GNSS Introduction

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Part VII

GPS System Architecture

Satellite Navigation Systems: towards GPS

- TRANSIT was the first satellite navigation system
- It was used by U.S. Navy to guide a new class of submarines
- Its genesis:
  - observation of signals received from Sputnik I:

    Doppler shifts measured by a ground station (known position) was enough to determine the satellite's orbit → with known satellite orbit the receiver can determine its own position on earth measuring the Doppler shifts

TRANSIT development

- 1957: Soviet Union launched Sputnik I
- 1958: Development of the initial idea at The Johns Hopkins University (Applied Physics Laboratory)
- 1961-62: Experimental satellites launched
- 1964: Final system operational

TRANSIT system

- 4-6 satellites (no. limited by mutual interference)
- Satellite orbits:
  - low-altitude (1100 Km)
  - polar
  - nearly circular
- Signal frequencies: 150 MHz, 400 MHz
- Continuous tone transmitted
- Total transmitted power: 1W
- 1 satellite visible at a time
- 35-100 minutes between successive satellite passes

TRANSIT receiver

- With satellite in view (for 10-20 minutes) the receiver:

1	recorded continuously the Doppler shift of the received signal
2	recorded the navigation message (satellite position)

- Measurements were then post-processed to obtain 2-D position for stationary or slow-moving users
- Ionospheric propagation delay was corrected with dual-frequency measurements.

TRANSIT performance

- It was used by U.S. Navy for the submarine fleet to
  - update the position of a ship
  - reset the inertial navigation system
- 2-D accuracy: ~25 m (rms) for stationary user
- 3-D accuracy:

absolute positioning

~5 m (measurements from multiple satellite passes over several days)

relative positioning

~1m (measurements from multiple satellite passes in two points)

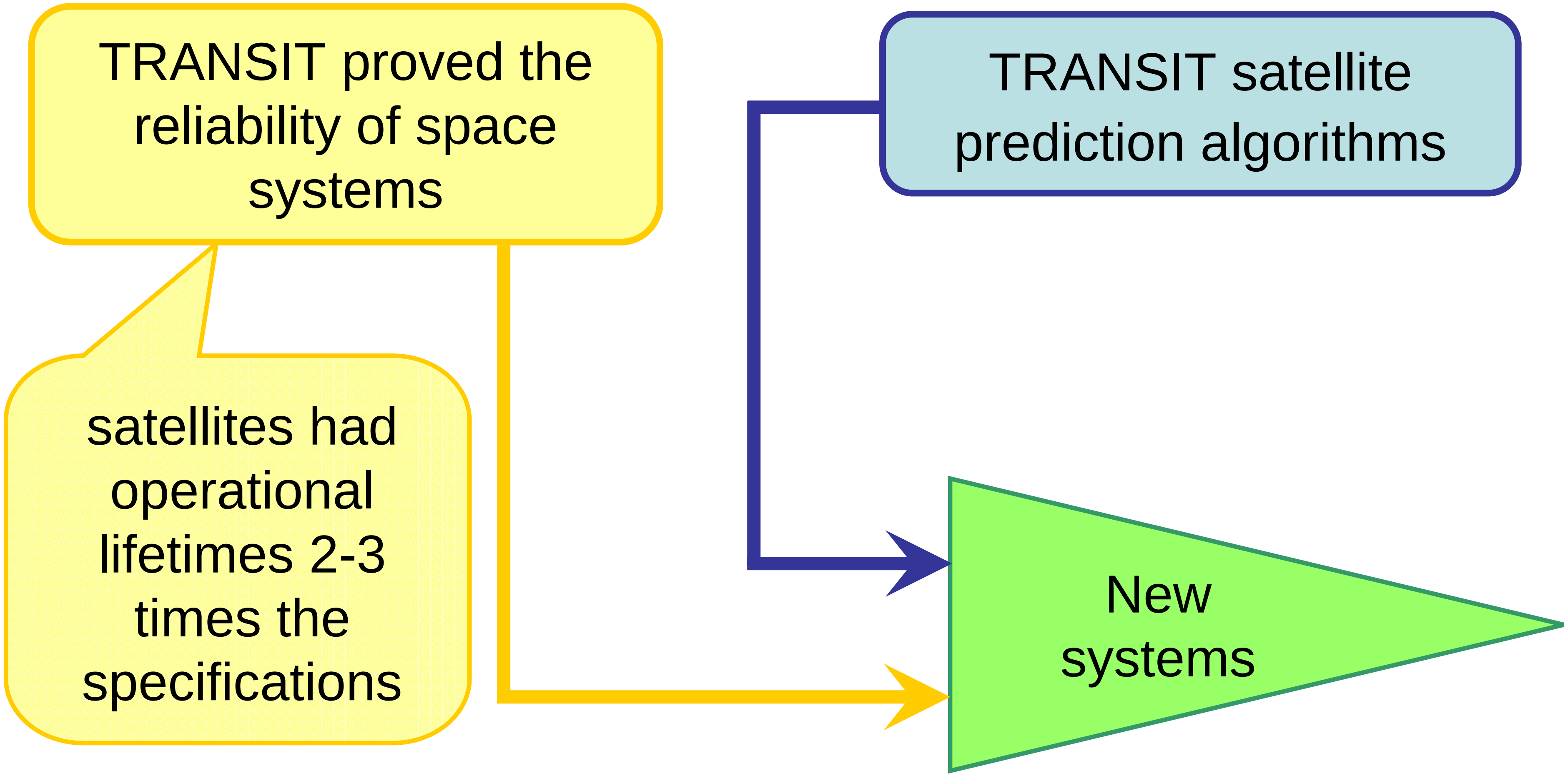
TRANSIT: the end

- TRANSIT was successful in positioning ships at sea (infrequent position updates and long lasting signal tracking)
- Used also for commercial marine navigators
- Not suited for aircraft or mobile users (frequent or continuous positioning)
- Decommissioned in 1996

Tsikada: Russian version of TRANSIT

Operative in 2000

TRANSIT outcomes



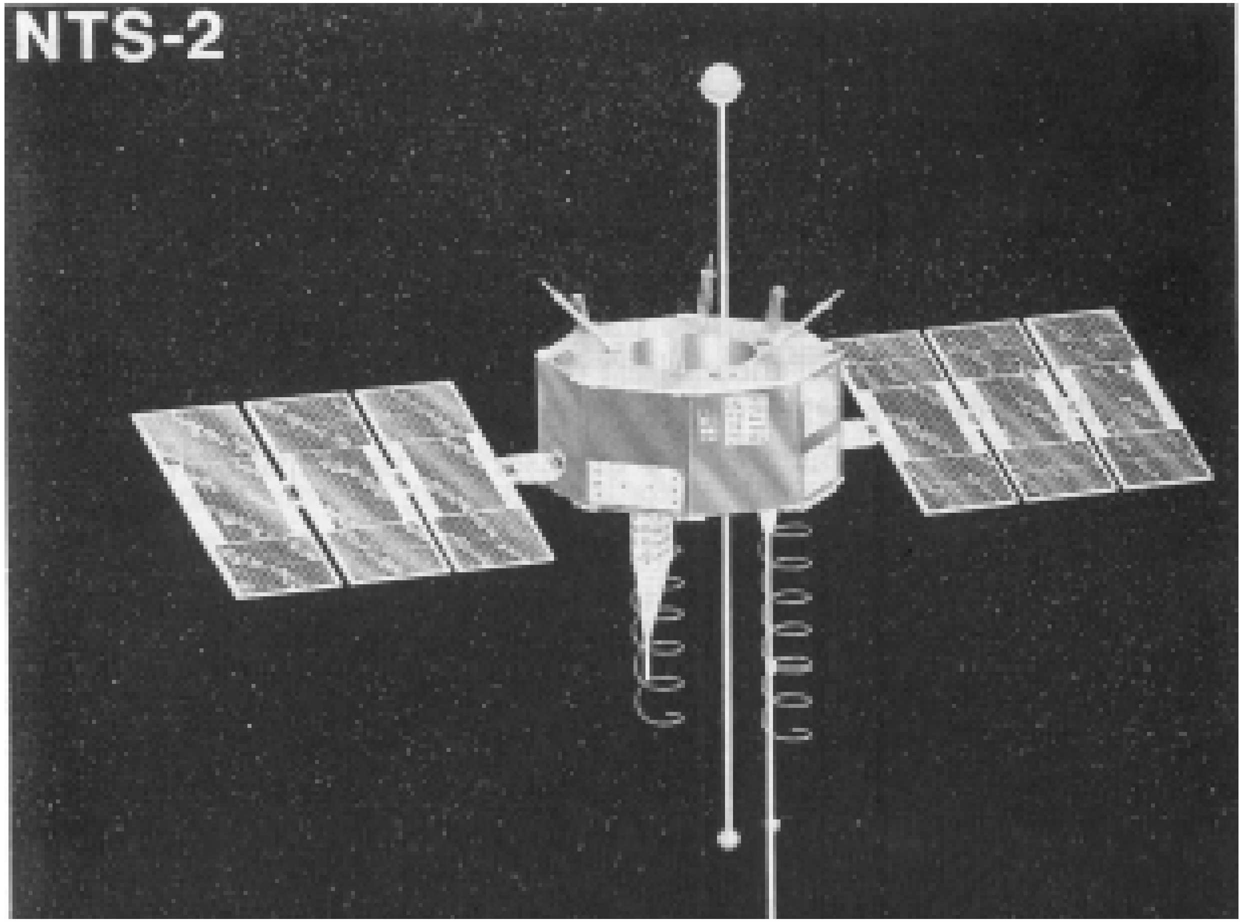
Timation

- Developed by Naval Research Laboratory
- Active in 1972
- Satellites with very precise clocks on board providing:
  - very precise time and time transfer between points on the Earth
  - navigation information
- Signals: side-tone ranging (various synchronized tones broadcasted) – resolved the phase ambiguities

Timation

- Clocks:
  - very stable quartz-crystal oscillators (first version)
  - rubidium and cesium atomic clocks (later versions) with very high frequency stability
- Satellites:
  - in inclined orbits
  - altitude of 500 nautical miles (~920 Km) – first two
  - altitude of 7500 nautical miles (~14000 Km) – last series

Timation



Project 621B

- U.S. Air Force programme
- Active in 1972
- New broadcasted signal based on pseudorandom noise (PRN)

The modulation was obtained repeating a pseudorandom digital (ones and zeros) sequence

- Users:
  - detected the start of the repeated sequence
  - determined the range to a satellite

Project 621B

- All satellites broadcasted on the same nominal frequency

PRN coding sequences were properly selected to be nearly orthogonal

- Signals could be detected also with power density lower than 1/100th of ambient power noise

Most forms of jamming or deliberate interferences could be easily rejected as noise was.

Low rate channel (50b/s) to transmit ephemeris and clock information

Project 621B

- Several constellations of highly eccentric satellites orbits with 24-hour periods

High line-of-sight accelerations

- Continuous measurement from ground to keep the signals time-synchronized

The synchronizing link was quite vulnerable

GPS: the start

- Programs of U.S. Navy and Air Force in the late 1960s started to converge.
- On 17th December 1973 NAVSTAR (the Global Positioning System) program was approved by U.S. DoD and the JPO (Joint Program Office)

1970

- ✓ enhanced spacecraft design
- ✓ new launching techniques
- ✓ better capability of tracking and maintaining satellites in orbit
- ✓ ultra-stable clocks
- ✓ spread spectrum signaling
- ✓ integrated circuits

GPS: design choices

- Active/Passive system (interaction with finite no. of users/broadcast to unlimited no. users) – PASSIVE
- Spread spectrum signaling: simultaneous transmissions on one frequency (first wide use of CDMA technique).
- Carrier frequency: compromise between required bandwidth (20 MHz) and increase in atmospheric attenuation and space loss (signal power loss due to distance traveled) – L-band

GPS: design choices

Satellite constellation and orbits

- LEO (< 2000 km):
  - – visible only for 10-20 minutes
  - – high Doppler rates
  - – high orbital perturbations
  - – 100-200 satellites for global coverage
  - + lower launch costs
  - + lower power transmission

GPS: design choices

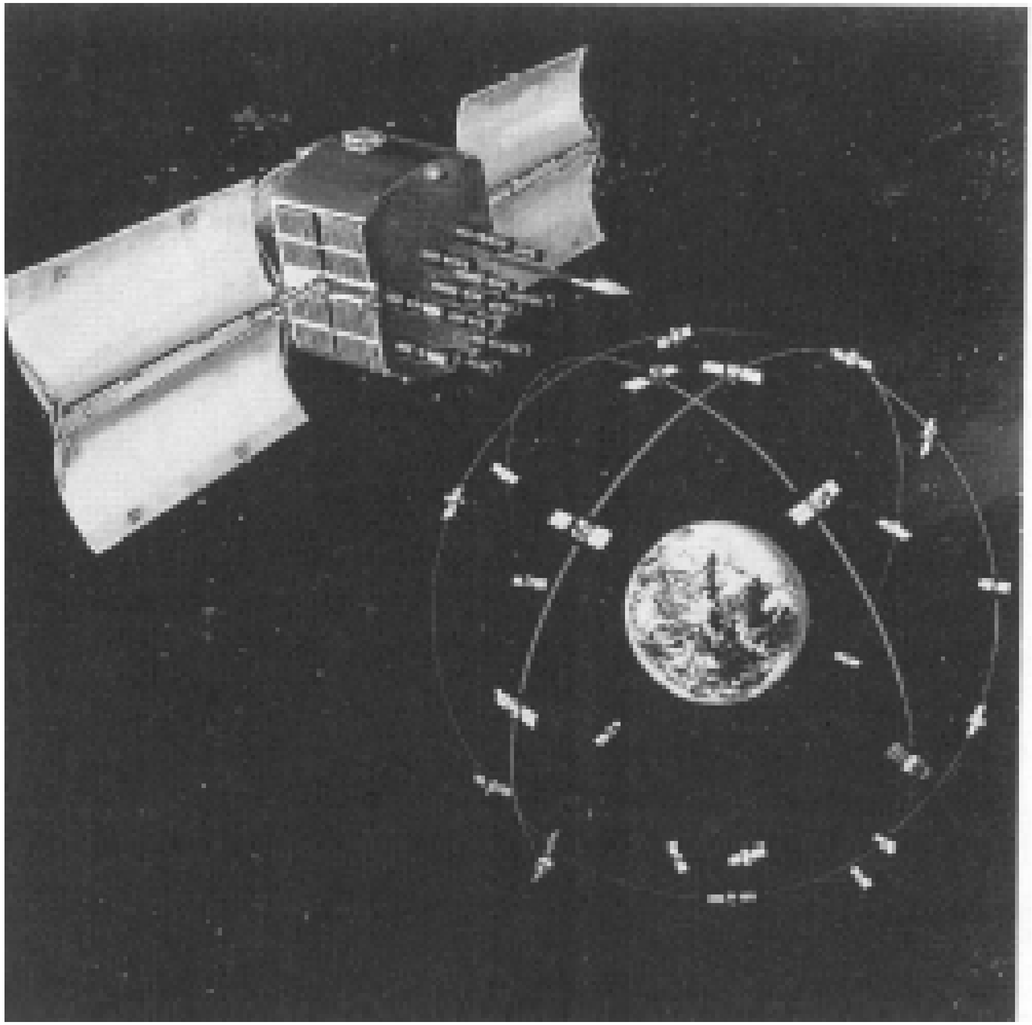
Satellite constellation and orbits

- MEO (5000-20.000 km):
  + visible for several hours
  + 24-36 satellites for global coverage
  – higher (w.r.t. LEO) launch costs
- GEO (36.000 km over Equator):
  + appear as fixed points to observer on earth
  + global coverage with a small no. of satellites
  – poor coverage at higher latitudes
  – higher launch costs

GPS: design choices

Satellite constellation and orbits

MEO constellation of 24 satellites



GPS: design choices

Satellite constellation and orbits

In 1973:

- 8 satellites in each orbit
- 3 circular ($e < 0.01$) orbits with inclination of 63 deg. (easier to have spares)
- orbits equally spaced around the equator
- orbital altitudes 20.162 km (26.651orbit radius; 6.378 Earth's equatorial radius)
- min. 6 – max. 11 satellites in view at any time

GPS: design choices

Satellite constellation and orbits

The chosen orbital altitude:

- ✓ produced repeating ground traces
- ✓ two orbital periods per sidereal day (a period of about 12 hours)
- ✓ compromise among:
  - user visibility
  - need to pass over ground stations in U.S periodically
  - launch costs

GPS: Milestones

- 1973: Architecture approved
- 1978: First test satellite launched
- 1989: First operational satellite launched
- 1995: System declared operational
- 2000: Intentional degradation of the civil signal stopped
- 2004: Interoperability GPS-Galileo agreement signed

GPS: Objectives and Policies

Main objectives of DOD: offer U.S. military

- an accurate estimation of
  - ✓ Position (position error of 10 m r.m.s.)
  - ✓ Velocity (velocity error of 0.1m/s r.m.s.)
  - ✓ Time (time error of 100 ns r.m.s.)

  all over the globe continuously and instantaneously
- a system with some resistance to jamming and interference
- a system not fully available to U.S. adversaries

GPS: Objectives and Policies

Two kinds of service formalized:

- Standard Positioning Service (SPS): peaceful civil use
- Precise Positioning Service (PPS): DoD-authorized use

GPS: Objectives and Policies

- PPS is restricted by cryptographic techniques: only DoD-authorized users with proper encryption keys can exploit the service (*Anti-Spoof)*
- SPS is unrestricted but until 2 May 2000 the signal was degraded by controlled errors that could be removed by DoD-authorized users (*Selective Availability)*

GPS: Objectives and Policies

1999 Federal Radionavigation Plan:

- gives the performance specifications as rms error or 95th percentile of the error distribution
- specifications conservatives and actual performances are better (no other specifications available)

GPS: Objectives and Policies

Error(95%)	PPS	SPS	
		SA on	SA off
Position **Horizontal** **Vertical**	 22 m 28 m	 100 m 156 m	 10 m 15 m
Time	200 ns	340 ns	50 ns
Velocity in any direction (not in FRP)	0.1 m/s	N.A.	N.A.

