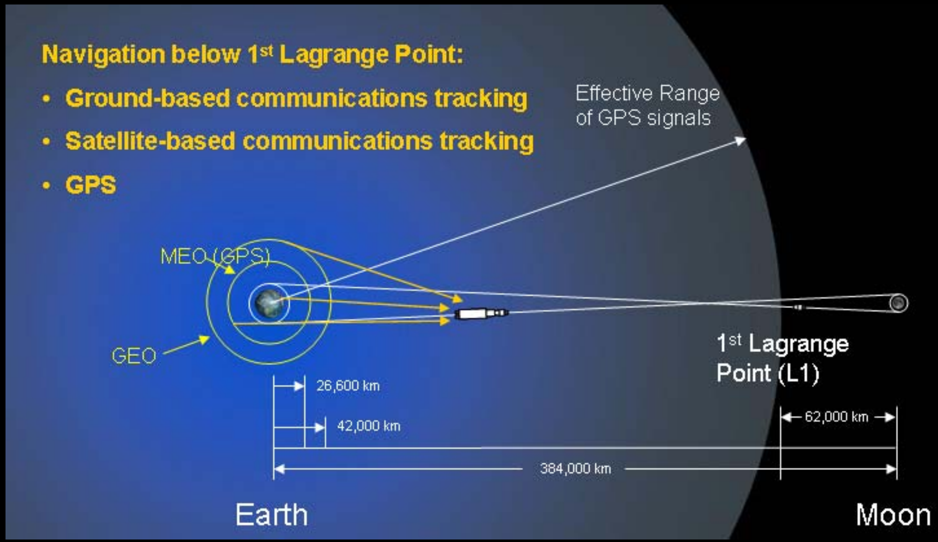
# GPS in Space – Beyond GEO, and on to the Moon

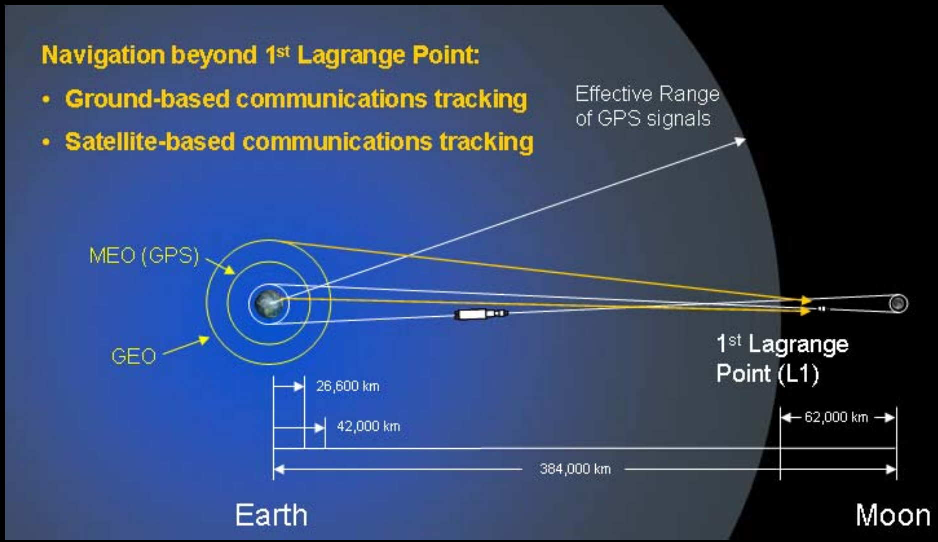
- GPS signals effective up to the Earth-Moon 1st Lagrange Point (L1)
  - 322,000 km from Earth
  - Approximately 4/5 the distance to the Moon
- GPS signals can be tracked to the surface of the Moon, but not usable with current GPS receiver technology



