
OHIO STATE
BUCKEYES

THE OHIO STATE UNIVERSITY COLLEGE OF ENGINEERING

Workshop on

Global Positioning System (GPS)

THE EARLY DAYS

by

Edward H. Martin

Goodbye, Columbus

June 7th 1957--- for the 2163 members --- class of 1957

"To you Ohio State, to you Columbus---
we say…
Thank you and goodbye. We will miss you,
In the fall, in the winter, in the spring,
But someday… we will return."

Philip Roth, May 1959---Winner National Book Award

The Dawn of Satellite Navigation

- 4 October 1957 – Sputnik
- US Failures and Success (31 January 1958)
- Guier and Wiefenbach (APL)
  - Doppler Signature Unique
  - Single Pass Orbit Determination

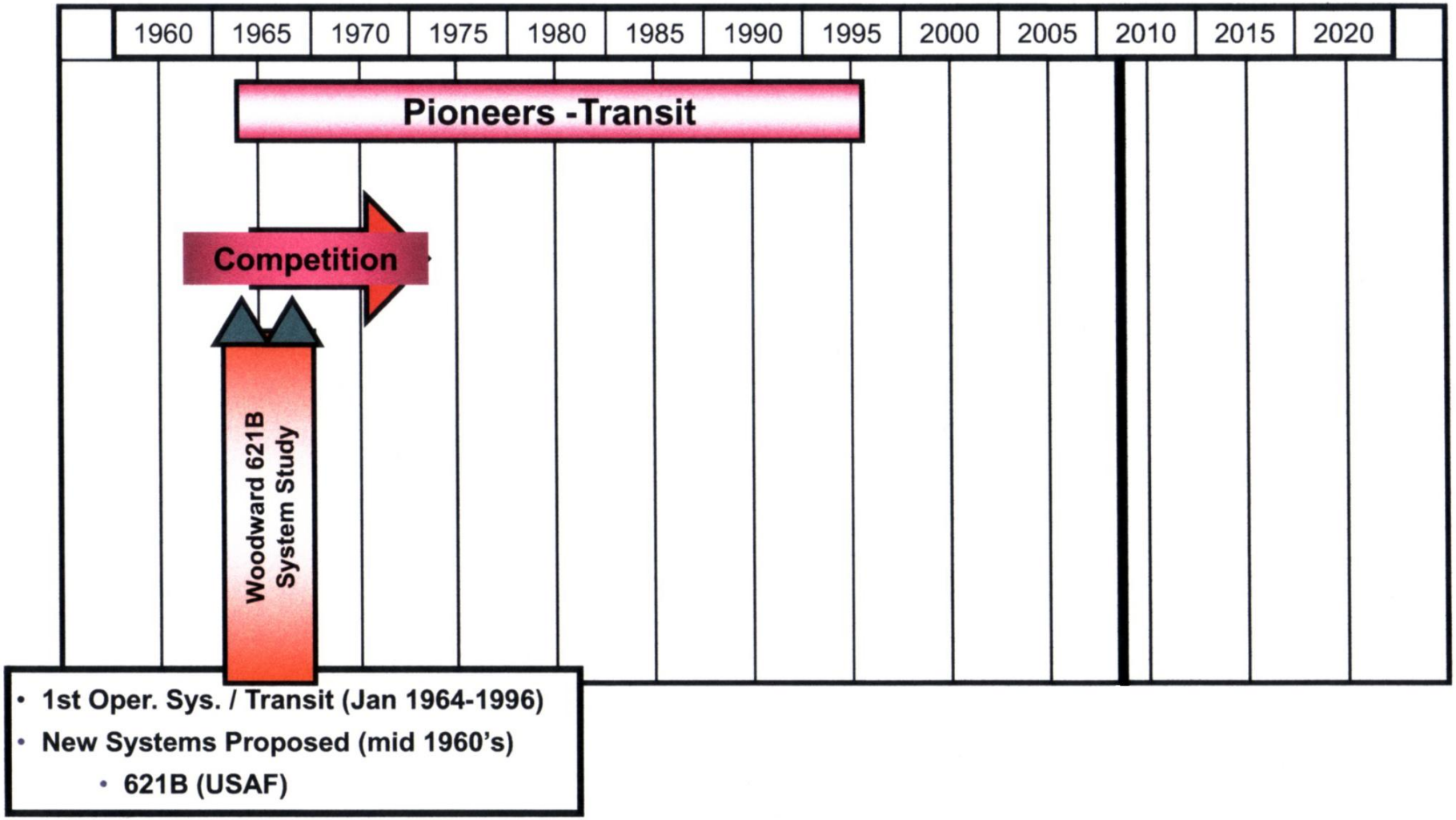
George Wiefenbach
and
William Guier

POST SPUTNIK
KEY TECHNOLOGY EVENTS

- Aug 1958: Nautilus INS transits the North Pole
- 1959: First Navy/APL TRANSIT satellite is launched
- 1960-61: Kalman/Bucy publish Optimal Estimation Paper
- May 1960: Optical Pulsed Laser developed by Hughes AC
- 1962: SINS/LORAN updating patent with KF estimation
- Jan 1964: Navy TRANSIT declared operational
- July 1967: VP Humphrey opens TRANSIT for civilians

Note the dichotomy of a military satellite Navigation system for upgrading Navy SLBM Missions evolving into a civilian commercial product in less than ten (10) years.

The Eras of Satellite Navigation



Competing USAF Space Systems

1964: SSD/Aerospace Corp. define need for a new navigation satellite system

June 1965: Study initiated by J. Woodford/H. Nakamura

Dec 1965: Initial views given to WPAFB resulted in tactical weapon delivery accuracy improvement needs.

July 1966: Study and technical plan completed with 621B Concept of 4 geosynch orbits and CDMA ranging.

1968: DoD establishes NAVSEG, a tri-service executive to manage competing studies and contracts in future concepts for frequency selection, ranging signal structure, and orbit selection and ephemeris tracking.

1971-72: User test sets with L-band PRN codes are evaluated at the White Sands with 4 ground and a ballon-borne transmitter array with position errors of a few meters!

SCOPE

- ALL MILITARY OPERATIONS REQUIRING POSITION FIXING ARE POTENTIAL USERS OF THE NAVIGATION SATELLITE SYSTEM
- THE PRIMARY SYSTEM OBJECTIVE IS TO SATISFY THE NEEDS OF TACTICAL OPERATIONS
- THE MOST CRITICAL TACTICAL USER IS THE HIGH SPEED MANEUVERING AIRCRAFT DELIVERING CONVENTIONAL WEAPONS AND STORES
- THE CURRENT STUDY IS DIRECTED ESPECIALLY TO THE TACTICAL AIRCRAFT NEEDS, BUT OTHER USER NEEDS ARE ALSO CONSIDERED