GPS: Objectives and Policies

Without SA, PPS has the following advantages over SPS:

– better positioning performance due to dual-frequency measurements compensating ionospheric errors
– faster codes leading to higher precision in range measurements
– lower error due to multipath

GPS: Objectives and Policies

Civil use of GPS:

- US policy for civil use of GPS first announced by DoD in late 1970's: assurance that SPS signals will remain freely available
- 1983: Korean airplane disaster (shot down by Soviet) drew attention to potential benefits of GPS to civil aviation
- 1991: agreement with UN-ICAO (International Civil Aviation Organization) signed – the SPS was declared "*available for the future on a continuous, worldwide basis, and free of direct users fees*"

GPS: Objectives and Policies

Civil use of GPS:

- 1995: report of National Academy of Public Administration and National Research Council recommending the removal of Selective Availability
- 1996: Presidential Decision Directive:
  - encourages the integration of GPS into peaceful applications (commercial, scientific,…) worldwide
  - promotes the acceptance of GPS as an international standard

GPS: Objectives and Policies

Civil use of GPS:

- 1996: Management assigned to the Interagency GPS Executive Board (IGEB), co-chaired by DoD and DoT (Department of Transportation)
- 2000: Presidential Decision deactivates the Selective Availability (until …)
- 2004: new Presidential Decision Directive:
  - renews the U.S. government commitment to provide a SPS free to all on a global basis for peaceful civil and commercial use

GPS: Objectives and Policies

Civil use of GPS:

- 2004: new Presidential Decision Directive:
  - concerns not only GPS, but all satellite-based positioning systems (augmentation systems under DoT control)
  - recognizes the agreement signed with European Union that commits both side to cooperate to assure GPS/Galileo interoperability
  - commits U.S. government to ensure the GPS performance for civil use exceeds or at least equals that of other systems

GPS: Objectives and Policies

Civil use of GPS:

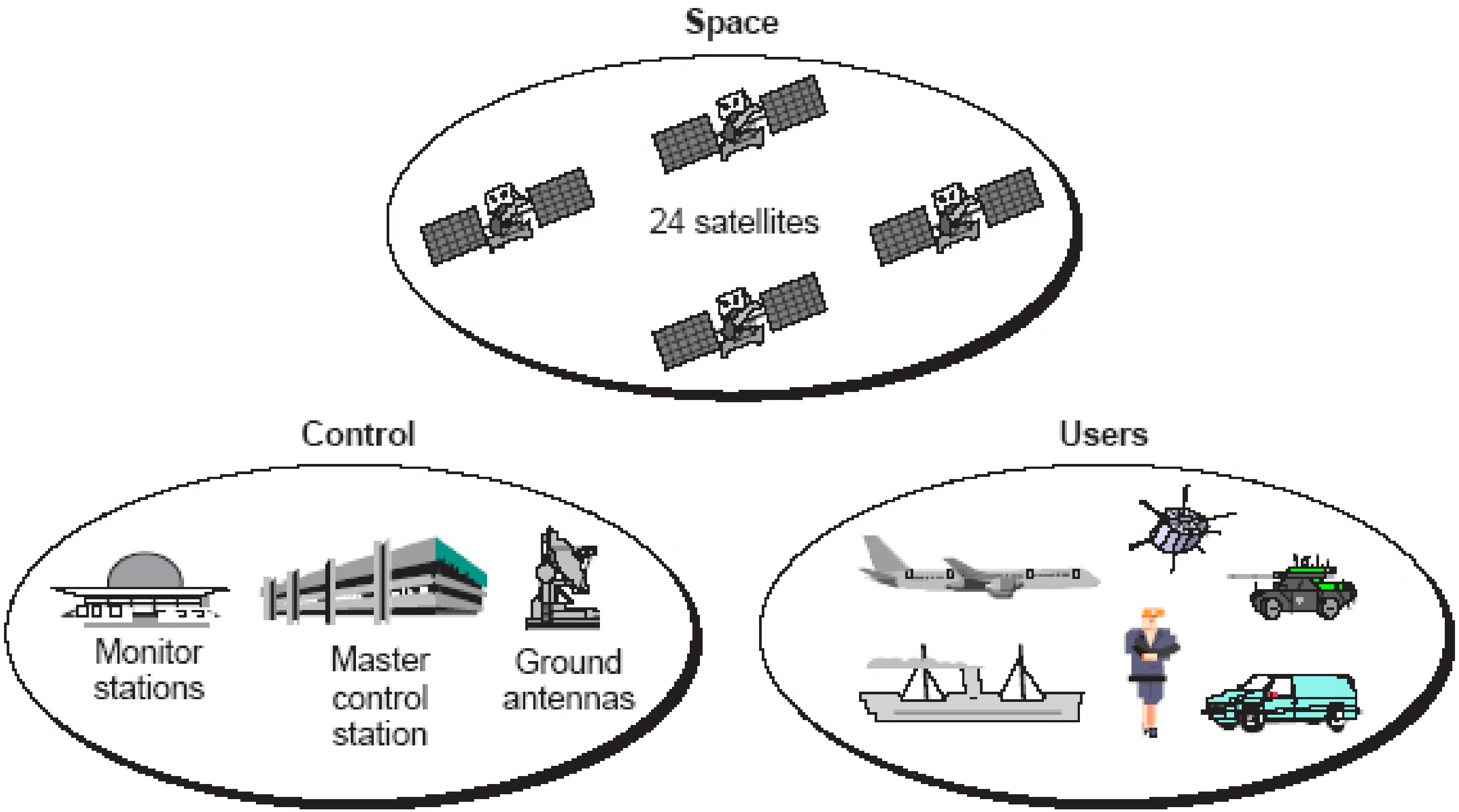
- 2004: new Presidential Decision Directive:
  - establishes of a permanent National Space-Based Positioning, Navigation, and Timing (PNT) Executive Committee
    - co-chaired by representatives of DoT and DoD
    - includes representatives of various Departments (State, Commerce, Homeland Security,…) and of National Aeronautics and Space Administration

GPS: Objectives and Policies

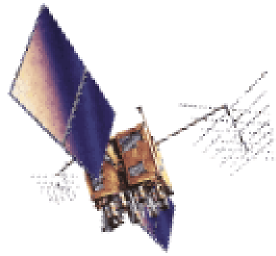
Civil use of GPS:

- 2004: new Presidential Decision Directive:
  - PNT Executive Committee shall coordinate the resource allocation for GPS and its augmentations on an annual basis
  - DoD is responsible for operation, development, security and modernization of GPS and for the enhancement of secondary payloads (SAR, …)
  - DOT is responsible for the development of requirements for civil applications

GPS Architecture

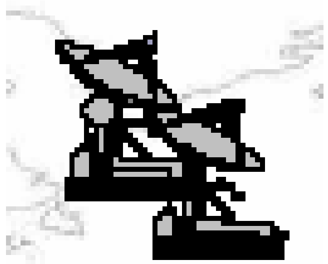


GPS Architecture

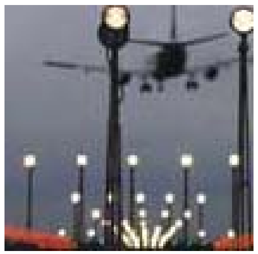


SPACE SEGMENT: 24 satellites

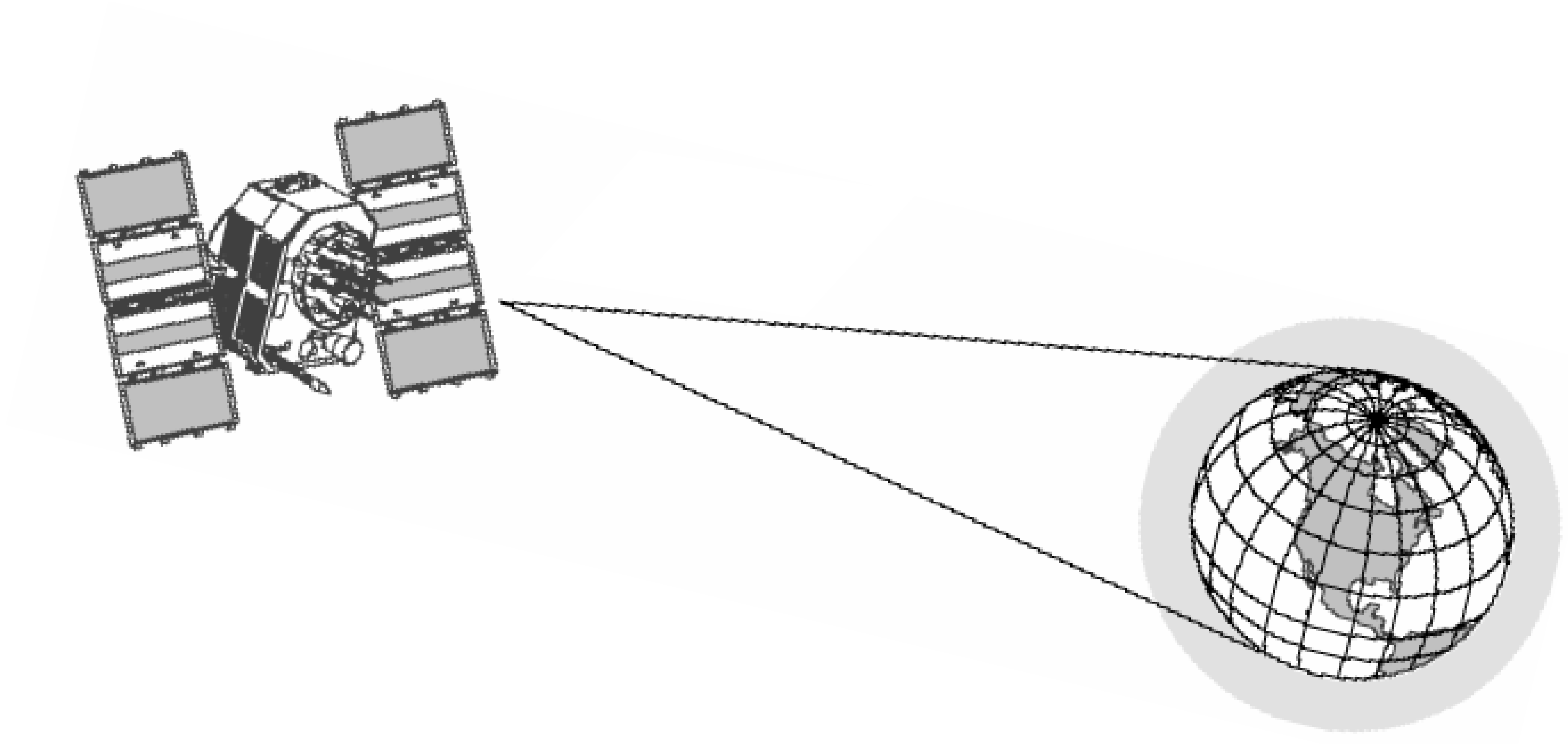
CONTROL SEGMENT: ground stations (control and monitoring) and antennas for the management of the satellites operations



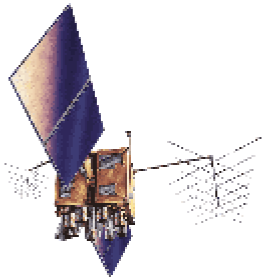
USER SEGMENT: civil and military GPS user equipment and all the activities related to their development



GPS Architecture – Space Segment



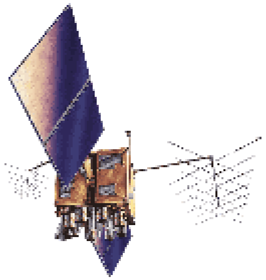
GPS Architecture – Space Segment



Satellite constellation

- 6 Orbital planes inclined of 55 degrees w.r.t. equatorial plane
- Right ascensions of the ascending node are separated by 60° in the equatorial plane
- Orbits eccentricity nominally zero, but generally $e < 0.01$
- Semi-major axis: 26.560 Km
- Altitude: 20.200 Km above the Earth (~4 earth radii)

GPS Architecture – Space Segment

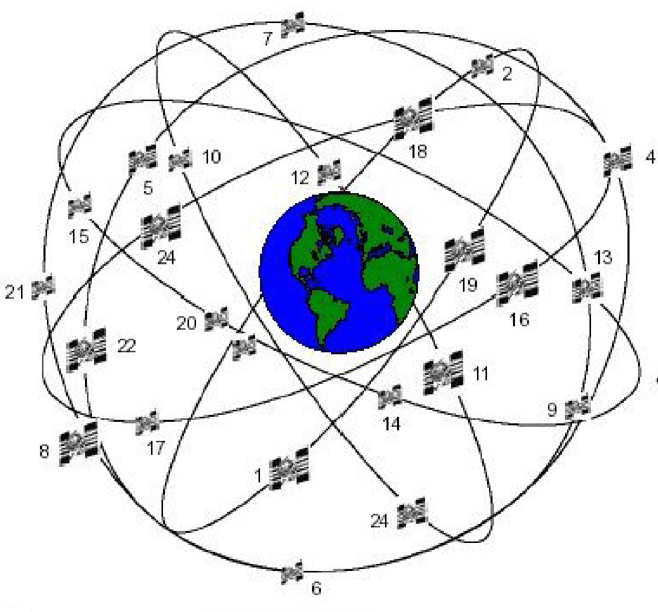


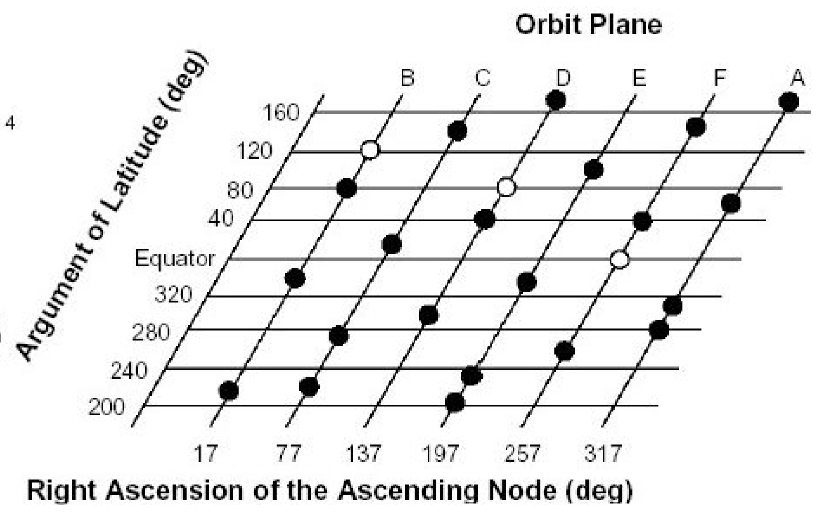
Satellite constellation

- Period: ½ mean sidereal day (~ 11h 58m)
- One satellite repeats the same ground track after two revolutions (a stationary user sees the same satellite spatial distribution after 23h 56m)
- 4 satellites per plane distributed unevenly to minimize the effect of single satellite failures.
- The satellite constellation was designed to offer the best global coverage (PDOP<10 for the best 4 satellite above 5° elevation with single satellite failure)