# Earth-Moon Navigation

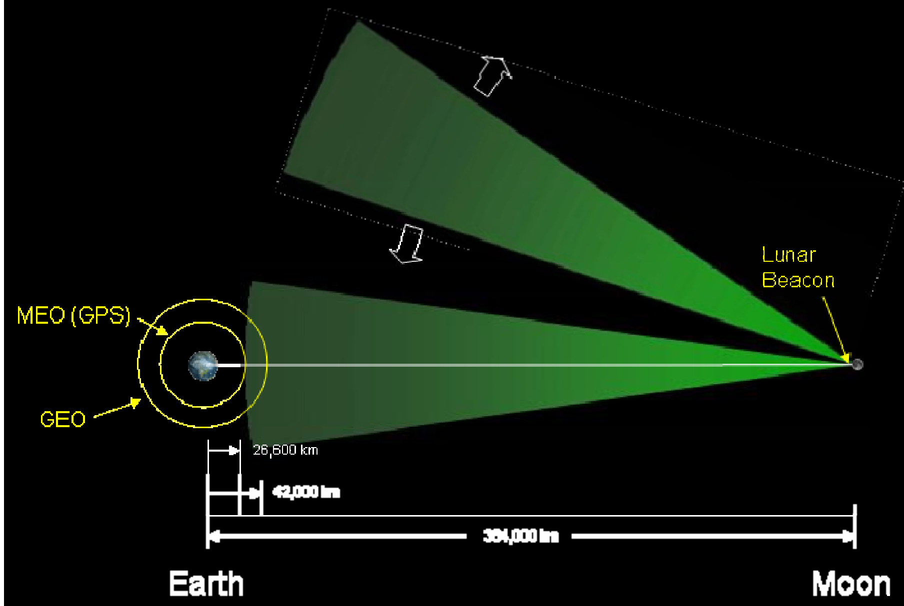
- Navigation options include:
  - Earth-based ground tracking
  - Earth-orbiting satellites (GEO Tracking and Data Relay Satellite System – TDRSS)
  - GPS
  - Integrated approach using all available signals described above via a software radio
  - Autonomous navigation (inertial, celestial)

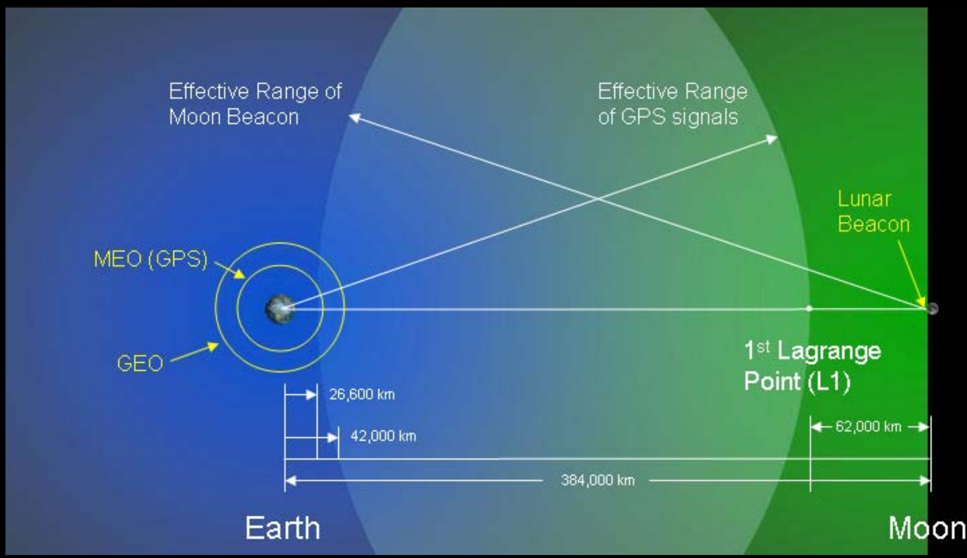


# Beyond GPS – Earth-Moon Navigation

- **Concept Lunar Beacon/s**
  - **Placing one, or more, GPS payloads (Moon Beacon) on the surface of the Moon***
    - **Fixed pointing and/or moving beam**
  - **The Moon beacon could be synchronized to GPS time via a space internet link**
  - **A hardware assisted network time transfer technique could be implemented providing 3 nanosecond time synchronization to GPS time**

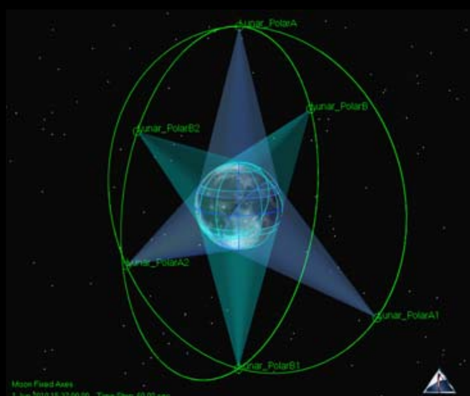


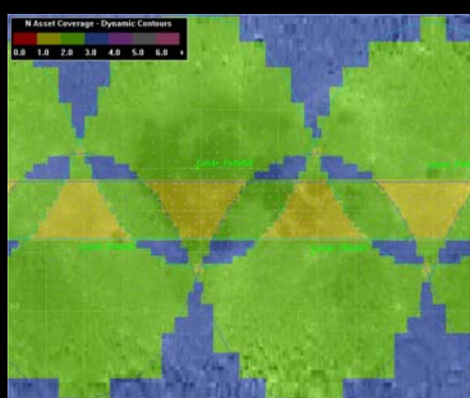

(*) concept architectures

# Beyond GPS – Lunar Surface Navigation

- **Lunar Satellite Constellations**
  - Provide integrated communications and navigation (Com/Nav)
  - Develop a communications capability to provide a substantial increase in data rates and connectivity