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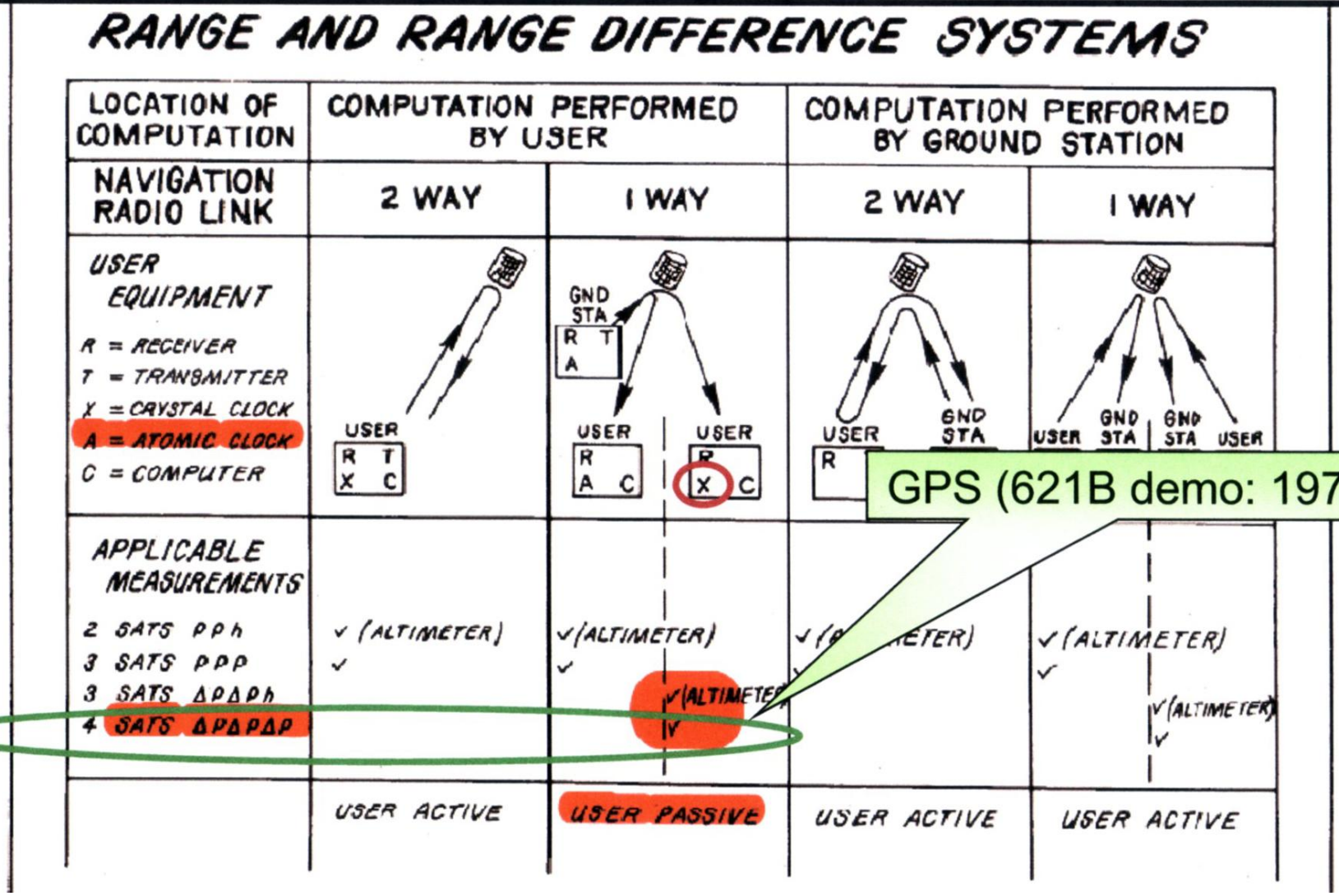
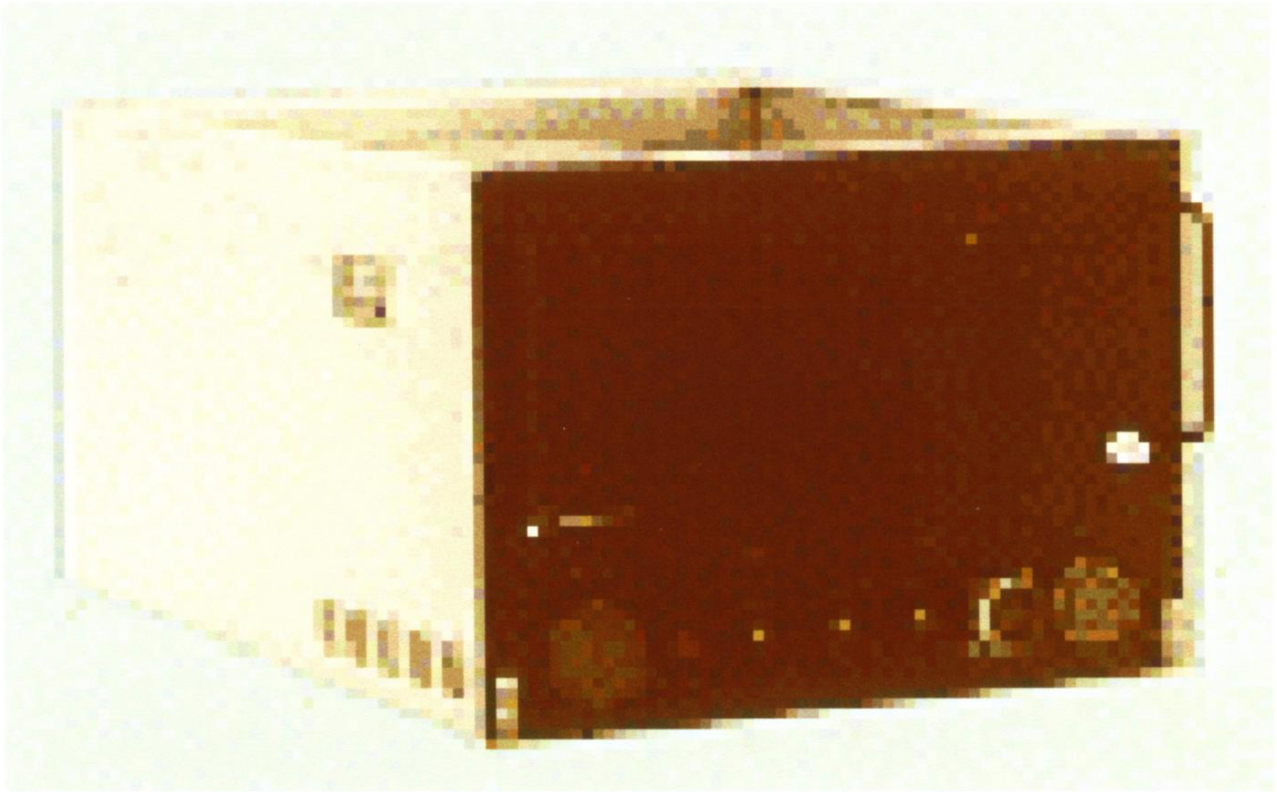
USAF/621B Woodford Study –

Alternative Passive Ranging Techniques (1966)



UE History

First Spread Spectrum Nav. Receiver



MX-450

1969

Stansell Consulting

Welcome To:

THE MILITARY / INDUSTRIAL COMPLEX

- ✓ **Hughes Aircraft Company 1957 – 1959**
- ✓ **F-102/ MG-10 Flight Test Line – 3 AFB's**
- ✓ **US Air Force, Dayton, Ohio 1959 – 1963**
- ✓ **GS – 13 Research Engr. & MSEE 1963 – 1964**
- ✓ **North American Autonetics 1964 – 1972**
- ✓ **Applied Research Engr. Tactical Aircraft Navigational and weapon guidance design For F-111, C-5, and F-15 Inertial Systems.**

JUNE 1972 - GOING INTO SPACE

-Left: close group of friends and Mentors at Autonetics:
Dr Blair Bona, Dr Tom Devries, Dr Tom Gunkel

-New Task: Product Development Manager
Military Navigation Satellites
Magnavox Research Labs

-New Customers: Naval Research Lab, Roger Easton
Air Force 621B Program, XR Plans
-New Mentors: Dr Charles Cahn, Bert Glazer

NOV 1972 - Lt. Col. Brad Parkinson is assigned to command AF 621B

JOINT PROGRAM OFFICE for TRI-SERVICE "PURPLE TEAM"