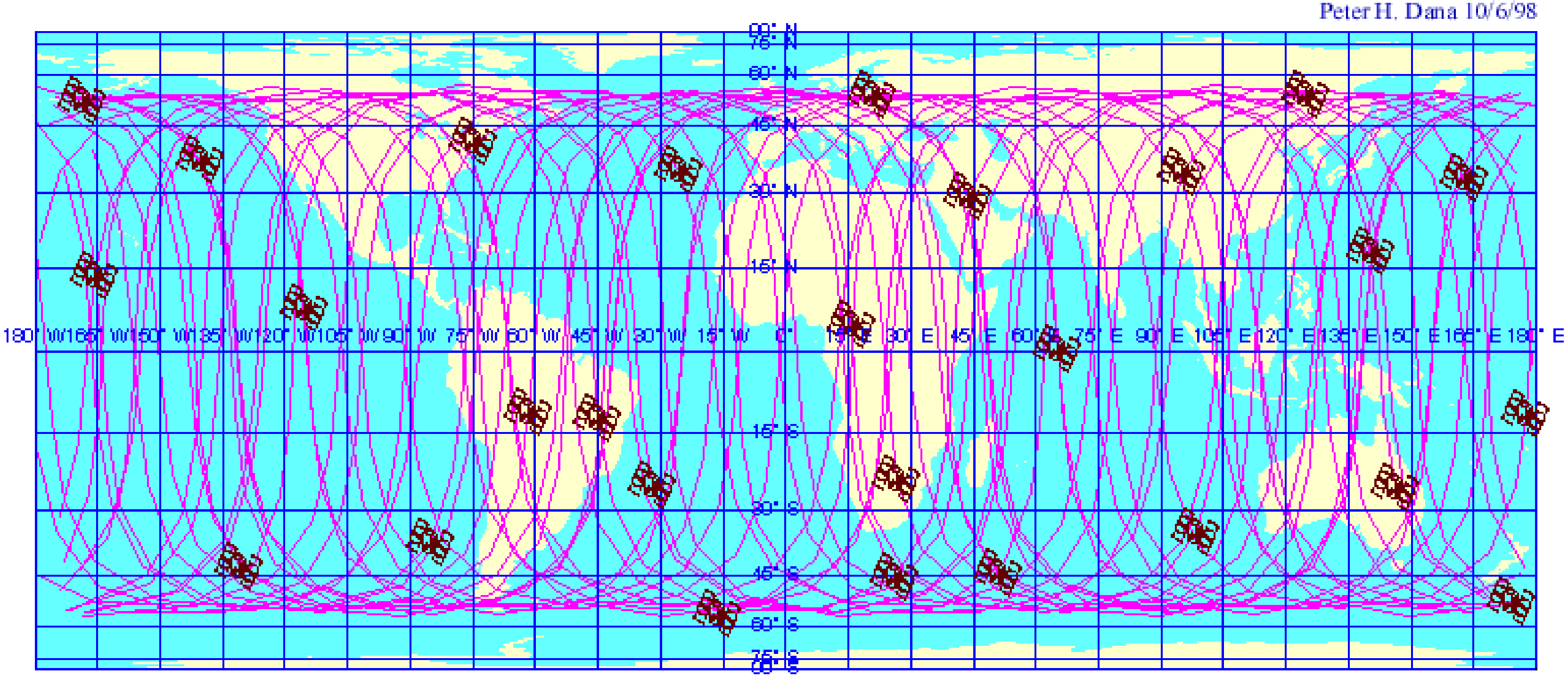
GPS Architecture – Space Segment

Satellite constellation and orbits



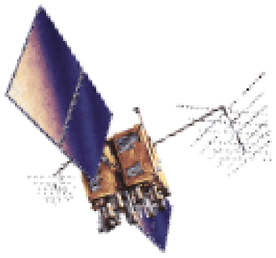


GPS Architecture – Space Segment



Global Positioning System Satellites and Orbits
for 27 Operational Satellites on September 29, 1998
Satellite Positions at 00:00:00 9/29/98 with 24 hours (2 orbits) of Ground Tracks to 00:00:00 9/30/98

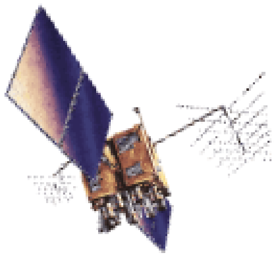
GPS Architecture – Space Segment



Satellite constellation

- Spare satellite slot in each orbital plane
- The constellation can support up to 30 satellites
- 6/8 satellites in view as average
- Satellites orbit velocity: 3,87 Km/s
- Angular Velocity: 2 x 7.29211 x 10-5 rad/s

GPS Architecture – Space Segment



Satellite constellation

- Each satellite is identified by a 2-character code:
  - ✓a letter for the orbital plane (A – F)
  - ✓a number for the slot in the plane (1 – 4)
- Each satellite has a PRN number corresponding to the PRN code transmitted by that satellite

GPS Architecture

Block I – Navigation development satellites

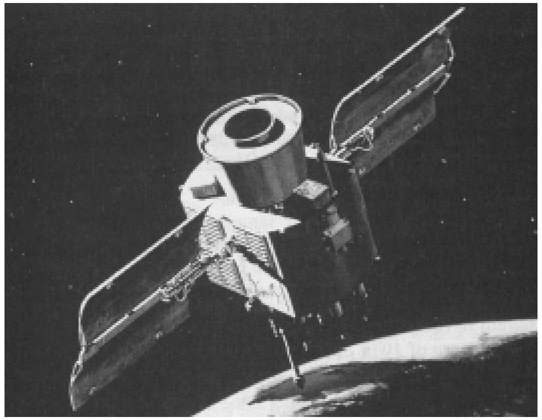
- Set of 11 satellites
- Demonstrated the feasibility of GPS
- Launched in orbit (63°) between 1978 and 1985 from Vandenberg Air Force Base, California
- Built by Rockwell International

ID Satellite	*PRN Code*	*Launch Date*	*Available from*
Block I			
	04	**22/02/1978**	**29/03/1978**
	07	**13/05/1978**	**14/07/1978**
	06	**06/10/1978**	**09/11/1978**
	08	**11/12/1978**	**08/01/1979**
	05	**09/02/1980**	**27/02/1980**
	09	**26/04/1980**	**16/05/1980**
	-	**18/12/1981**	**Launch failed**
	11	**14/07/1983**	**10/08/1983**
	13	**13/06/1984**	**19/07/1984**
	12	**08/09/1984**	**03/10/1984**
	03	**09/10/1985**	**30/10/1985**

GPS Architecture

Block I – Navigation development satellites

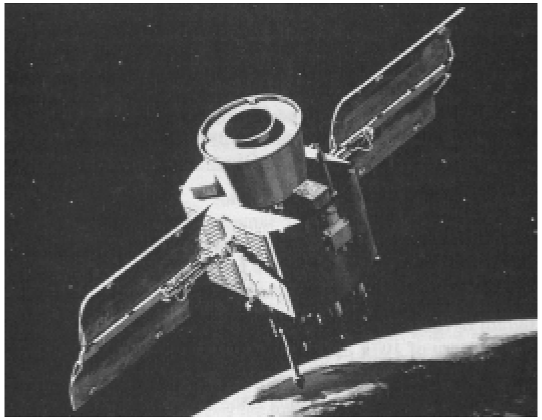
- Onboard storage capability: 14 days of navigation message
- Navigation message valid only for 1-hr period
- Momentum management not present onboard



- Frequent ground contact needed (satellite lose attitude determination after a short time)

GPS Architecture

Block I – Navigation development satellites

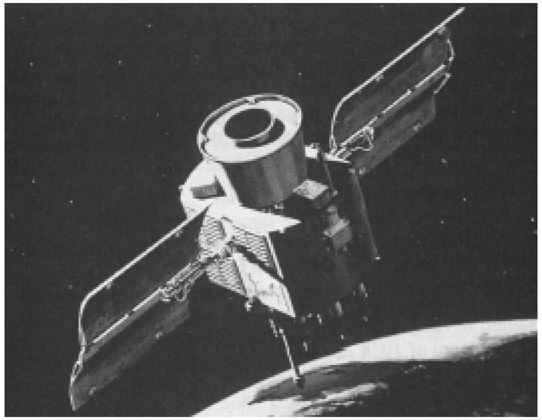


- Two cesium and rubidium atomic frequency standards
- Designed for:
  - a mean mission duration of 4.5 years
  - a design life of 5 years
  - inventory expendable of 7 years (fuel, battery life, solar panel power capacity)

GPS Architecture

Block I – Navigation development satellites

- Improved reliability of the atomic clocks on later satellites
- Some satellites operated for more than double their design life.



GPS Architecture – Satellites

Block II – Operational satellites

- Production models (9 units)
- Built by Rockwell International
- First launch in February 1989 (55°orbit) from Cape Canaveral Air Force Station, Florida
- Weight: 900 Kg
- Power/Solar panels: 1100 W
- Unit cost: 43 M$

GPS Architecture – Satellites

Block II – Operational satellites

- Onboard navigation message storage capacity: 14 days as in Block I
- No autonomous onboard momentum control
- Satellites may start to tumble between 28 and 45 days after the last ground contact
- Multiple rubidium and cesium atomic standards onboard (reliability and survivability)

GPS Architecture – Satellites

Block II – Operational satellites

- Designed for a mean mission duration of 6 years
- Design life of 7.5 years
- Inventory expendables of 10 years
- Improved reliability and survivability w.r.t. Block I

GPS Architecture – Satellites

Block II – Operational satellites

- Enhancements in subsystem design (w.r.t. B-I):
  - ✓ radiation hardening (prevention of memory upset due to cosmic rays)
- Refinements included to support fully operational GPS system requirements:
  - ✓ control segment/space interface
  - ✓ user signal interface

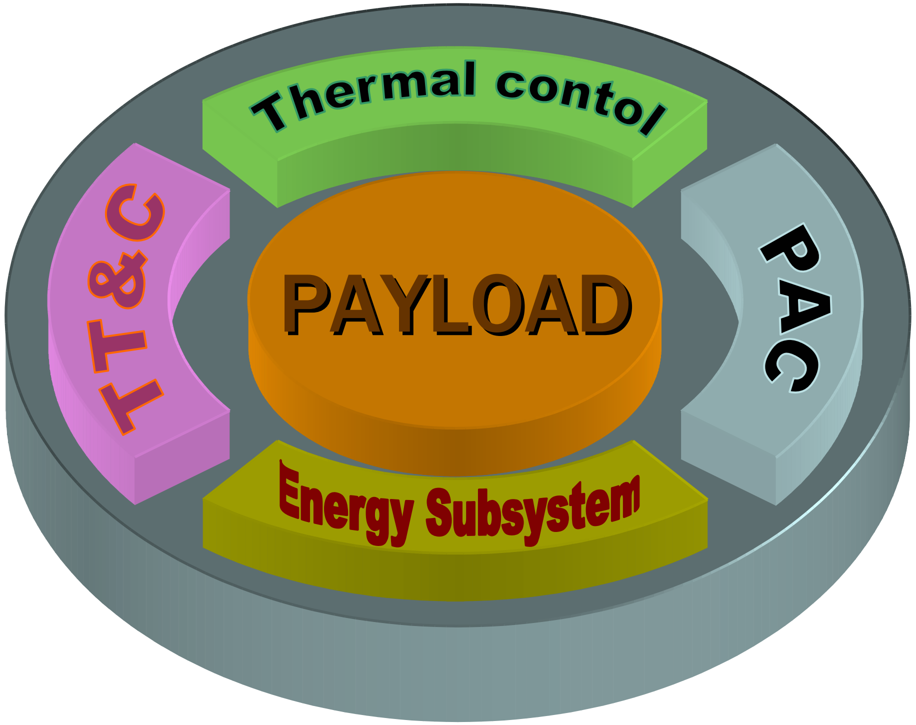
GPS Architecture – Satellites

Block II – Operational satellites

- ✓ Selective Availability and Anti-Spoof added
- ✓ Automatic error detection for certain error conditions added
- ✓ After detection of an error, the satellite transmits non standard pseudorandom code to prevent usage of corrupted signal or data (improvement of the system integrity)

GPS Architecture – Satellites

Block II – Operational satellites



GPS Architecture – Satellites

Block II – Operational satellites - Payload

- Payload: PseudoRandomNoise Signal Assembly (PNSA)
- PRNSA components:
    - base-band processor
    - frequency synthesizers (L_1 and L_2)
    - modulators (L_1 and L_2)
    - power amplifiers (L_1 and L_2)
    - diplexer

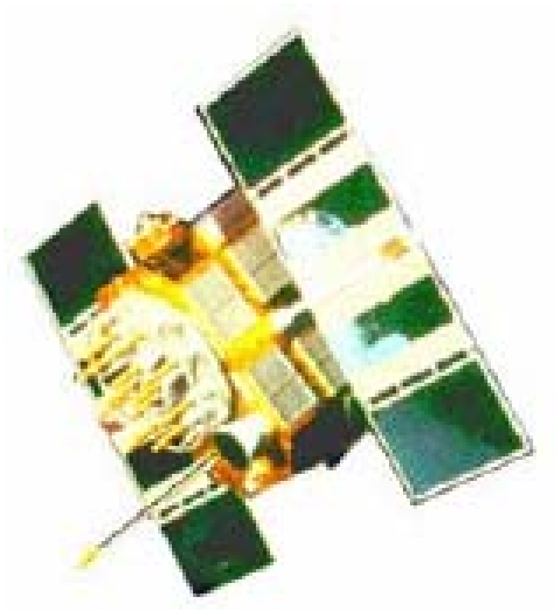
GPS Architecture – Satellites

Block II	PRN Code	Launch Date	Available from	Orbital Plane
II – 1	14	14/02/1989	14/04/1989	
II – 2	02	10/06/1989	12/07/1989	B3
II – 3	16	17/08/1989	13/09/1989	
II – 4	19	21/10/1989	14/11/1989	A5
II – 5	17	11/12/1989	11/01/1990	D3
II – 6	18	24/01/1989	14/02/1990	
II – 7	20	25/03/1990	19/04/1990	
II – 8	21	02/08/1990	31/08/1990	E2
II – 9	15	01/10/1990	20/10/1990	D5

GPS Architecture – Satellites

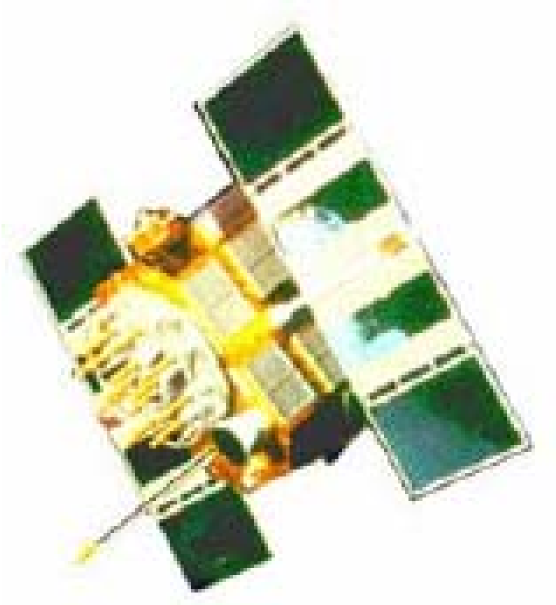
Block IIA – Operational satellites (Advanced)

- Very similar to Block II satellites
- Several system enhancements introduced:
  - ✓ Onboard navigation message storage capability: 180 days
  - ✓ Navigation message valid for a 4-hr period for the first 14 days on-orbit
  - ✓ Navigation message valid for a 6-hr period after the first 14 days on-orbit