**Polar 6/2/1 Com/Nav Constellation & Surface Coverage***



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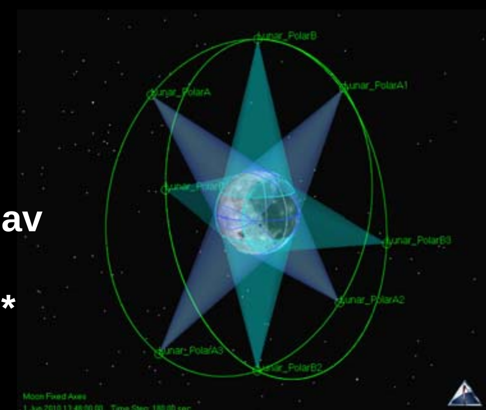
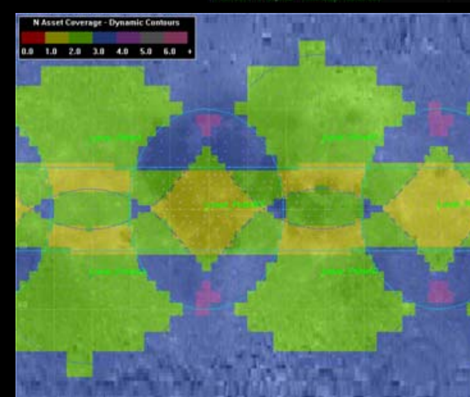




(*) <u>concept</u> architectures

# Planetary Time Transfer

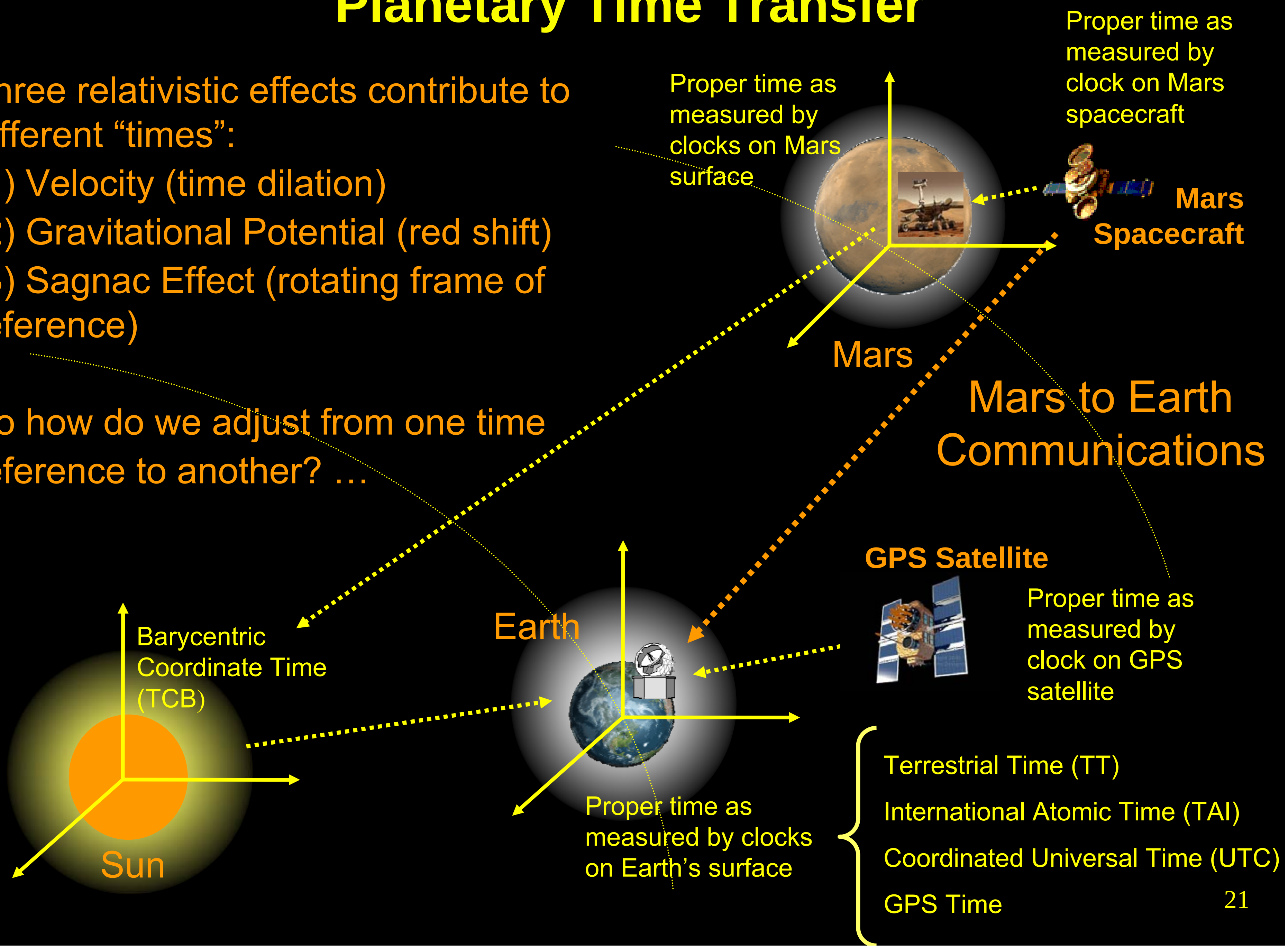
Three relativistic effects contribute to different "times":