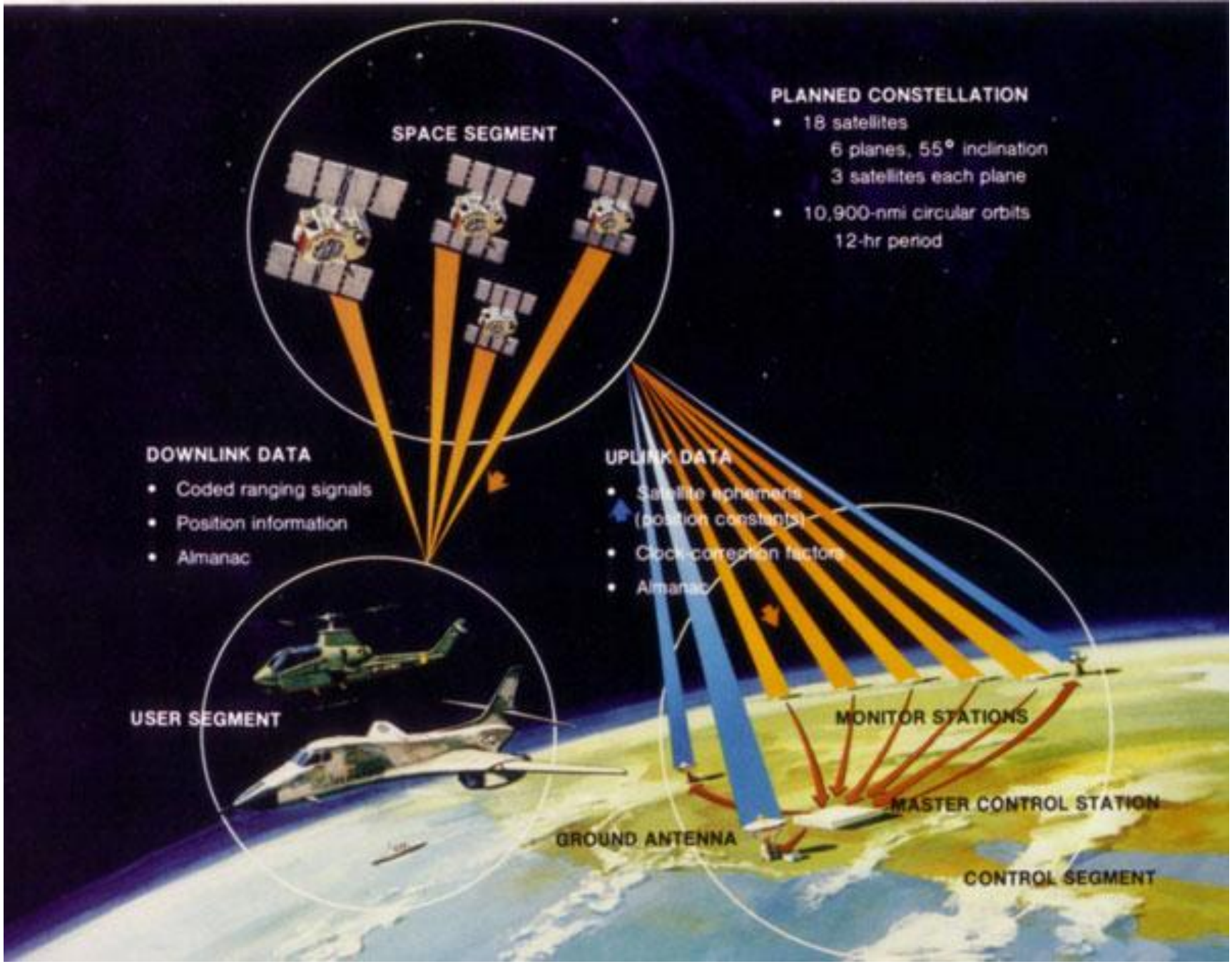
April 1973 DOD stipulates consolidation of Nav concepts into a single Military system. Col. Parkinson is named JPO Director.

August 17, 1973 Initial review of 621B/24 hr Synch Orbit design is denied approval for lack of alternative concept consensus.

Sept 1973 Labor day weekend at the Pentagon with 25 military officer staff results in "new" concept 7 page DCP presentation.

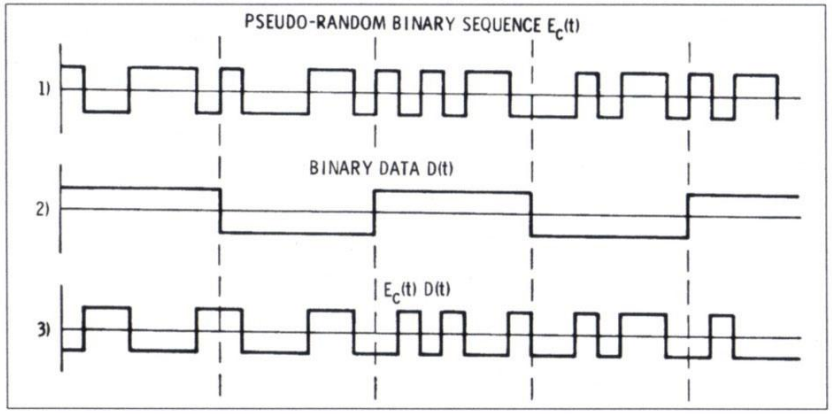
Dec 14, 1973 The NAVSTAR GPS concept is approved at the DSARC 1 Meeting with a 24 satellite configuration placed in about 12 hour (717.973 minutes) inclined orbits.

Jan 1974 Competition begins for the three segment contract designs that would be termed Phase I Concept Validation during the next 6 years from 1974 through 1980.


SPACE SEGMENT
PLANNED CONSTELLATION
• 18 satellites
6 planes, 55° inclination
3 satellites each plane
• 10,900-nmi circular orbits
12-hr period
DOWNLINK DATA
• Coded ranging signals
• Position information
• Almanac
UPLINK DATA
• Satellite ephemeris (position constants)
• Clock-correction factors
• Almanac
USER SEGMENT
MONITOR STATIONS
MASTER CONTROL STATION
GROUND ANTENNA
CONTROL SEGMENT

BASELINE SIGNAL DECISIONS FOR GPS

PRN CODE C/A = 1023 Bit GOLD CODE @ 1.023 Mhz RATE
PRN CODE P = 7-DAY, 1.5 Sec PRODUCT CODE @ 10.23 Mhz RATE



DATA MESSAGE @ 50 BPS
MESSAGE LENGTH = 1500 Bit
SYSTEM TIME EPOCHS @ 1.5 Sec
Z-COUNT = 403,200/Week
DATA MODULO-2 ADDED + CODES

BASE FREQUENCY = 10.23Mhz
L1 CARRIER = 154 X 10.23 Mhz
L2 CARRIER = 120 X 10.23 Mhz
SATELLITE MINIMUM POWER
@ L1 C/A= -160 DBw, L1P=-163 DBw,
L2 P = -166DBw

Code Period Trade vs Bit Length

	511	1023	2047
Peak X-Corr (any doppler)	-18.6	-21.6	-24.6
Peak X-Corr (zero doppler)	-23.8	-23.8	-29.8
Prob of Worst case doppler	0.5	0.25	0.5
Acquisition Time	25sec	50sec	100sec

PHASE I SATELLITE CONTRACT

Awarded to Rockwell International Space Div in June ’74.

- **Provided Space-Hardened Rb and Cs atomic clocks**
- **Operation at 12 hour period (10,900nm) @ 63 degrees**
- **Four initial satellites to be operational for 5 years**

Total contract delivered 11 NDS vehicles for flight, with the 12th being a Phase II prototype for Shuttle launch, with improved survivability.

The last 5 vehicles included Nuclear Detection payloads and insured coverage for Navy Trident tracking tests.

Atomic Clock Requirement

- Critical need for stability over one day.