Satellites can work continuously for 6 months without ground support

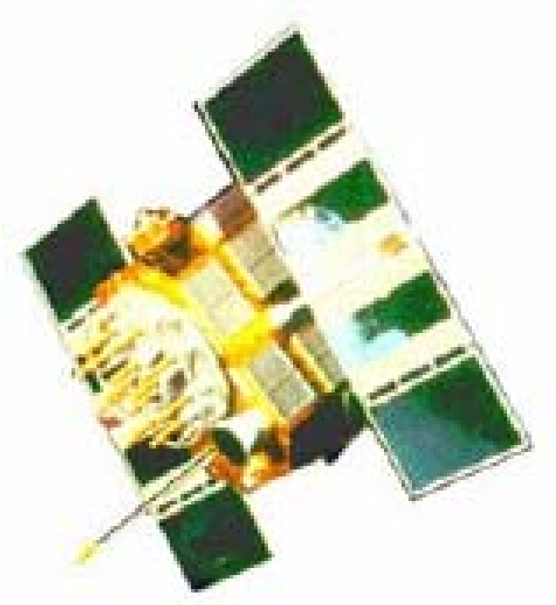
GPS Architecture – Satellites



Block IIA – Operational satellites (Advanced)

- Without ground contact, the navigation data message accuracy will gradually degrade over time
- User Range Error (URE) bounded by 10000 m after 180 days (w.r.t. typical URE of 5.5.m with daily uploads of navigation message)
- Autonomous onboard momentum management capability added (less frequent ground contact required)

GPS Architecture – Satellites



Block IIA – Operational satellites (Advanced)

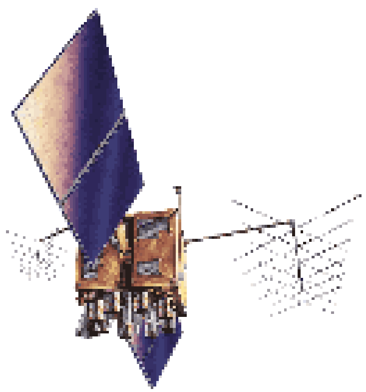
- Electronics of the satellites radiation hardened
- Built by Rockwell International
- First launch in November 2000 from Cape Canaveral Air Force Station, Florida
- Life expectancy equal to Block I satellites

Block IIA	*PRN Code*	*Launch Date*	*Available from*	*Orbital Plane*
II – 10	23	26/11/1990	10/12/1990	E5
II – 11	24	03/07/1991	30/08/1991	D1
II – 12	25	23/02/1992	24/03/1992	A2
II – 13	28	09/04/1992	25/04/1992	
II – 14	26	07/07/1992	23/07/1992	F2
II – 15	27	09/09/1992	30/09/1992	A4
II – 16	01	22/11/1992	11/12/1992	F4
II – 17	29	18/12/1992	05/01/1993	F5
II – 18	22	02/02/1993	04/04/1993	B1
II – 19	31	30/03/1993	13/04/1993	C3
II – 20	37	13/05/1993	12/06/1993	C4
II – 21	09	26/06/1993	21/07/1993	A1
II – 22	05	30/08/1993	28/09/1993	B4
II – 23	04	26/10/1993	29/11/1993	D4
II – 24	06	10/03/1994	28/03/1994	C1
II – 25	03	28/03/1996	09/04/1996	C2
II – 26	10	16/07/1996	15/08/1996	E3
II – 27	30	12/09/1996	01/10/1996	B2
II – 28	08	06/11/1997	18/12/1997	A3

GPS Architecture – Satellites

Block IIR – Replenishment Operational satellites

- Replaced inoperative Block II/IIA satellites
- Based on technological innovation
- In-orbit positioning was performed by Space Shuttle.

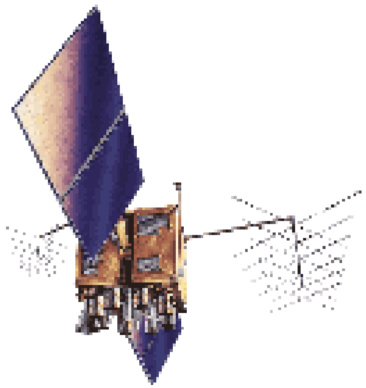


- Built by Lockheed Martin
- Weight: 1100 Kg
- Power/Solar panels: 1700 W
- Unit cost: 30 M$

GPS Architecture – Satellites

Block IIR – Replenishment Operational satellites

- One cesium and two rubidium atomic frequency standards onboard
- Same signal and data transmission to the user of B II/IIA
- System-level operations very different from Block II/IIA



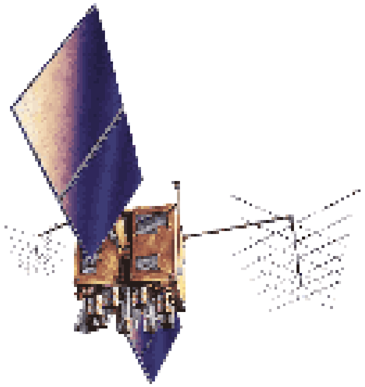
- Designed for a mean mission duration of 7.5 years
- Design life of 10 years
- Inventory expendables of 10 years

Block IIR	*PRN Code*	*Launch Date*	*Available from*	*Orbital Plane*
IIR – 1	12	17/01/1997	Launch failed	
IIR – 2	13	23/07/1997	31/01/1998	F3
IIR – 3	11	07/10/1999	03/01/2000	D2
IIR – 4	20	11/05/2000	01/06/2000	E1
IIR – 5	28	16/07/2000	17/08/2000	B5
IIR – 6	14	10/11/2000	10/12/2000	F1
IIR – 7	18	30/01/2001	15/02/2001	E4
IIR – 8	16	29/01/2003	19/02/2003	B1
IIR – 9	21	31/03/2003	12/04/2003	D3
IIR – 10	22	21/12/2003	12/01/2004	E2
IIR – 11	19	20/03/2004	05/04/2004	C3
IIR – 12	23	23/06/2004	09/07/2004	F4
IIR – 13	02	06/11/2004	22/11/2004	D7

GPS Architecture – Satellites

Block IIR – Replenishment Operational satellites

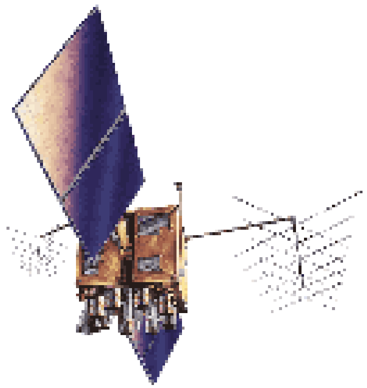
- The satellites "drift“ from their assigned orbital positions (also for the earth's gravitational pull)
- Station keeping manoeuvre (repositioning or Delta-V)
  - once per year
  - satellite back to its original orbital position

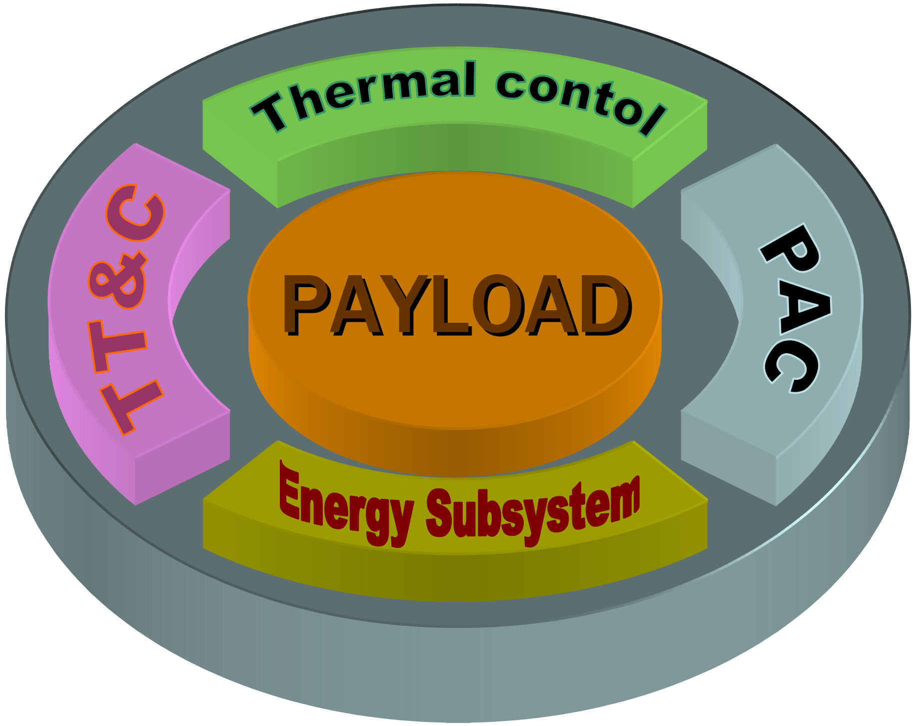


- These manoeuvres require, on average, 12 hours of unusable time for each satellite.

GPS Architecture – Satellites

Block IIR – Replenishment Operational satellites





GPS Architecture – Satellites

Block IIR – Replacement Operational satellites

Total Navigation Payload element functionalities

Atomic frequency standards	accurate, stable and reliable timing for GPS signals accurate navigation
Onboard processing	Generate navigation message Calculate ephemeris Perform data encryption Generate P and C/A code Monitor payload health Provide clock error corrections

GPS Architecture – Satellites

Block IIR – Replacement Operational satellites

Total Navigation Payload element functionalities

Software	Implements onboard processing functions
L-band system	Generates and modulates the signals and combines them for the transmission to Earth

GPS Architecture – Satellites

Block IIR – Replacement Operational satellites

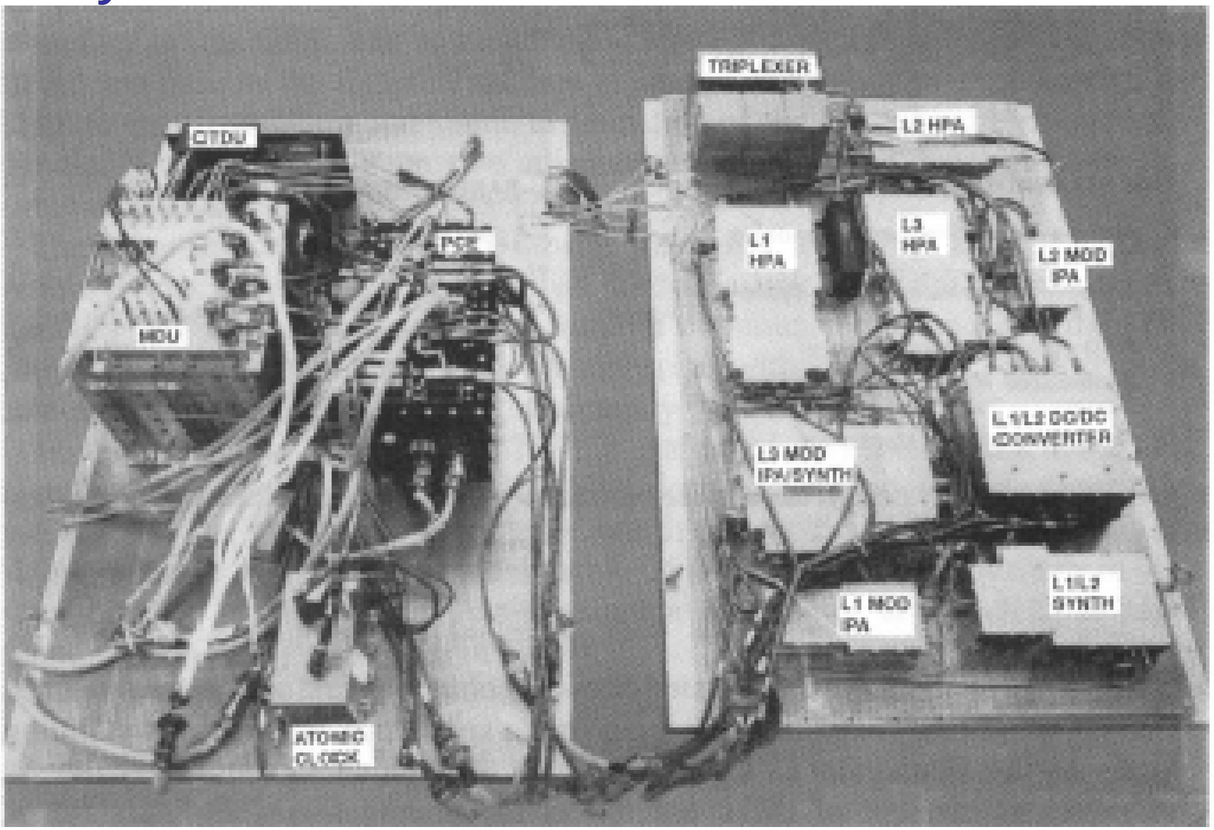
Total Navigation Payload element functionalities

Crosslink	Provides satellite-to-satellite communications and ranging
Auto navigation	Provides accurate autonomous operation without regular communications from ground

GPS Architecture – Satellites

Block IIR – Replacement Operational satellites

Navigation Payload

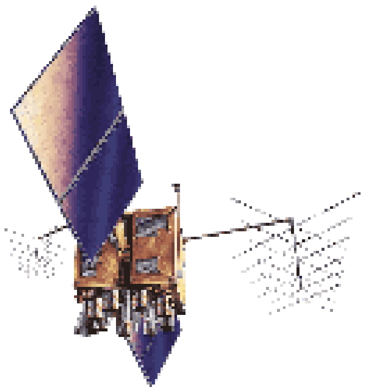


GPS Architecture – Satellites

Block IIR – Replacement Operational satellites

Total Navigation Payload:

- Generates and transmits the navigation signal
- Components mounted on 2 adjacent and stand-alone panels → easy integration and testing
- Made of:
  - ✓ Time-Keeping System
  - ✓ Mission Data Unit (MDU)
  - ✓ *L*-band Subsystem (LBS)
  - ✓ Crosslink Transponder and Data Unit
  - ✓ Auto Navigation

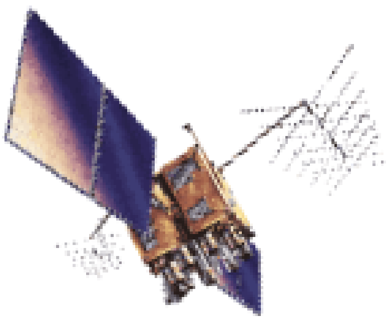


GPS Architecture – Satellites

Block IIR – Replacement Operational satellites

Time-Keeping System (TKS):

- distributes precise clock and frequency
- made of:
  - ✓ Atomic Frequency Standards
  - ✓ Frequency Synthesizer Unit
  - ✓ System and reference clock generators



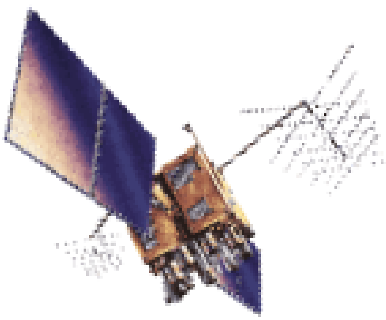
TKS is controlled by the Mission Processor (part of MDU)

GPS Architecture – Satellites

Block IIR – Replacement Operational satellites

Time-Keeping System (TKS):

- System clock frequency of 10.23 MHz generated by VCO
- 10.23 MHz used to generate a system clock (system epoch = time interval of 1.5 s)



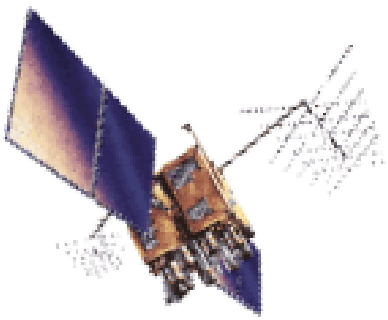
- 10.23 MHz output frequency is deliberately perturbed by an algorithm

GPS Architecture – Satellites

Block IIR – Replacement Operational satellites

Time-Keeping System (TKS):

- Atomic Frequency Standard at 13.4 MHz drives a reference clock generator
- This generator produces the reference epoch of 1.5 s



- System epoch and reference epoch are asynchronously generated
- The two epochs are synchronized by the Mission Processor