(1) Velocity (time dilation)

(2) Gravitational Potential (red shift)

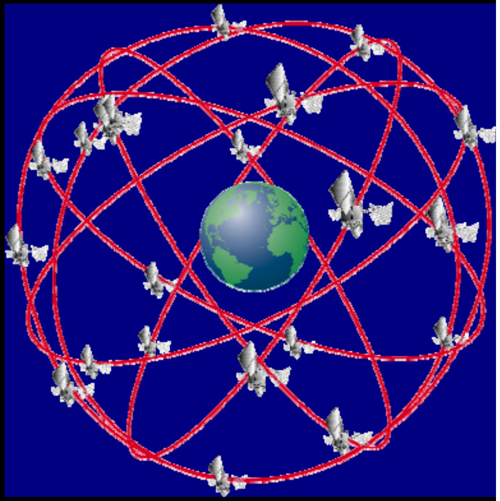
(3) Sagnac Effect (rotating frame of reference)

So how do we adjust from one time reference to another? …



# GPS as Solar System Time

- GPS provides a model for timekeeping and time dissemination
- GPS timekeeping paradigm can be extended to support NASA space exploration objectives
- Common reference system with appropriate relativistic transformations

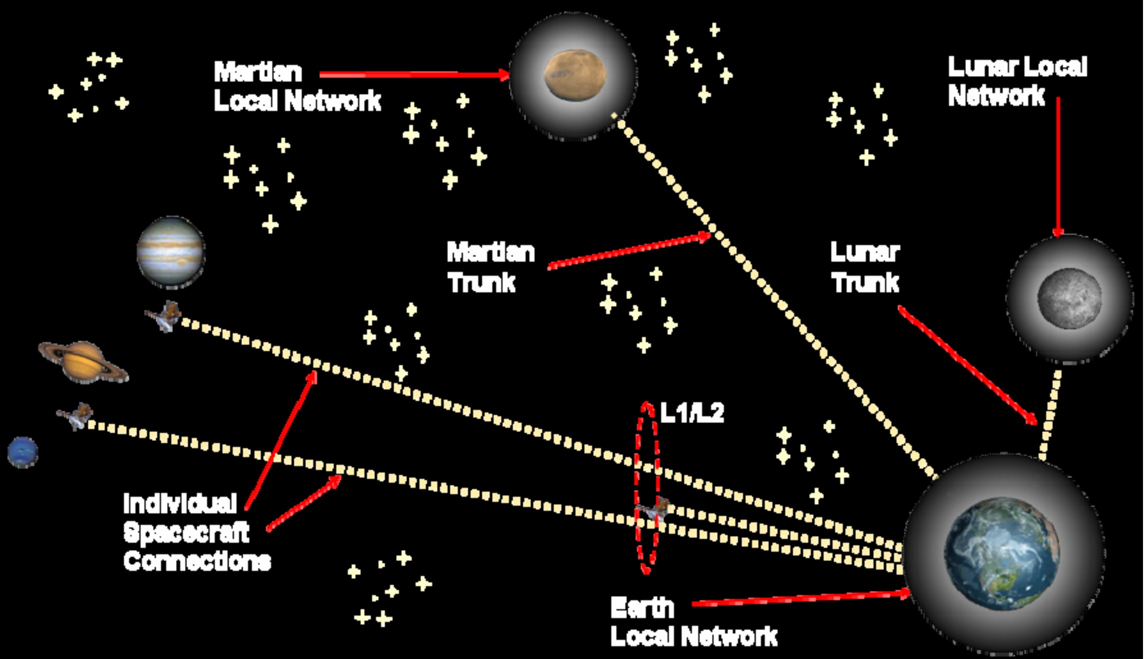


Objective: Integrated Interplanetary Navigation and Communications

***Relativistic corrections in the GPS***

| | |
|---|---|
| Time dilation (μs per day) | − 7.1 |
| Redshift (μs per day) | + 45.7 |
| Net secular effect (μs per day) | + 38.6 |
| Residual periodic effect * (amplitude for *e* = 0.02) | 46 ns |
| Sagnac effect * (maximum for receiver at rest on geoid) | 133 ns |

*Corrected in receiver

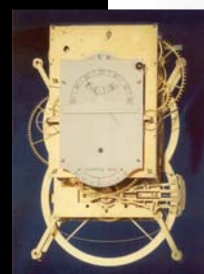