  24 hours = 86,400 seconds

And one nanosecond = 1 x 10^{-9}sec ≈ 30 cm of range

For a ranging error of no more than 3.0 meters

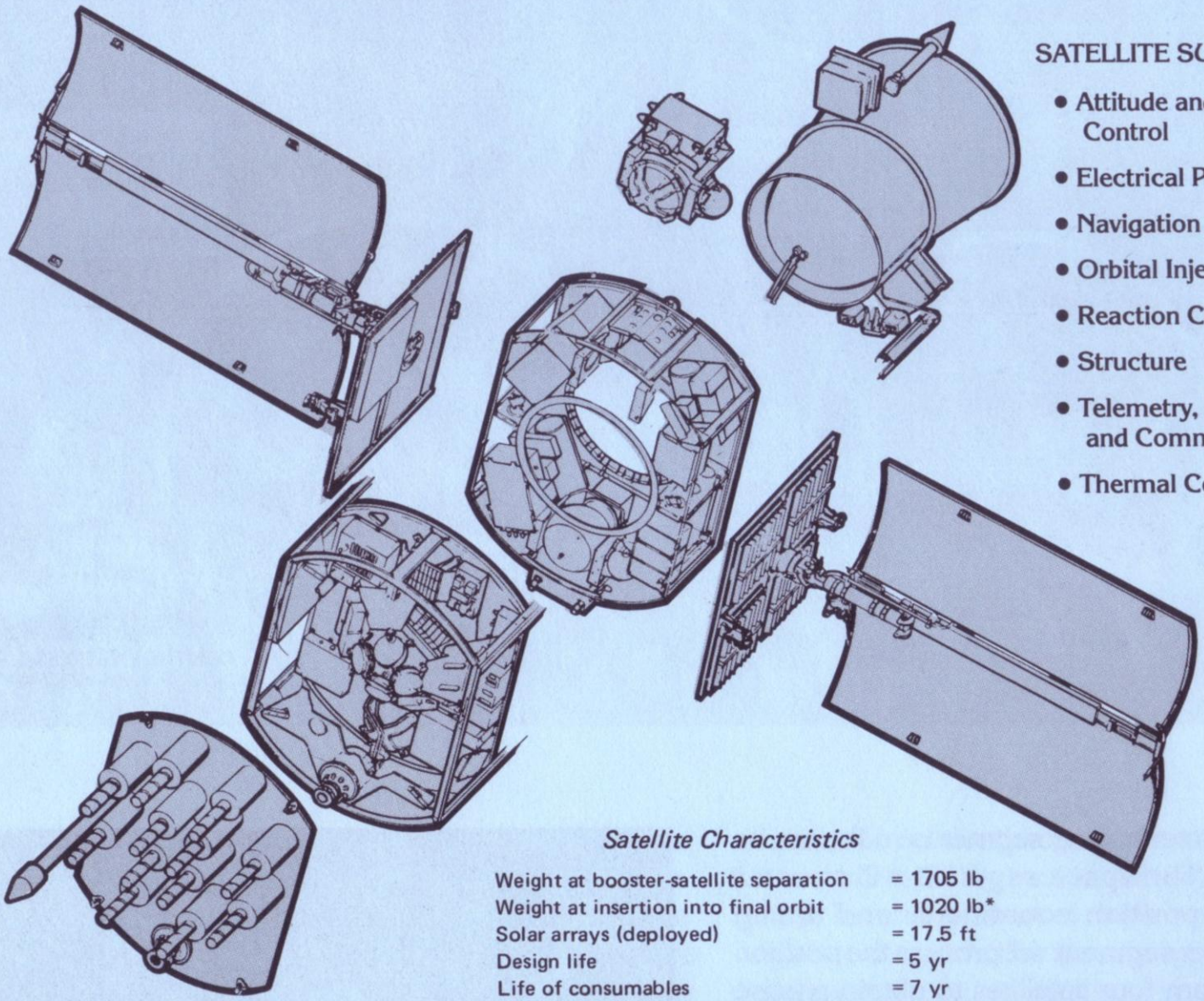
Δt = allowable drift = 10 nanosec. = 10 x 10^{-9}sec

$$\text{Required clock stability} = \frac{10 \times 10^{-9}\,\text{sec}}{86{,}400\ sec} = 1.157 \times 10^{-13}$$

- Phase I Rockwell/Efratom Rubidium clock

  Demonstrated stability of 2 x 10^{-13} / day

  With subsequent Cesium at 1 x 10^{-13} / day



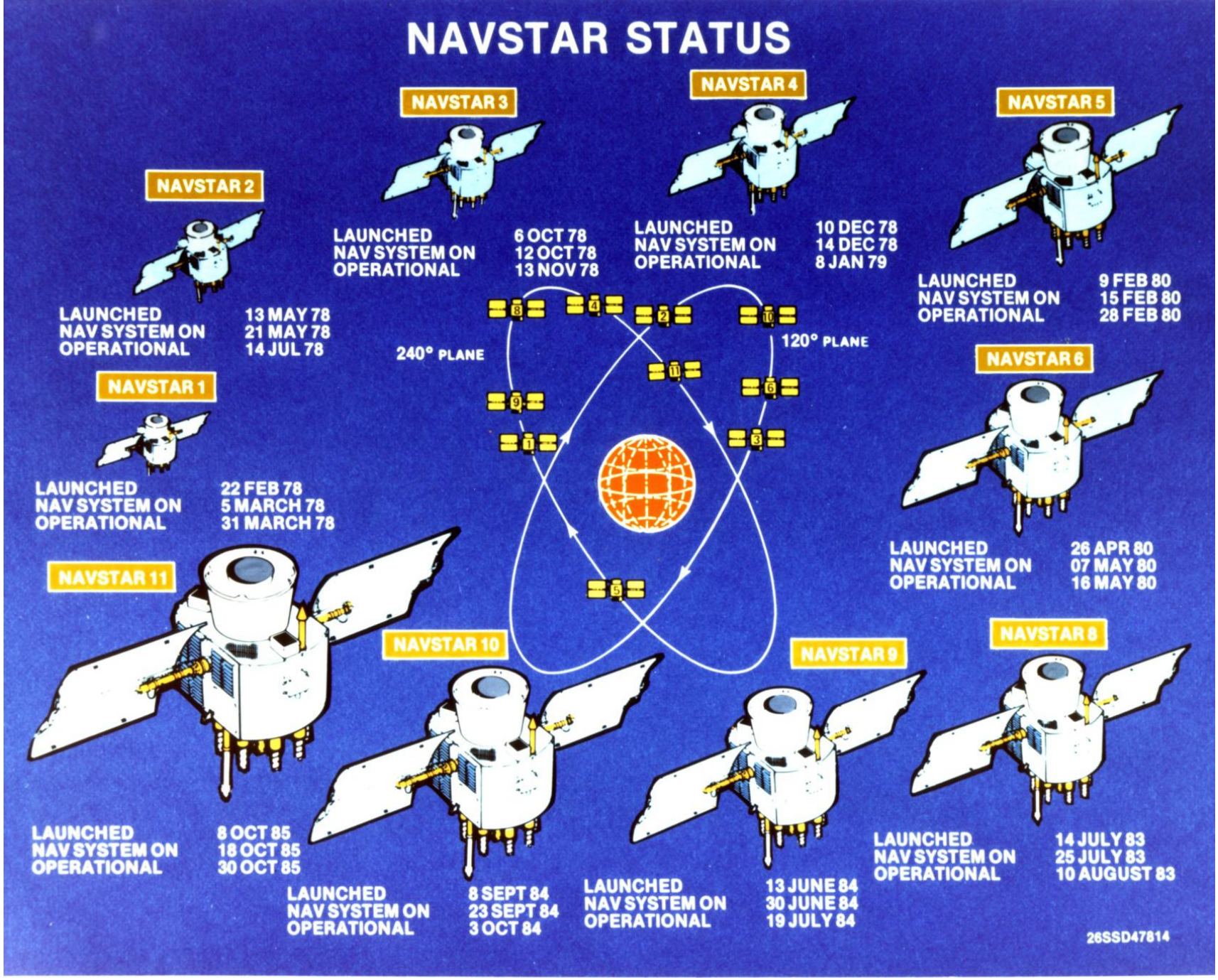
SATELLITE SUBSYSTEMS

- Attitude and Velocity Control
- Electrical Power
- Navigation
- Orbital Injection
- Reaction Control
- Structure
- Telemetry, Tracking, and Command
- Thermal Control