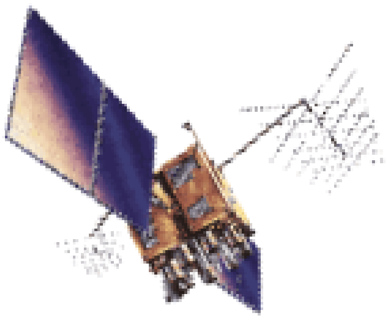
GPS Architecture – Satellites

Block IIR – Replacement Operational satellites

Time-Keeping System (TKS)

Stability of system clock w.r.t to GPS time:

- short term maintained by the stability of VCO
- long term maintained by coupling the system clock to the more stable reference clock:
  - phases of reference clock and system clock are compared
  - the target phase difference is of 100 ms



GPS Architecture – Satellites

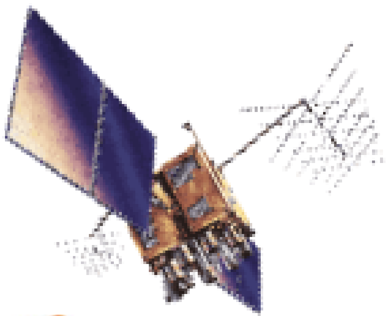
Block IIR – Replacement Operational satellites

Mission Data Unit (MDU): brain of Total Navigation Payload

- integrates all mission functions
- is packaged with the Frequency Synthesizer Unit (FSU)

Functions:

- provides storage to navigation data uploaded by Control Station (CS) through TT&C system
- generates PRN code and the navigation message and send it to *L*-band subsystem (LBS)

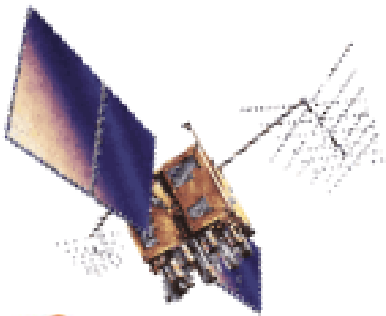


GPS Architecture – Satellites

Block IIR – Replacement Operational satellites

Mission Data Unit functions:

- performs AntiSpoof
- autonomously operates for at least 180 days without update from CS:
  - ✓ modify navigation data on a periodic basis by processing ranging data from other in-view satellites
  - ✓ exchange navigation data with other sats
  - ✓ enable autonomous determination of ephemeris and clock corrections

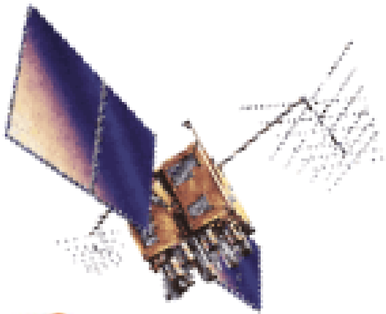


GPS Architecture – Satellites

Block IIR – Replacement Operational satellites

Mission Data Unit functions:

- quickly turn on and perform Selective Availability
- provide precise timing for other components controlling the Frequency Synthesizer Unit
- provide telemetry, diagnostics, and self-check capabilities

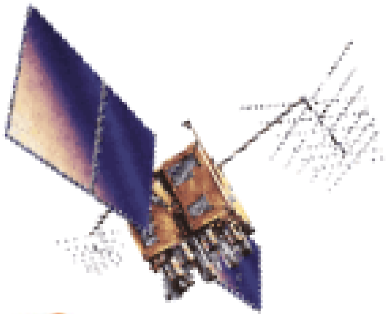


GPS Architecture – Satellites

Block IIR – Replacement Operational satellites

Mission Processor Software:

- Large and complicated
- perform many functions of Control Segment (for 180 days autonomy)
- variety of hardware and software interfaces
- written entirely in Ada

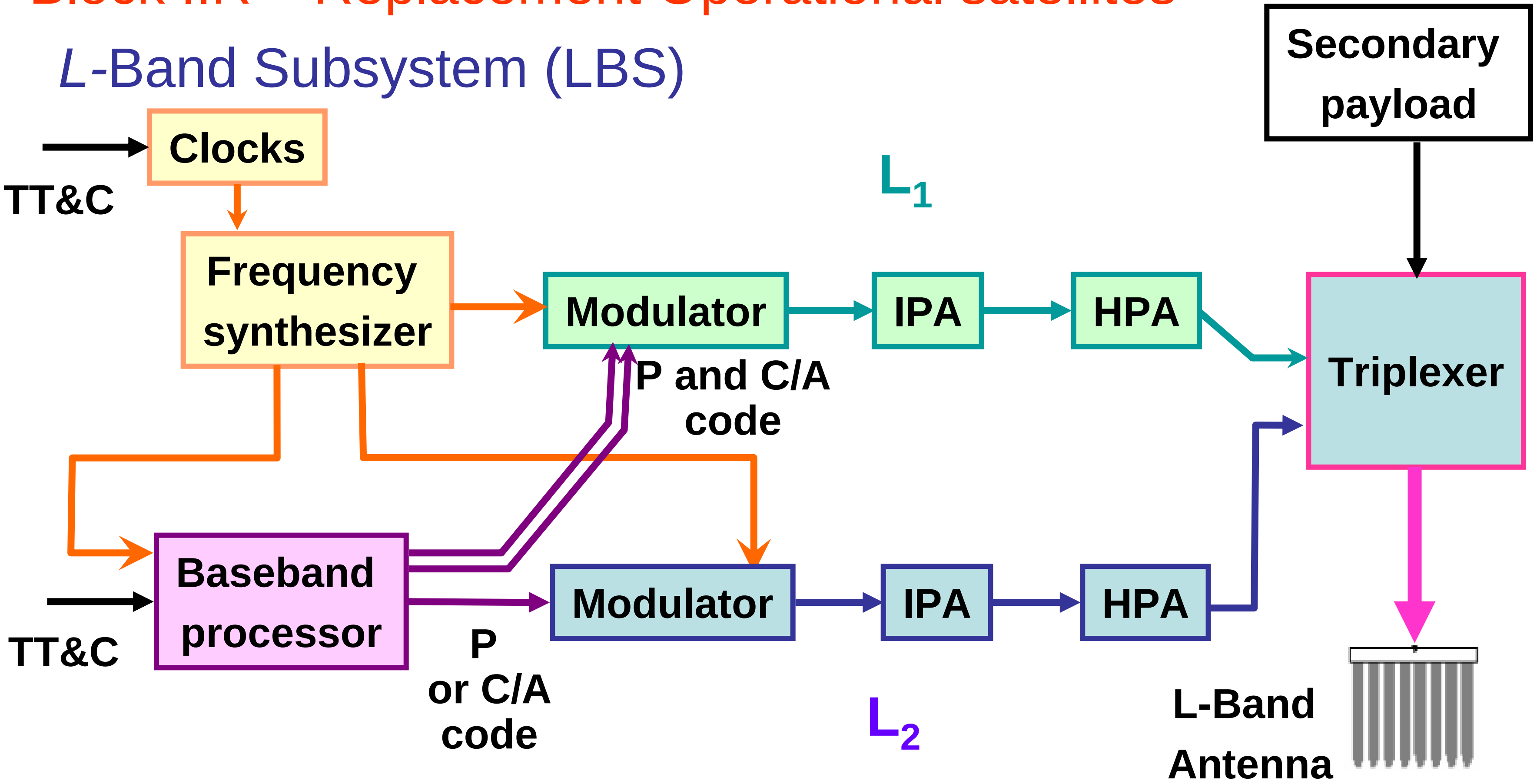


The operational flight software can be reprogrammed from the ground (partial and total)

GPS Architecture – Satellites

Block IIR – Replacement Operational satellites

L-Band Subsystem (LBS)

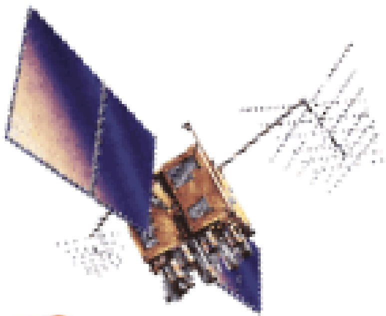


GPS Architecture – Satellites

Block IIR – Replacement Operational satellites

L-Band Subsystem (LBS):

- <u>Base-band Processor</u>:
  - ✓ processes the telemetry and ephemeris data (updated when sat passes over a ground control site)
  - ✓ produces a 50 b/s data stream that is modulo-2 added to the two PRN codes (P code at 10.23 MBs rate and C/A code at 1.023 MBs rate)

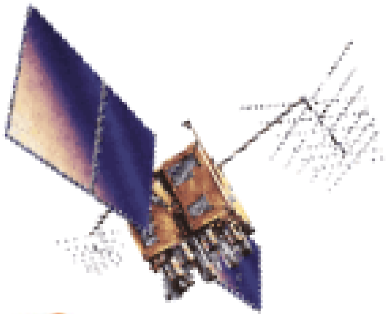


GPS Architecture – Satellites

Block IIR – Replacement Operational satellites

L-Band Subsystem (LBS):

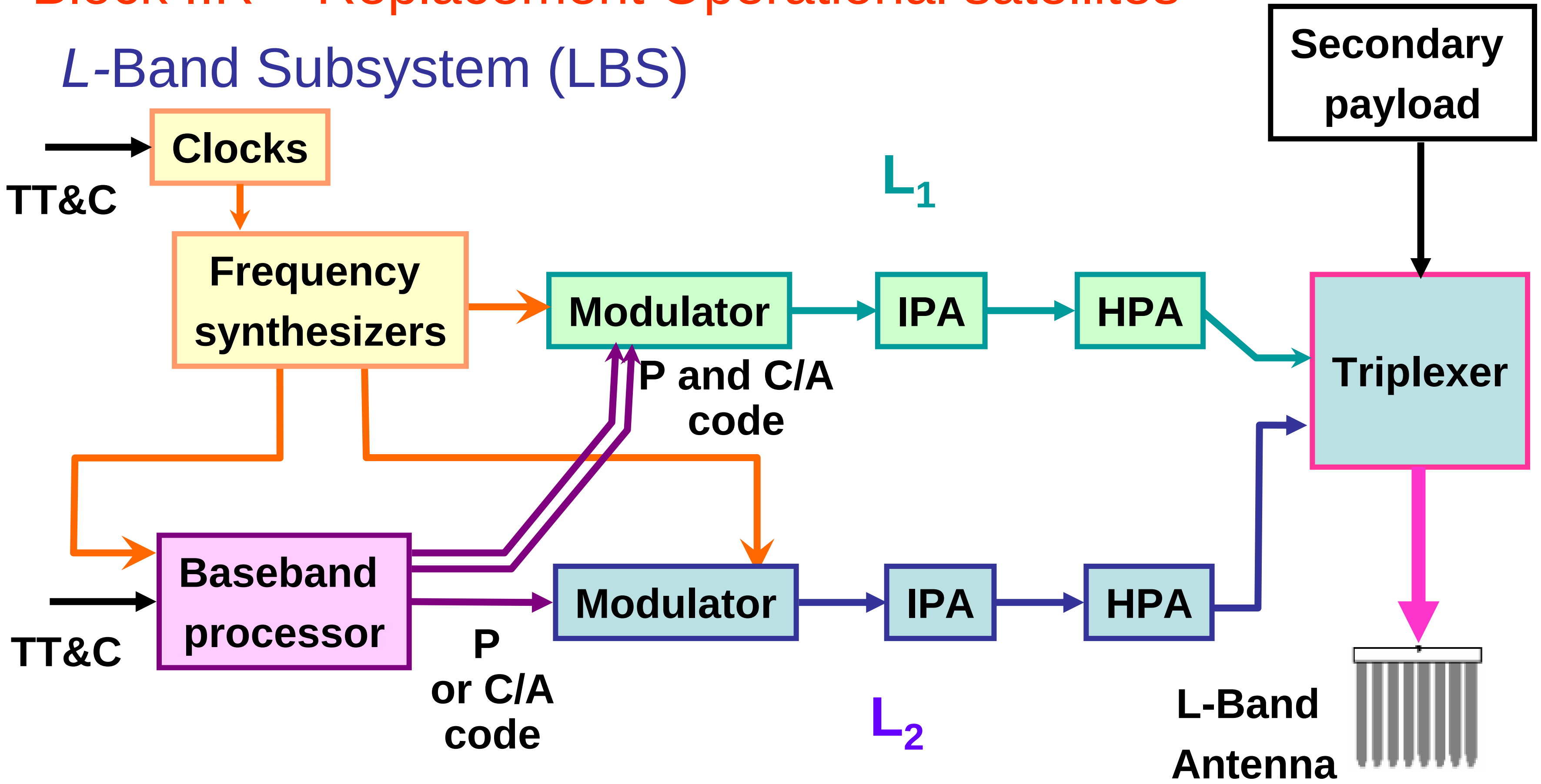
- Base-band Processor outputs:
  - a P-code output and a C/A code output to the L_1 modulator
  - a single output (P or C/A) to the L_2 modulator



GPS Architecture – Satellites

Block IIR – Replacement Operational satellites

L-Band Subsystem (LBS)



GPS Architecture – Satellites

Block IIR – Replacement Operational satellites

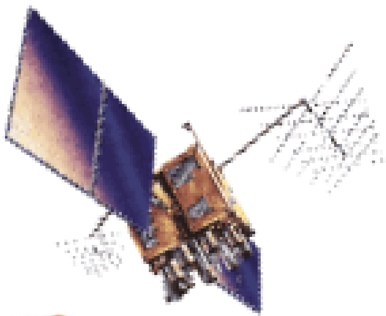
L-Band Subsystem (LBS):

- Frequency synthesizers:

  generate the two carrier frequencies by multiplying the 10.23 MHz frequency standard input:

  L_1) 10.23 x 14 x 11 = 1575.42 MHz

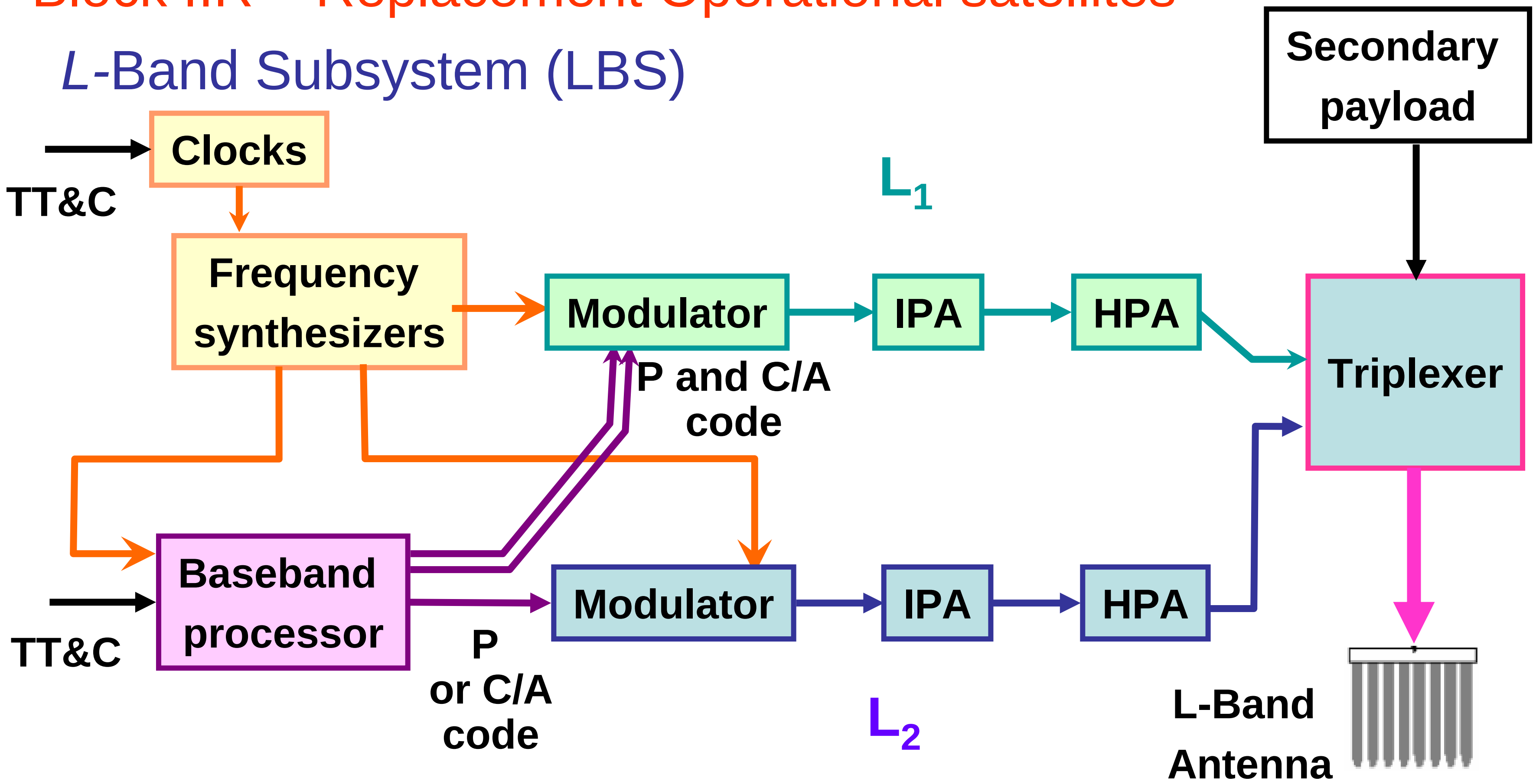
  L_2) 10.23 x 12 x 10 = 1227.60 MHz



GPS Architecture – Satellites

Block IIR – Replacement Operational satellites

L-Band Subsystem (LBS)