# The Future of Positioning, Navigation, and Timing?

Pharos of Alexandria, Egypt

Ancient Sun Dial

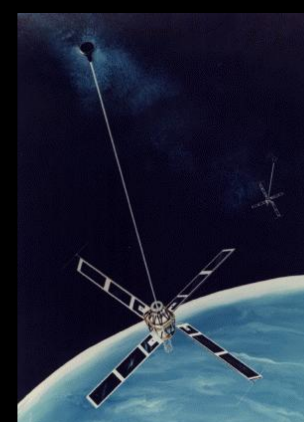
Cape Henry, VA, Lighthouses (old and new)



Harrison Clock

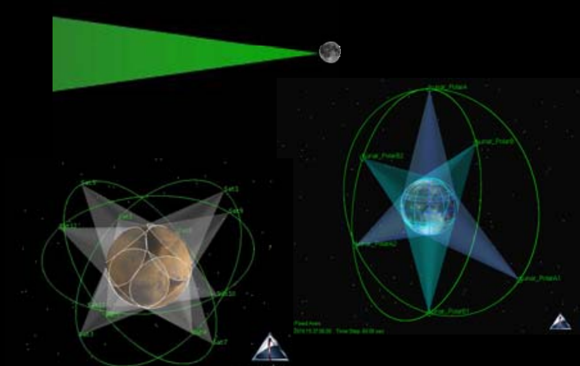
USCG Loran-C station, Pusan, South Korea, 1950s

Transit Satellites



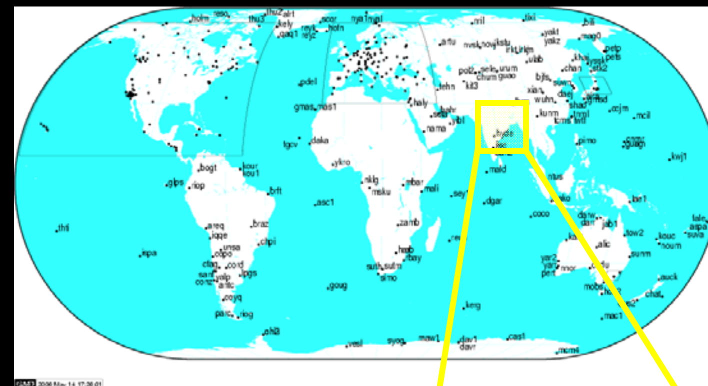
GPS Satellites

Beacons and/or GPS-like Satellites on other Planetary Bodies



# India – US Cooperation

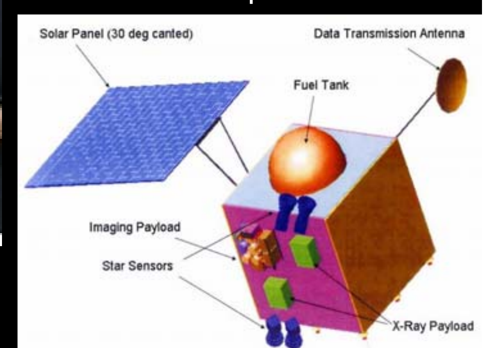
- India – US consultations on the development of the GPS and Geo-Augmented Navigation System (GAGAN)
- Participation in the International GNSS Service (IGS)
  - Currently tracks GPS and GLONASS
  - Galileo to be added
- Participating in the Big 6 Space Faring Nation Moon & Mars Spectrum Coordination Meetings
- US instruments on Chandrayaan-1 lunar mission



IGS World Tracking Network


Signing of ISRO-NASA Memorandum of Understanding in May 2006

Chandrayaan-1 Spacecraft



# VSE: Mission Operation Assets