Satellite Characteristics

Weight at booster-satellite separation	= 1705 lb
Weight at insertion into final orbit	= 1020 lb*
Solar arrays (deployed)	= 17.5 ft
Design life	= 5 yr
Life of consumables	= 7 yr

**Includes weight of apogee kick motor's empty case (55 lb)*


NAVSTAR STATUS
NAVSTAR 1
LAUNCHED 22 FEB 78
NAV SYSTEM ON 5 MARCH 78
OPERATIONAL 31 MARCH 78
NAVSTAR 2
LAUNCHED 13 MAY 78
NAV SYSTEM ON 21 MAY 78
OPERATIONAL 14 JUL 78
NAVSTAR 3
LAUNCHED 6 OCT 78
NAV SYSTEM ON 12 OCT 78
OPERATIONAL 13 NOV 78
NAVSTAR 4
LAUNCHED 10 DEC 78
NAV SYSTEM ON 14 DEC 78
OPERATIONAL 8 JAN 79
NAVSTAR 5
LAUNCHED 9 FEB 80
NAV SYSTEM ON 15 FEB 80
OPERATIONAL 28 FEB 80
NAVSTAR 6
LAUNCHED 26 APR 80
NAV SYSTEM ON 07 MAY 80
OPERATIONAL 16 MAY 80
NAVSTAR 8
LAUNCHED 14 JULY 83
NAV SYSTEM ON 25 JULY 83
OPERATIONAL 10 AUGUST 83
NAVSTAR 9
LAUNCHED 13 JUNE 84
NAV SYSTEM ON 30 JUNE 84
OPERATIONAL 19 JULY 84
NAVSTAR 10
LAUNCHED 8 SEPT 84
NAV SYSTEM ON 23 SEPT 84
OPERATIONAL 3 OCT 84
NAVSTAR 11
LAUNCHED 8 OCT 85
NAV SYSTEM ON 18 OCT 85
OPERATIONAL 30 OCT 85
240° PLANE
120° PLANE
26SSD47814

PHASE I USER EQUIPMENT CONTRACT

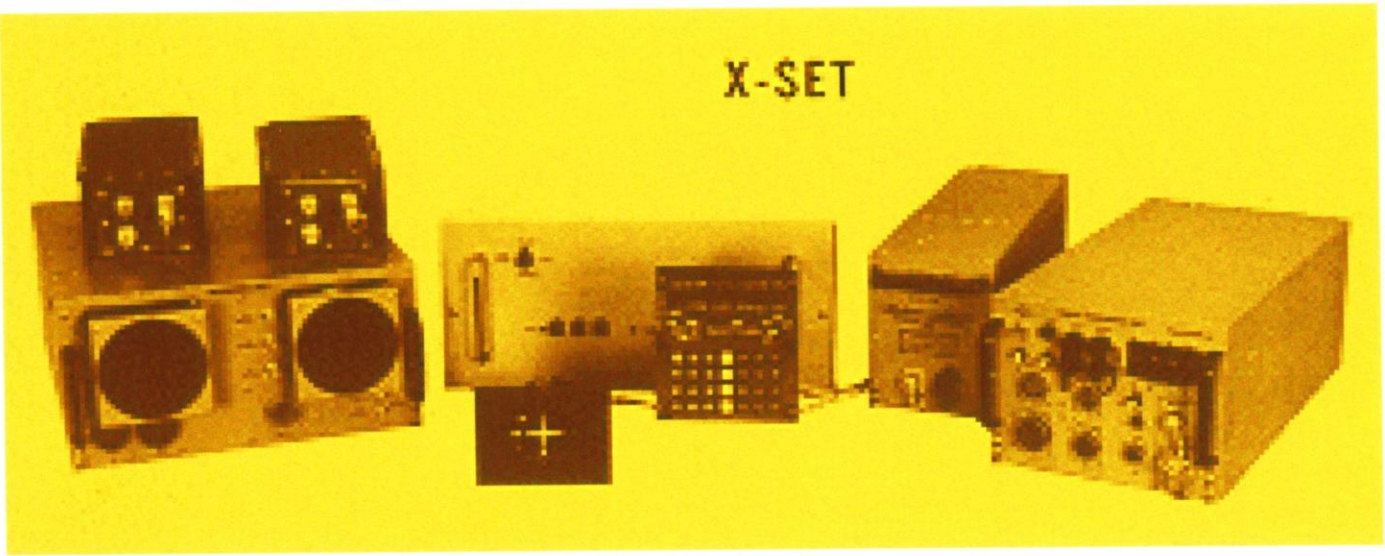
Combined CS/UE awarded to General Dynamics/Magnavox on Sept 18, 1974 to insure exact signal data interfaces and timing.

-User set design based on passive pseudo ranging to 4 or more satellites, with similar CS tracking at 4 monitor locations.
-Fixed carrier frequency with CDMA satellite unique PRN codes for a clear C/A signal, and a protected military P code.
-Data messages providing SV orbit and timing with low rate inversions of both codes.
-Dual frequency allocations to avoid ionospheric delay errors.

Proposal definitions of an X, Y, Z and Manpack family of User sets was pursued with INS-aided AJ goals emphasized.