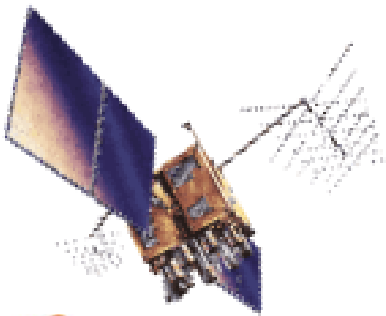


GPS Architecture – Satellites

Block IIR – Replacement Operational satellites

L-Band Subsystem (LBS):

- L_1 Modulator: QPSK modulator with P-code on the in-phase component and C/A code on the quadrature component
- L_2 Modulator: BPSK modulator. The code (either P or C/A) is selectable by ground control

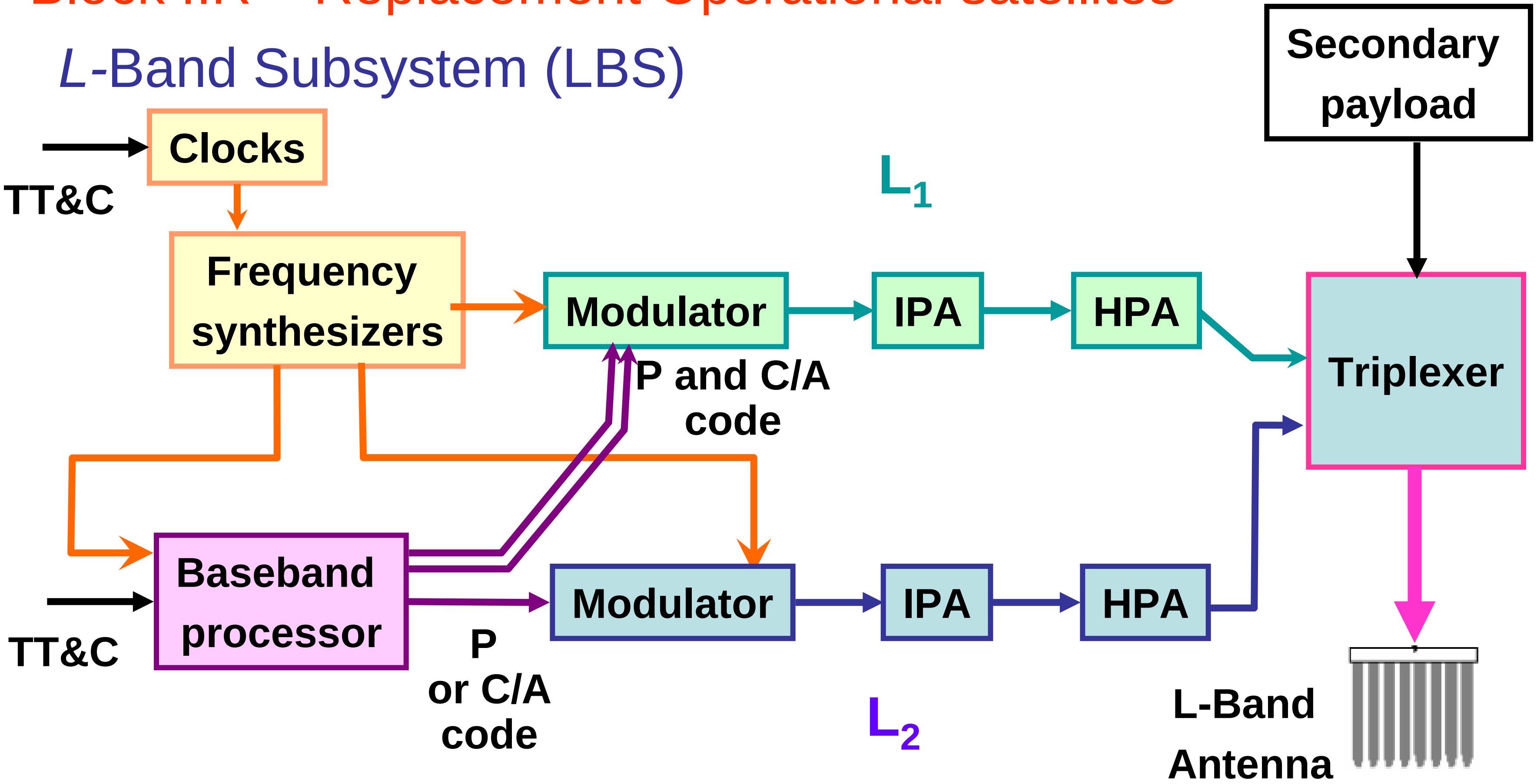


  - IPA: performs active biasing to maintain the performance over radiation, voltage, and aging

GPS Architecture – Satellites

Block IIR – Replacement Operational satellites

L-Band Subsystem (LBS)

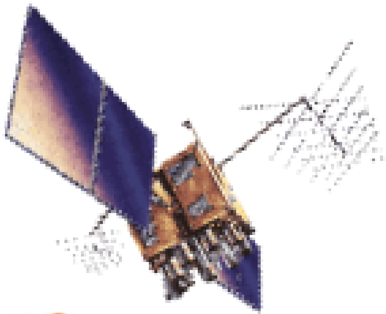


GPS Architecture – Satellites

Block IIR – Replacement Operational satellites

L-Band Subsystem (LBS):

- HPA:
  - ✓ provide the final RF amplification for transmission to Earth
  - ✓ the amplification is performed before filtering
  - ✓ high efficiency is critical (limited power available)

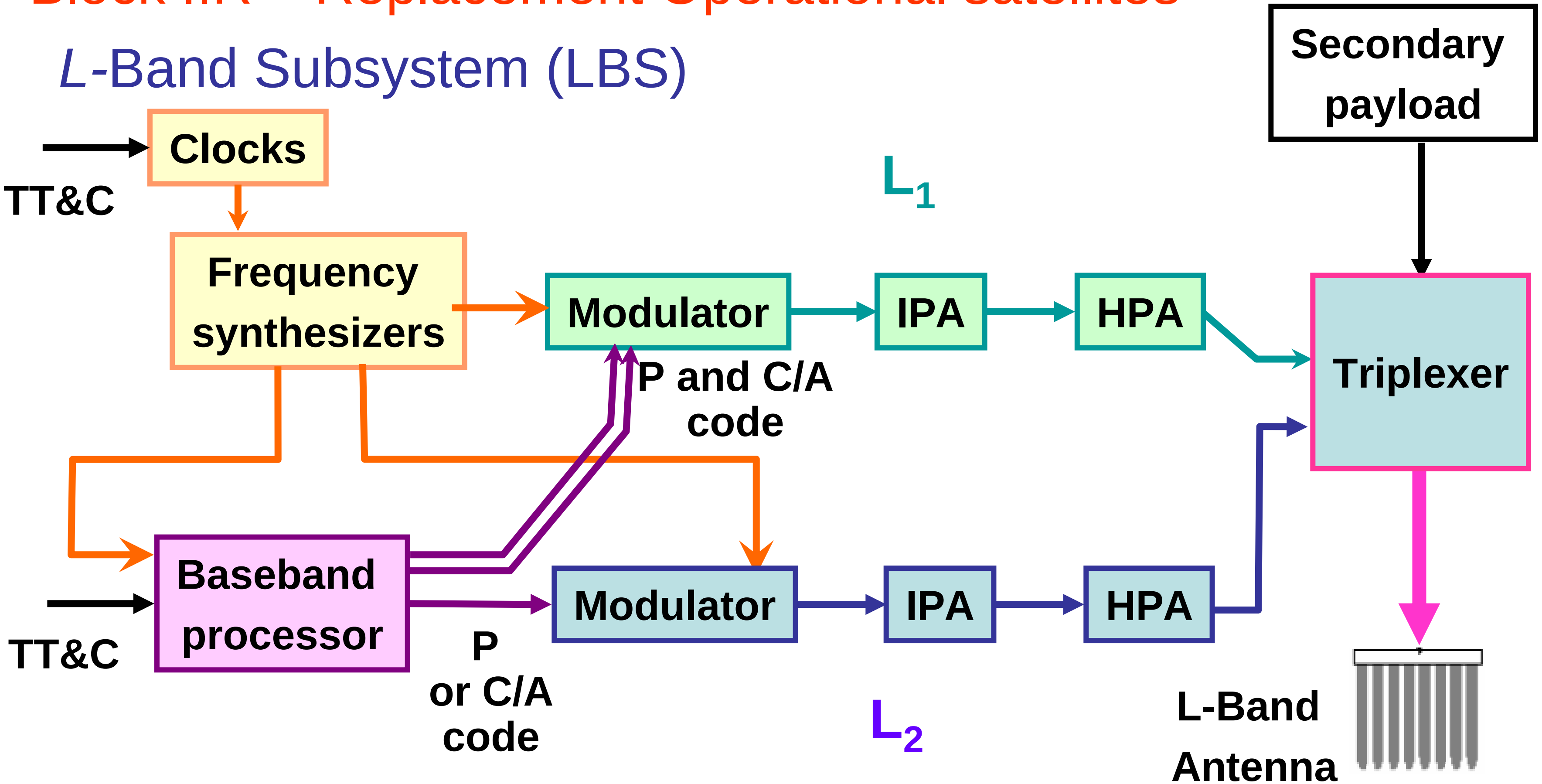


- L_1 HPA: nominal output power level of 50 W
- L_2 HPA: nominal output power level of 10W

GPS Architecture – Satellites

Block IIR – Replacement Operational satellites

L-Band Subsystem (LBS)

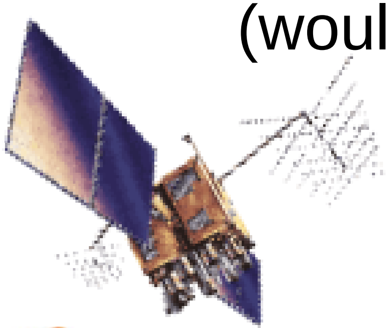


GPS Architecture – Satellites

Block IIR – Replacement Operational satellites

L-Band Subsystem (LBS):

- Triplexer:
  - ✓ filters the modulated signals and combines them into a single output
  - ✓ has extremely stable performance over temperature changes to minimize the group delay variations (would degrade URE)

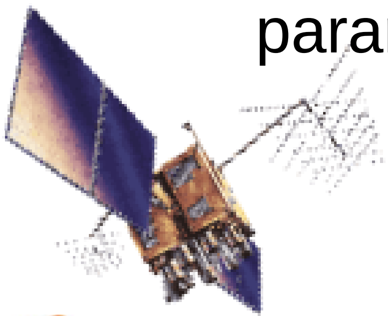


GPS Architecture – Satellites

Block IIR – Replacement Operational satellites

Crosslink Transponder Data Unit (CTDU):

- Has both data and ranging modes for direct sat-to-sat communications
- Its purpose is twofold:
  - to supply a precise ranging signal to AutoNavigation
  - to exchange AutoNav state vector (Keplerian orbit parameter and clock states) among spacecrafts



- TDMA, spread-spectrum signal in the UHF band with 108 W output power

GPS Architecture – Satellites

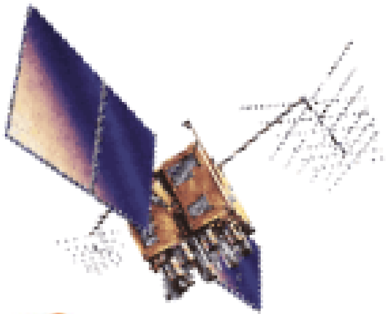
Block IIR – Replacement Operational satellites

AutoNavigation:

- Estimates ephemeris and clock autonomously
- Generates the navigation message

Why AutoNav ?

- Mitigate dependence by Control Segment (most vulnerable)
- Reduce upload requirements
- Provide an independent reference
- Improve accuracy (parameters updated 4 times an hour)



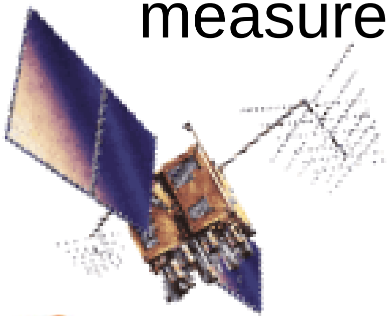
Nav&RA

GPS Architecture – Satellites

Block IIR – Replacement Operational satellites

AutoNavigation: How it works

- Satellites broadcast a ranging signal in a TDMA frame using 2 frequencies to correct errors
- On next frames satellites broadcast their pseudorange measurements (2-way ranging available) and ephemeris
- Separate clock and ephemeris Kalman filters receive the measurements from other satellites

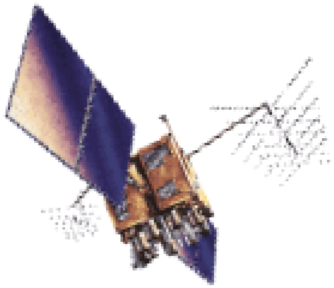


  - TDMA frame: 36 s (24 time slots of 1.5 s)
  - Each satellite is assigned 1 slot to transmit and listens on the other 23

GPS Architecture – Satellites

Block IIR-M – Modernization satellites

- Heritage Signals: Same as Blocks II/IIA/IIR
- Modernized Signals:
  - ✓ 2nd civil signal on L2 (L2C)
  - ✓ New L1 & L2 M-Code Signal (2010) with increased power and less vulnerability to signal jamming
- First Launch: 26th September 2005 (at launch site – Kennedy Space Center in Florida)



GPS Architecture – Satellites

Block IIR-M – Modernization satellites

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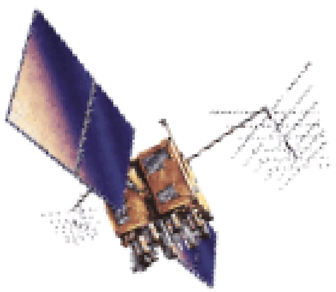
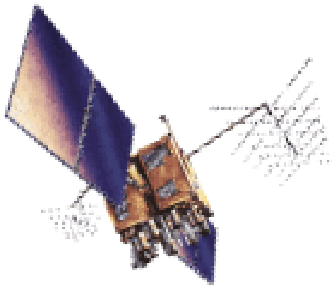


- New external antenna panel
- Re-designed Higher-Power Transmitters

GPS Architecture – Satellites

Block IIM – Modernization satellites

- Weight: 2000 Kg
- Power/Solar panels: 1136 W
- Built by Lockheed Martin
- Launch Vehicle: Delta II
- Design life: 10 years
- Unit cost: 75 M$