UE History

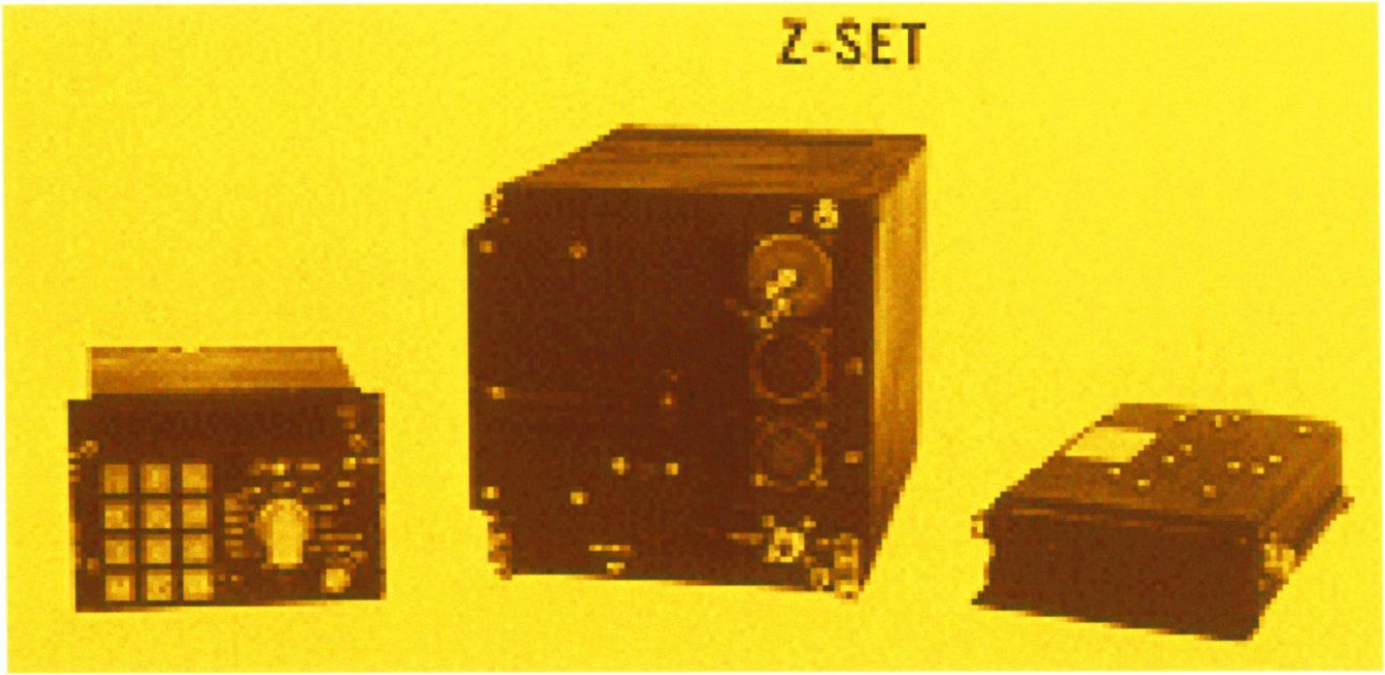
Phase I GPS X-Set



1975

UE History

Phase I GPS Z-Set

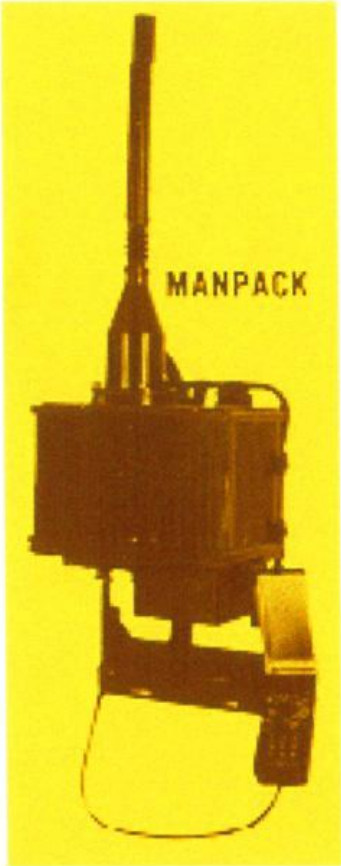


1975

Stansell Consulting

UE History

GPS Phase I Manpack



1975

System error budget (Block II)

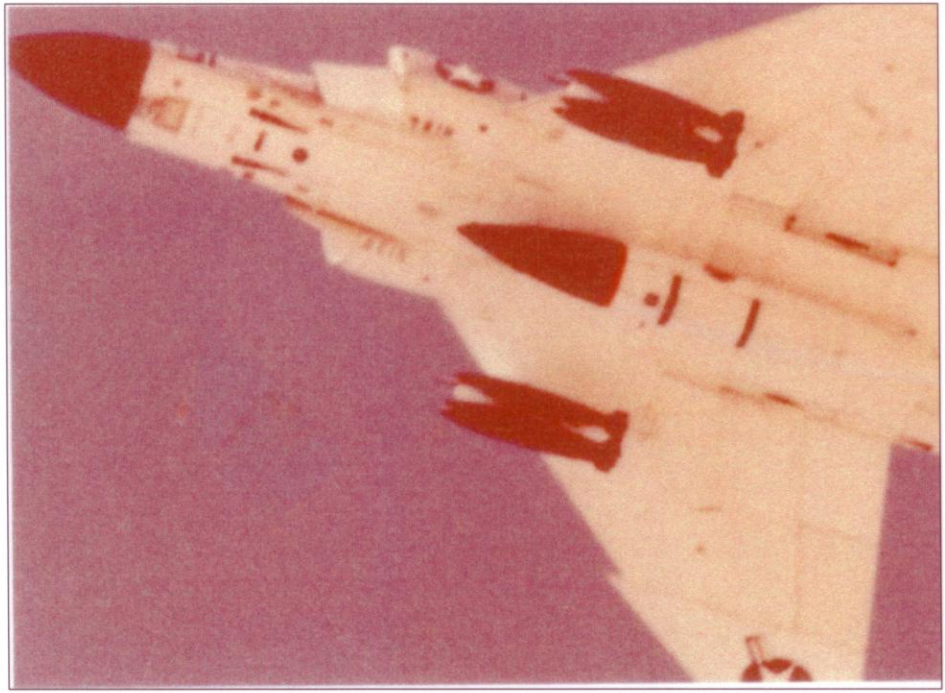
Error Sources	User range error (1σ), m
Space segment	
Clock and navigation subsystem stability	**3.0**
L-Band phase uncertainty	**1.5**
Predictability of SV parameters	**1.0**
Other	**0.5**
Control Segment	
Ephemeris prediction and model implementation	**4.2**
Other	**0.9**
User segment	
Ionosperic delay compensation	**2.3**
Tropospheric delay compensation	**2.0**
Receiver noise and resolution	**1.5**
Multipath	**1.2**
Other	**0.5**
Total (root-sum-square) rss URE	**6.6**

PROGRAM OFFICE INNOVATIONS

- ✓ JPO handled overall integration and segment interfaces
- ✓ Deputy managers from all services, DMA, & Coast Guard
- ✓ Launch by refurbished Atlas F and VAFB facilities
- ✓ Expanded User set competition with 3 contractors
- ✓Imposition of Structured Software, and HOL algorithms

------and a focused mission imperative as a Motto:

The mission of this Program is to:
• Drop 5 bombs in the same hole, and
• Build a cheap set that navigates,
and don't you forget it!



PHASE II FULL SCALE DEVELOPMENT

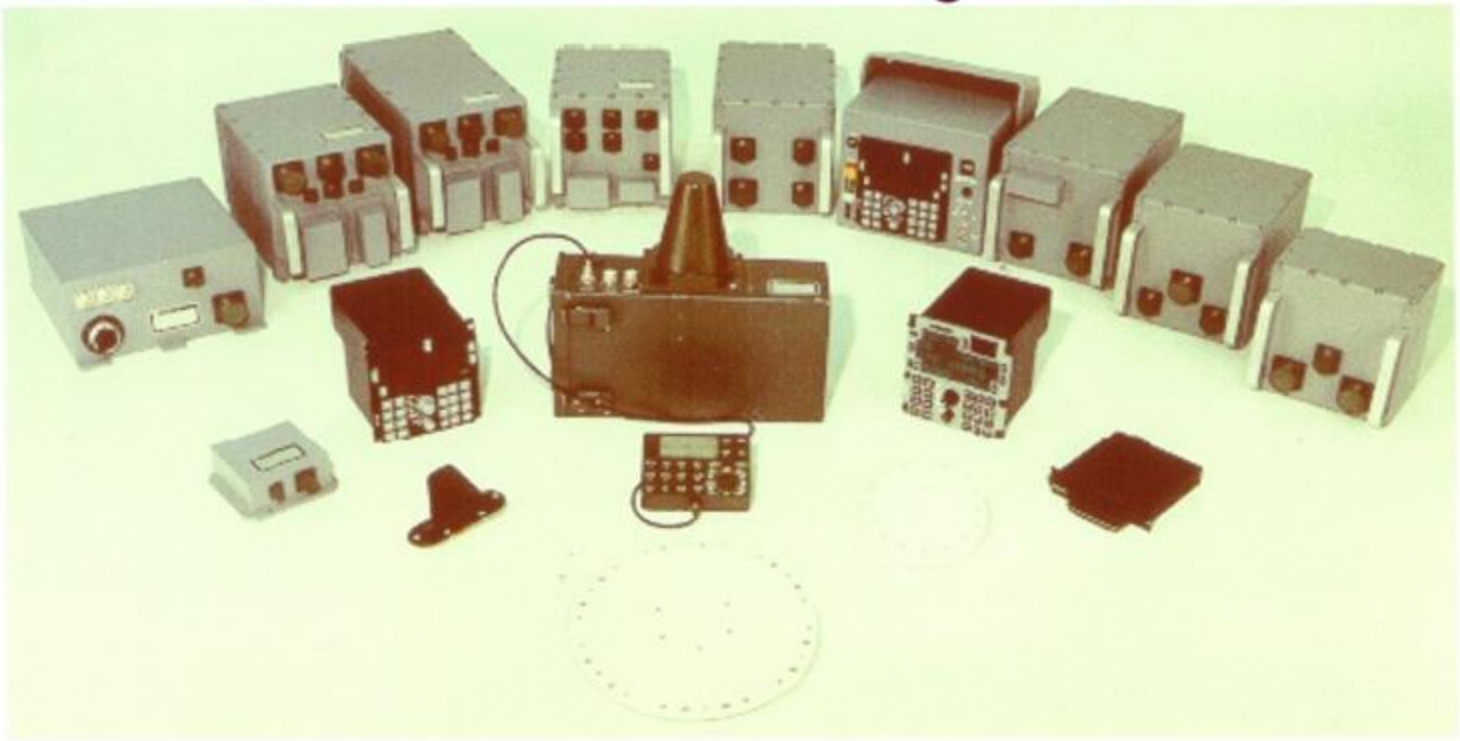
JULY 1979 Dual 50 month contracts are awarded for military form, fit, and function user equipment for environmental and mission effectiveness testing to: Rockwell International, Collins Govt. Avionics Div. and Magnavox Advanced Products/Systems Co.

Installation on: USAF F-16 Fighter, B-52 Bomber, Navy A-6 Attack aircraft, CV-59 Aircraft Carrier, SSN-700 Submarine, Army M-60 Tank, UH-60 Helicopter, and Manpacks.

APRIL 1985 Initial Production and Deployment of GPS Military Units for 1-, 2-, and 5 Channel and Manpack sets is awarded to Rockwell –Collins.

UE History

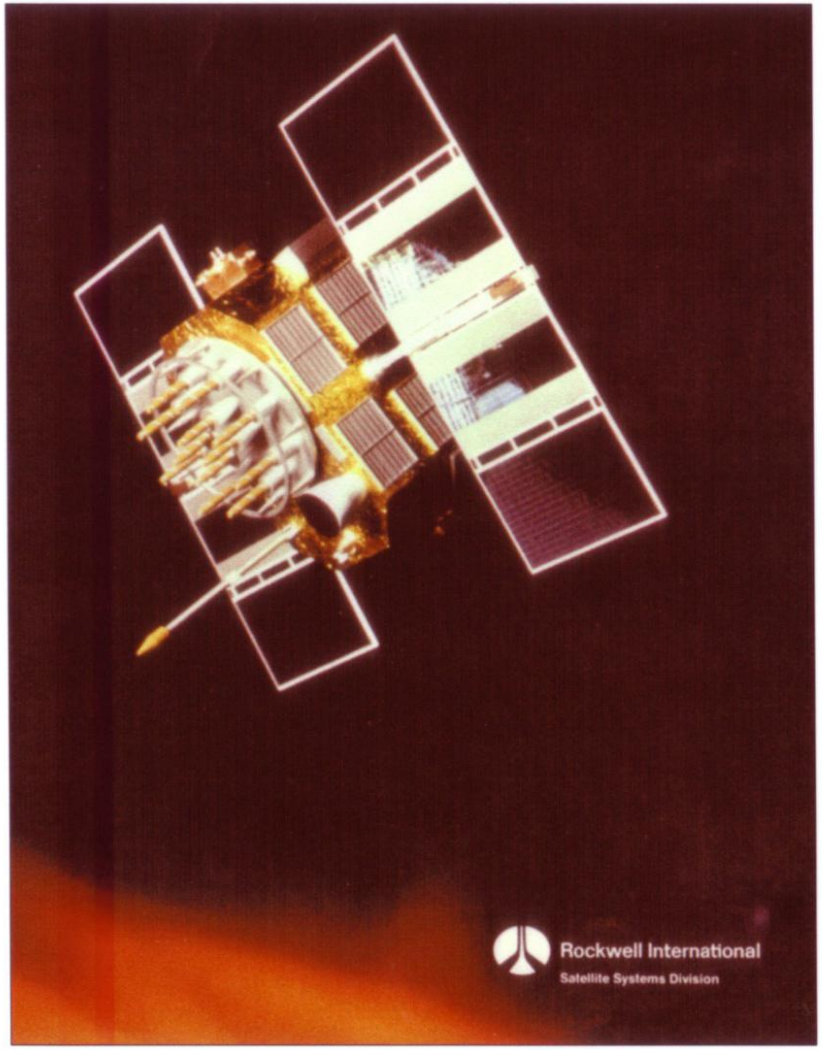
GPS Phase II Navigators

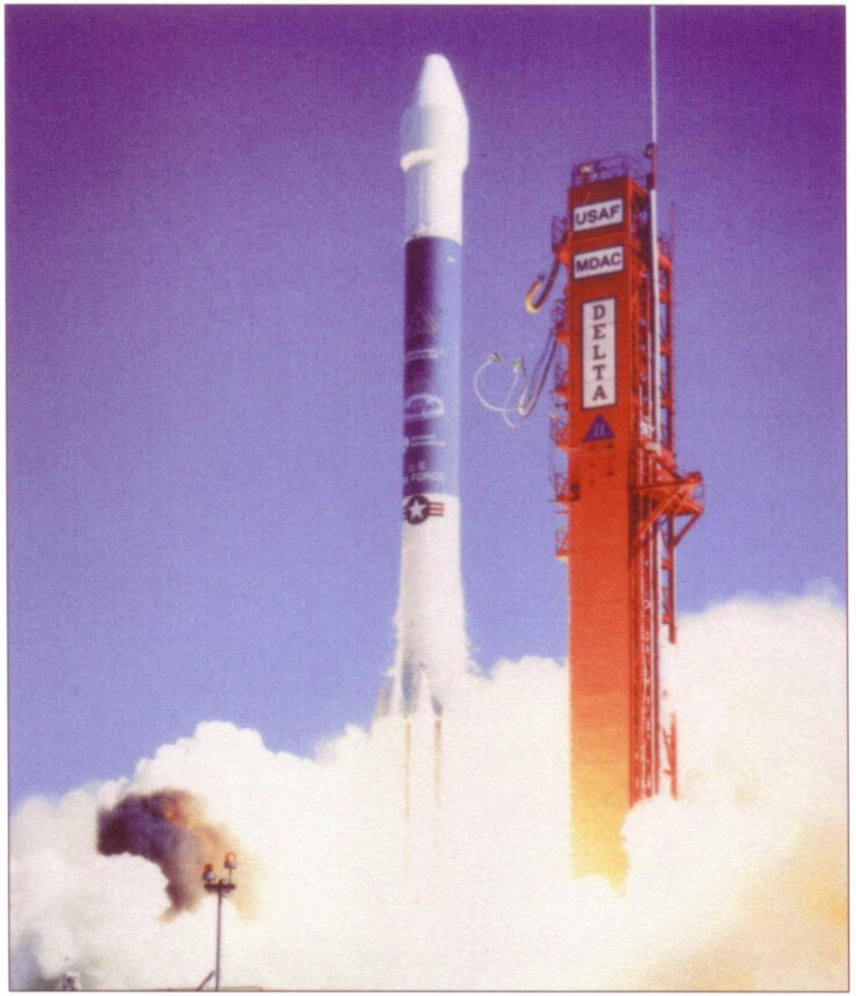


1983

BLOCK II / IIA OPERATIONAL SATELLITES

1978 Shuttle designated as AF Mission Launch Vehicle with NDS 12 as Qual
1979 Carter Administration deletes $500M from GPS over FY 81-86
1982 Operational orbits reduced from 24 to 18 (6 x 3)
May 1983 Block II Multi-Year award to Rockwell for 28 vehicles with 7.5 yr life, Selective Availability, Anti-spoof, NDS crosslinks
Oct 1984 Block IIA revisions for new W-sensor, threat hardening, L3, and extended 180-day survivable mission data operation
Jan 1986 Challenger is destroyed, Delta II designated as launch vehicle requiring redesign and testing for new vibration/shock.
May 1988 Operational orbits expanded back to 24 (6 x 4)
Feb 1989 First of 9 Block II vehicles is launched into 55 degree orbit from FL
Mar 1990 Selective Availability is operationally activated on all 7 SV's
Aug 1990 Iraq invades oil fields in Kuwait beginning Gulf War, SA goes off
Jan 1990 Desert Storm begins after final 2 Block II and first Block IIA provide a total of 16 GPS for partial 3-D, C/A coverage in Iraq.
July 1990 SA is turned back on


Rockwell International
Satellite Systems Division


USAF
MDAC
DELTA

CONTROL SEGMENT DEVELOPMENT

General Dynamics Electronics Division wins contract for Phase I Master Control Station, three Monitor sites, and Data Upload and Telemetry operations at Vandenburg AFB.

1977 Inverted Range test operations begin at Yuma, Arizona. MCS mainframe mechanized with 85 state Kalman filter for Ephemeris and Clock estimation using Monitor signals.