8 Block IIR will be modernized into IIR-M

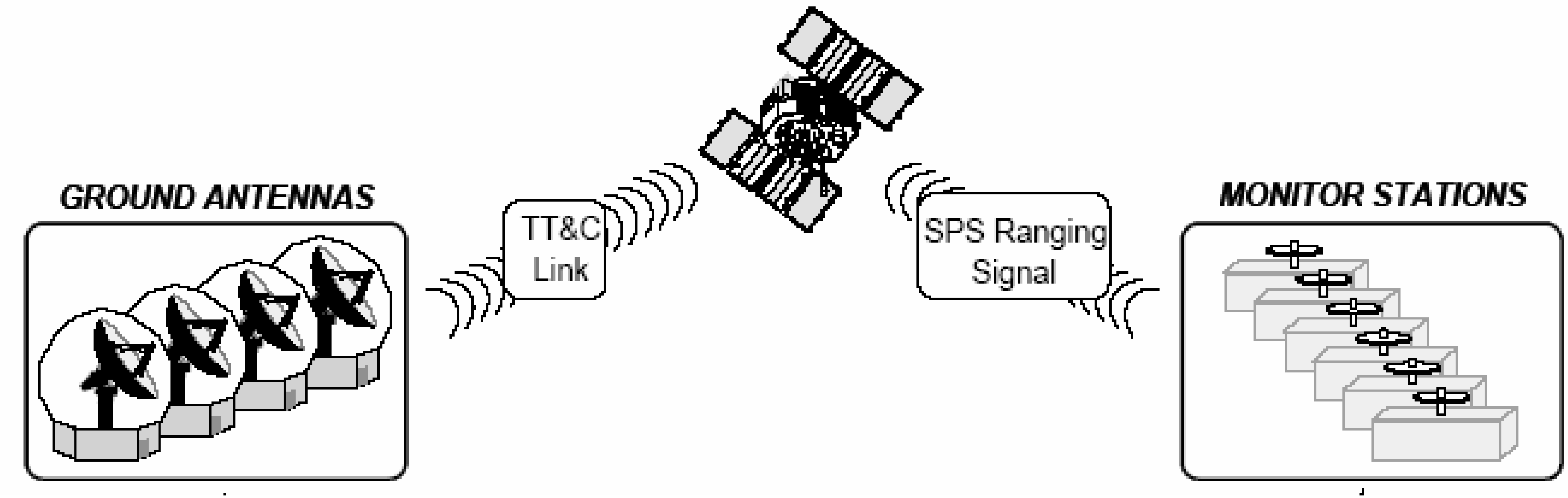
GPS Architecture – Satellites

Block IIF – Follow-on Sustainment satellites

- All the capabilities of previous Blocks
- Added a 3rd civil signal on L_5 (1176.45 MHz)
- First Launch: 2006 (forecast)
- 12-16 satellite production run

- Weight: 1560 Kg
- Power/Gallium Arsenide solar panels: 2900 W
- Launch vehicle: Delta IV and Atlas V
- Design life: 12 years
- Unit cost: 28 M$ (estimated)

GPS Architecture – Control Segment

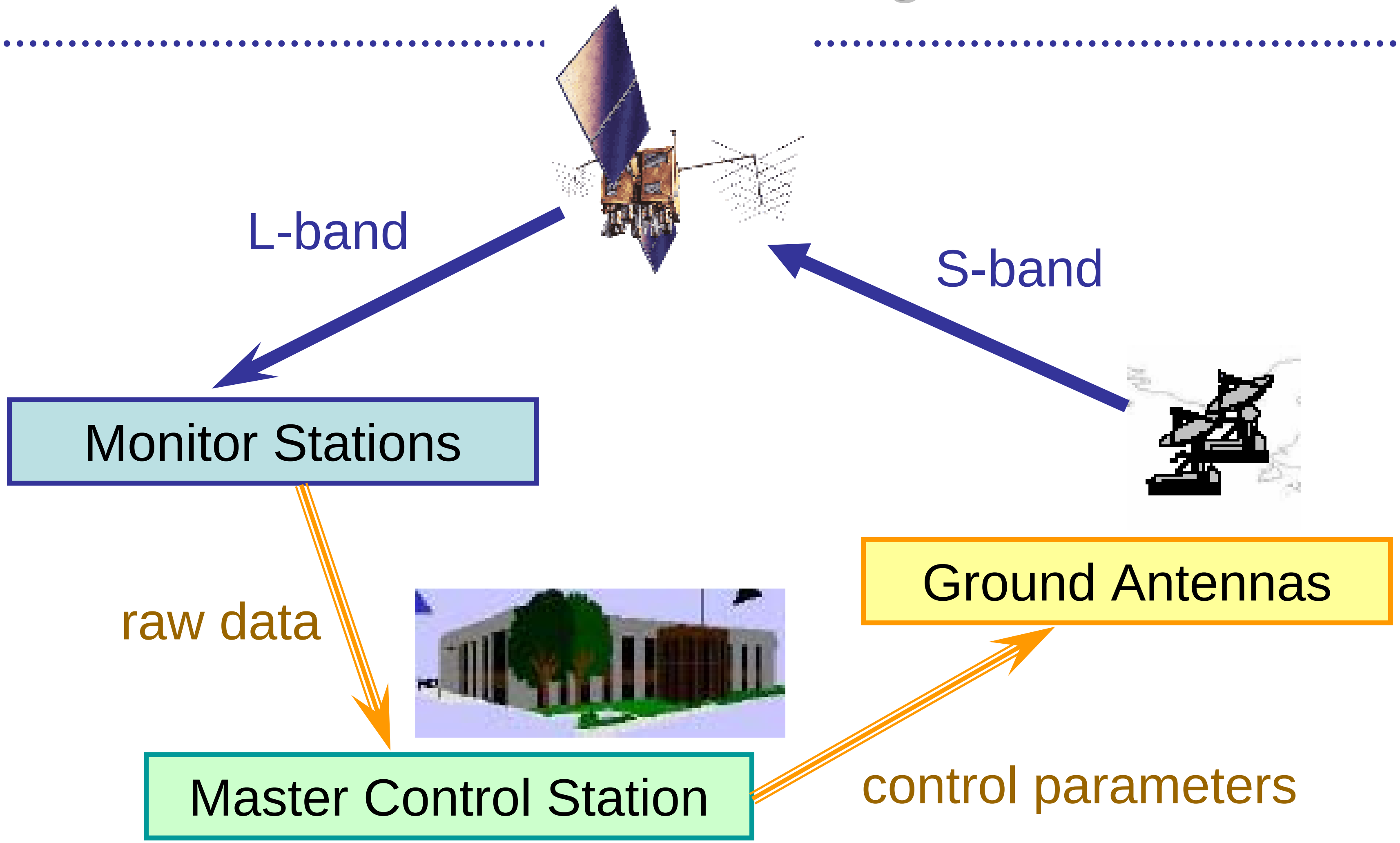


GPS Architecture – Control Segment

Objectives:

1. Maintain each satellite in its proper orbital position (station keeping)
2. Make corrections and adjustments to the satellite clocks and payload
3. Track the GPS satellites, generate and upload the navigation data to each satellite
4. Command major relocations in the event of satellite failure to minimize the impact

GPS Architecture – Control Segment



GPS Architecture – Control Segment

(Operational) Control Segment operations:

1. Monitor stations passively track GPS satellites (pseudorange and delta range measurements using L_1 and L_2)
2. Raw data + received navigation message + local weather data transmitted to Master Control Station via ground communication systems and via Defense Satellite Communications System
3. MCS processes data and monitor status of configuration of satellites and ground station
4. Data uploaded to satellites via one of the Ground Antennas

GPS Architecture – Control Segment

1985: Operational Control Segment (OCS) began operations

Master Control Station

Schriever Air Force Base

5 Monitor Stations

Hawaii

Colorado Springs

Cape Canaveral

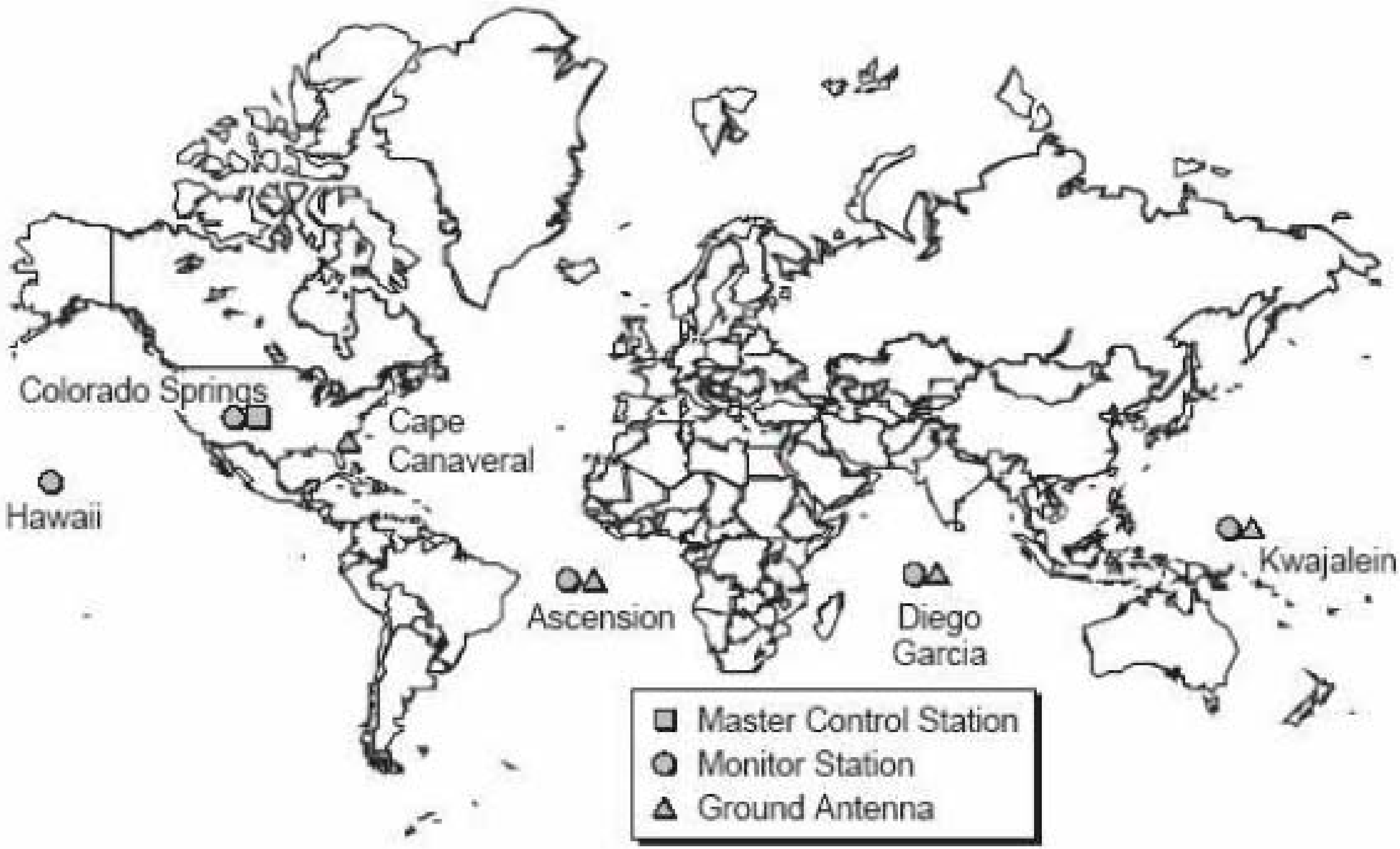
Ascension Island

Diego Garcia

Kwajalein

4 Ground Antennas

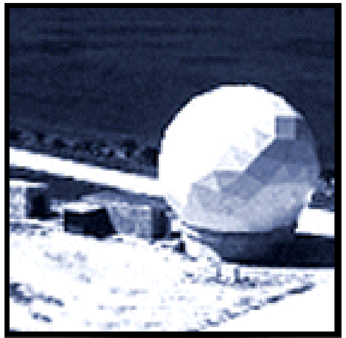
GPS Architecture – Control Segment



GPS Architecture – Control Segment

Monitor Station - It is made up of:

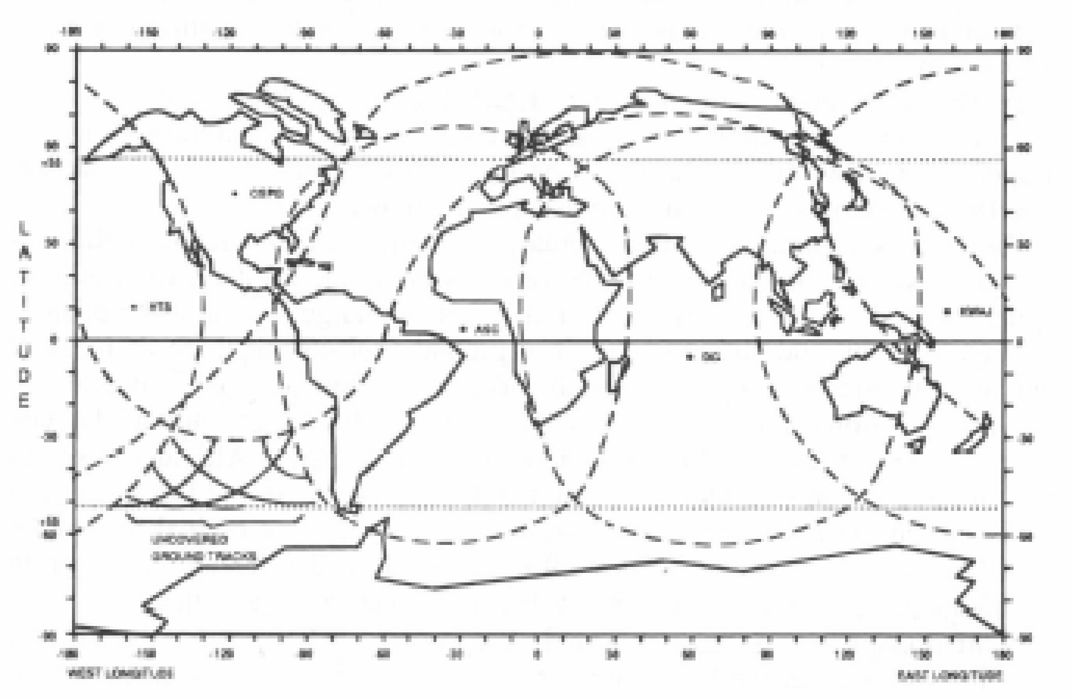
- A dual-frequency GPS receiver
- Two cesium clocks referenced to GPS system time
- Remote sensors of barometric pressure, temperature, dew point to have approximate corrections of tropospheric delay



- MS is unmanned
- 5 MS provide 92% tracking coverage of the GPS satellites
- Extended network allow all satellites to be monitored without any gap

GPS Architecture – Control Segment

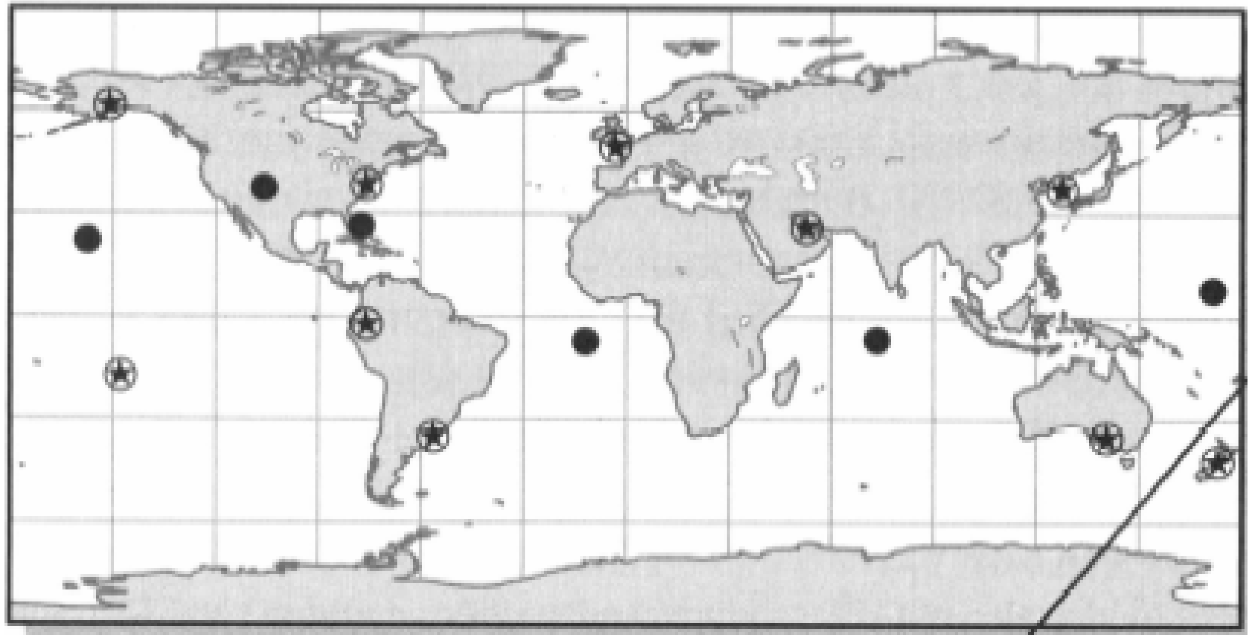
Monitor Stations tracking coverage



GPS Architecture – Control Segment

Extended Network of Monitor Stations:

10 stations of National Imagery and Mapping Agency distributed all around the world



GPS Architecture – Control Segment

NIMA network stations

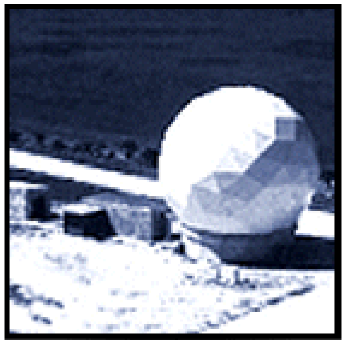
- ✓ Measurements are post-processed to generate precise ephemeris and clock parameters
- ✓ Quality control of the parameters predicted real-time
- ✓ DoD's GPS Accuracy Improvement Initiative (AII) has proposed to include a subset of NIMA measurements in real-time processing

  (operative since July 2005 – extimated improvement of 15-20%)

GPS Architecture – Control Segment

Monitor Station – Operations

- Receive the same signal structure as the user community
- Track the apparent pseudoranges and carrier phase between satellite and MS
- Collect the transmitted navigation message



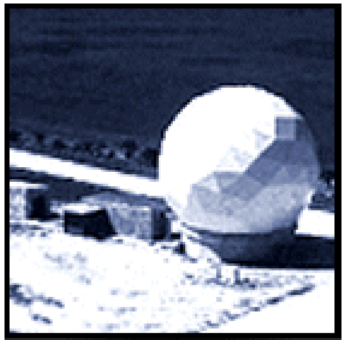
Purposes

- Provide MCS with data to derive precise ephemeris, clock calibration data for each satellite and service info to be sent to users

GPS Architecture – Control Segment

Monitor Station – Operations

- Performance must exceed that of a high-precision user
- MS receiver must accommodate and detect abnormal signal structures



Dedicated and secure communication channels (duplex) between MS and MCS:

- Tracking orders are received from MCS
- Measurements and status data are sent to MCS

GPS Architecture – Control Segment

Ground Uplink Antenna Facility

- Upload navigation message, commands and telemetry data to satellites
- 10 m *S*-band antennas are used

- Antenna at Cape Canaveral used only to verify system compatibility during pre-launch operations and for emergencies due to severe restriction on radio frequency transmissions at launch sites

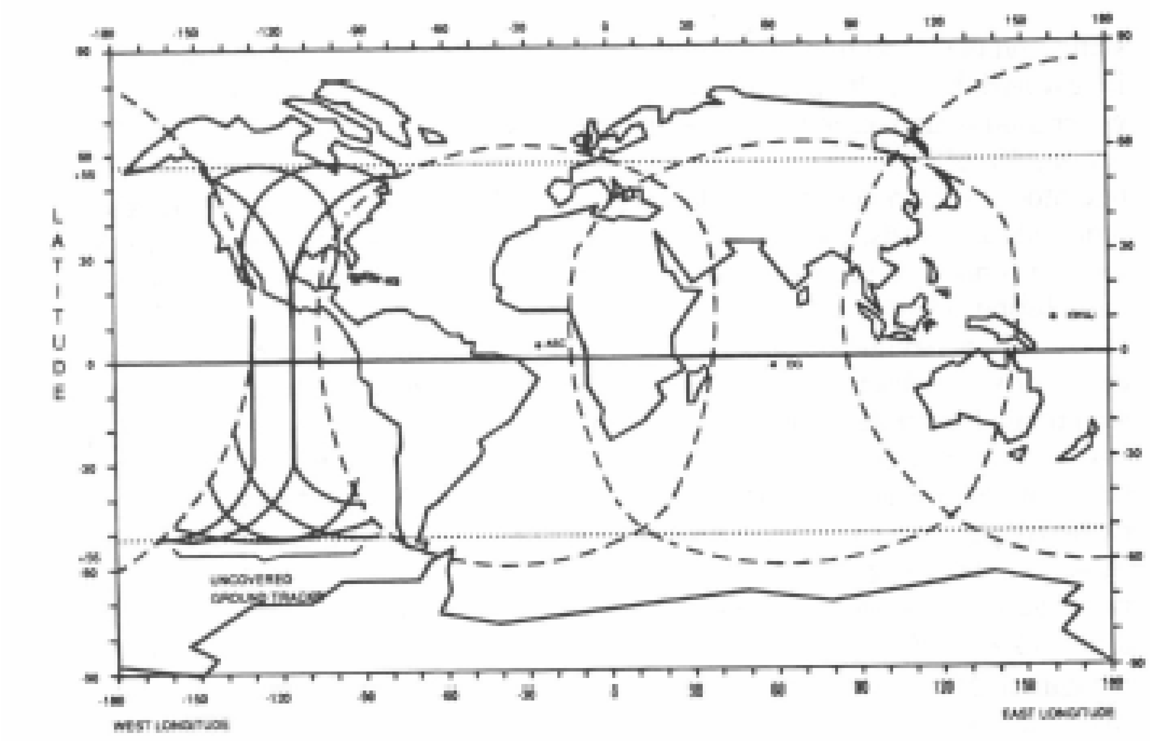
GPS Architecture – Control Segment

Ground Uplink Antenna Facility – Operations

- A unique TT&C data set is prepared by the MCS for each satellite
- TT&C (Telemetry, Tracking and Command) and navigation data received over secured channels
- Ground Antenna processor stores data until the satellite is in view
- Once satellite in view, S-band data uplink (full-duplex) is used
- GA locations have been selected to maximize satellite coverage

GPS Architecture – Control Segment

Ground Uplink Antenna Coverage

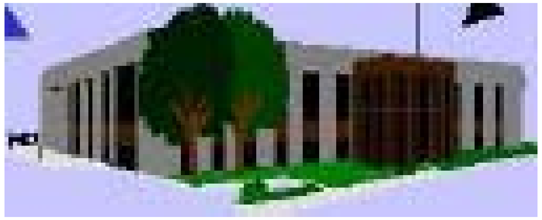


GPS Architecture – Control Segment

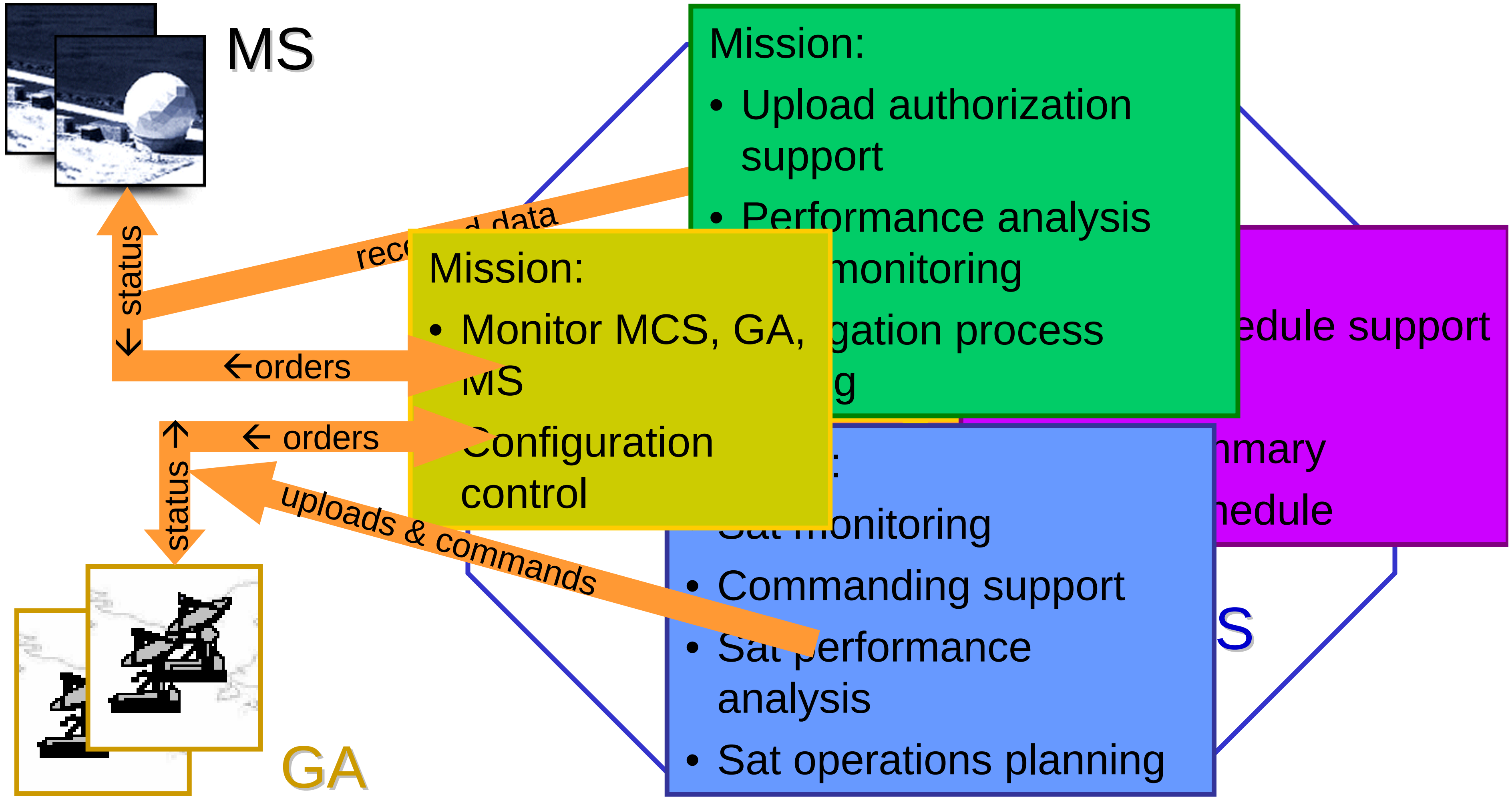
Master Control Station

Functions

1. Monitor satellite orbits
2. Monitor and maintain satellite health
3. Maintain GPS Time
4. Predict satellite ephemeris and clock parameters
5. Update satellite navigation messages
6. Command small maneuvers of satellites to maintain orbit
7. Command relocations to compensate for failures



GPS Architecture – Control Segment



GPS Architecture – Control Segment

Master Control Station

Navigation Operations

- Processing of MS data to evaluate correction of pseudorange measurements for tropospheric and ionospheric delays
- The corrected pseudorange measures from all the MSs are processed by an epoch-state Kalman filter to have a precise satellite ephemeris and clock offset solution at the time of the data collection.
- The filter is updated every 15 minutes with the satellite positions

GPS Architecture – Control Segment

Master Control Station

Navigation Operations

- The estimations must be predicted forward to be of use to GPS users at some later time (prediction interval)

- FORCE INTEGRATION:
    - model made of a set of differential equations describing the dynamic behaviour of the satellite
    - forces operating on the satellite: gravity field perturbations, sun and moon third-body mass attractions, solar radiation pressure on the space vehicle, Earth polar motion perturbations

GPS Architecture – Control Segment

Master Control Station

Navigation Operations

- Prediction interval: divided into 4-hr or 6-hr time intervals
- For each sub-interval: predicted satellite Cartesian position data transformed to 15 orbital elements using a least squares fit algorithm
- Almanac and clock data formed by this accurately predicted data

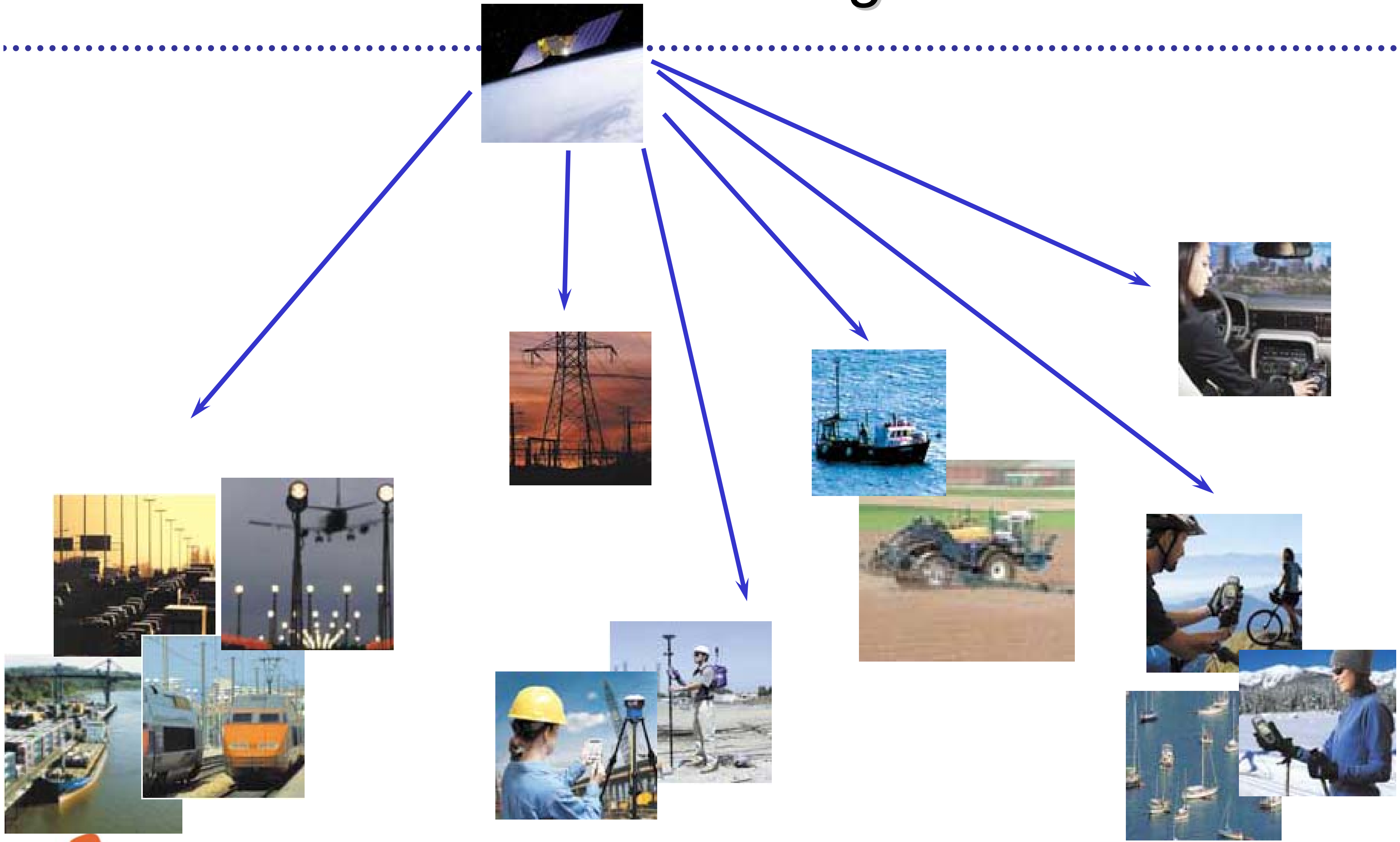
GPS Architecture – Control Segment

Master Control Station

Navigation Operations

- Navigation message: formed by scaling and truncating ephemeris, almanac, and clock data to the proper format
- Data are sent to Ground Antenna for upload
- Normally 1 upload/day – Max 3 times/day

GPS Architecture – User Segment



GPS Architecture – User Segment

GPS Receivers

Mid-1980s: first precise positioning receiver

Prized over $100.000

Now: receivers with higher performances

Prized < $10.000

1992: first hand-held receiver (< $1000)

1997: pocket-size receiver running with two AA batteries (< $100)

2000: wristwatch receiver priced at $500

End of Part VII