July 1977 Uploaded data from Navy NTS-2 is received by X-set at Magnavox Lab and Yuma-----1st GPS signal tested.

Sept 1980 IBM Federal Systems Co. awarded Phase II Full Scale Effort to transition Vandenburg MCS with new mainframe to an updated operational status for 24 orbiting satellites.

New MCS is moved to Consolidated Space Operations Center at Schriever AFB Co. with Monitor sites in Hawaii, Ascension, Kwajalein, and Diego Garcia, and Colorado

Dec 1993 GPS attains Initial Operational Capability status!

1992 Robert J. Collier Award

To the GPS Team: " For the most significant development for safe and efficient navigation and surveillance of air and spacecraft since the introduction of radio navigation fifty years ago."

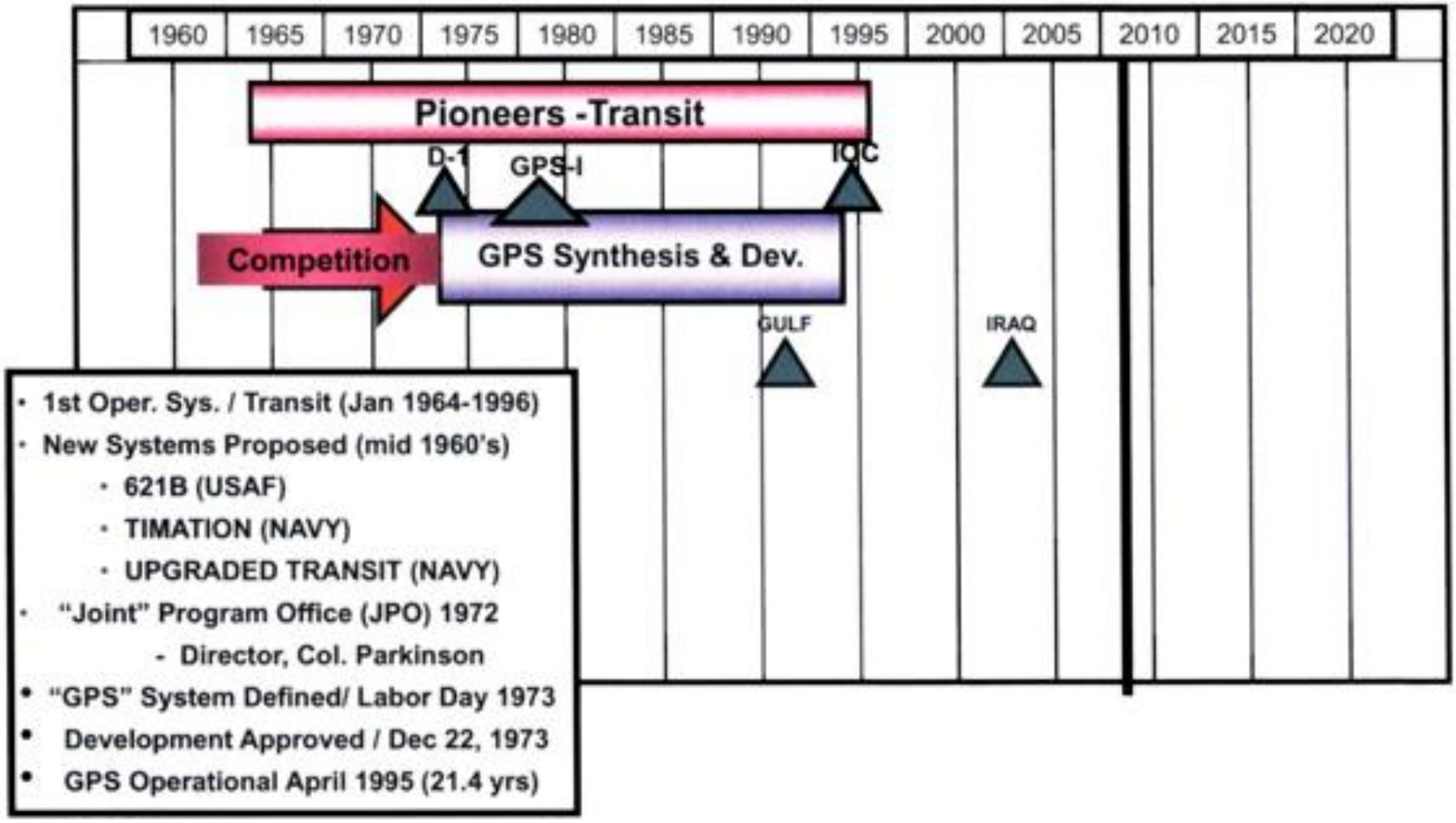
The United States Air Force JPO
U.S. Naval Research Laboratory
The Aerospace Corporation
IBM Government Systems Co.
Rockwell International Corporation

The creation of GPS was based on teamwork-------in many aspects by synthesis of ideas from rival team developments and study efforts.

To quote from Coach John Wooden—

“ It is amazing what a team can accomplish if no one cares about who ends up getting the credit.”

The Eras of Satellite Navigation



CONCLUDING OBSERVATIONS OVER 40 YRS

PRODUCED A DUAL-USE GLOBAL NAVIGATION UTILITY
PROVIDED FREE OF ANY CHARGES (but tax supported)
FUNDED AND MANAGED BY THE PENTAGON (a monopsony)
SUBJECTED TO NEW STAKEHOLDER'S IMPERATIVES
and a changing *POLITICAL*/MILITARY/INDUSTRIAL complex

From Phase 0 to Phase III
Covered 7 to 8 AF Managers careers with GPS
Over 7 changes in Administrations, and DOD Sect. appointments
Over 10 terms of the Congress
10 turnovers for Senate and House Science/Technology staffers

NEXT BIG QUESTION FOR GPS: WITH WHOM, AND HOW, SHOULD WE SUSTAIN THIS THING?

THE END