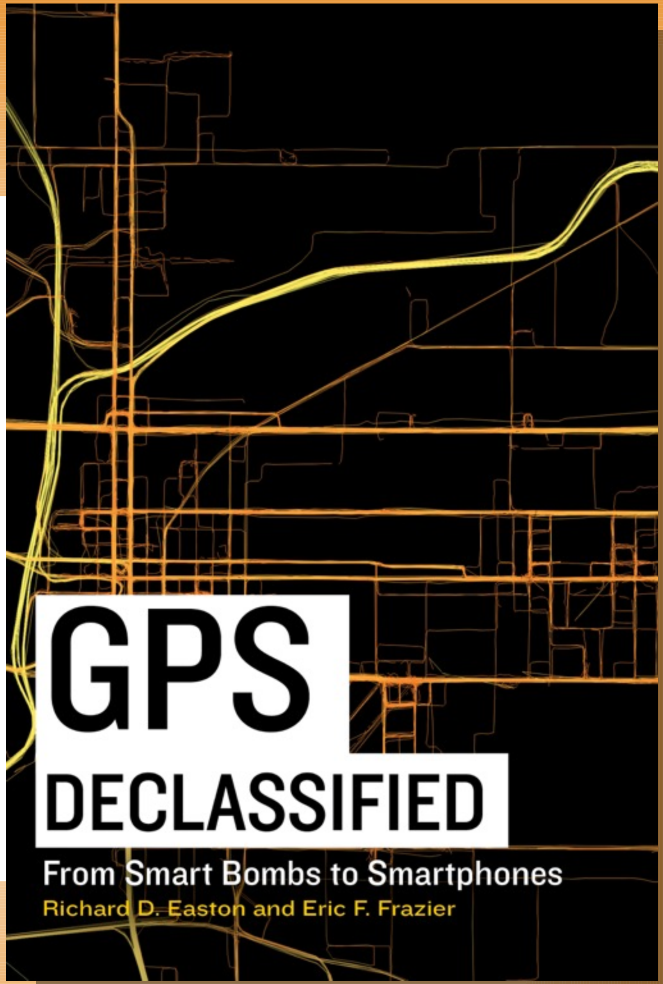
The Celestial Transformation and the Origins of GPS



Major takeaways from “GPS Declassified”

- Space tracking led directly to satellite navigation/GPS
- GPS is the most important navigational advance since John Harrison invented the marine chronometer (~1761)
- Positioning, Navigation & Timing (PNT) are now critical to commerce and daily civilian life, making GPS a vital public utility for users worldwide

Test Your GPS IQ: True of False?

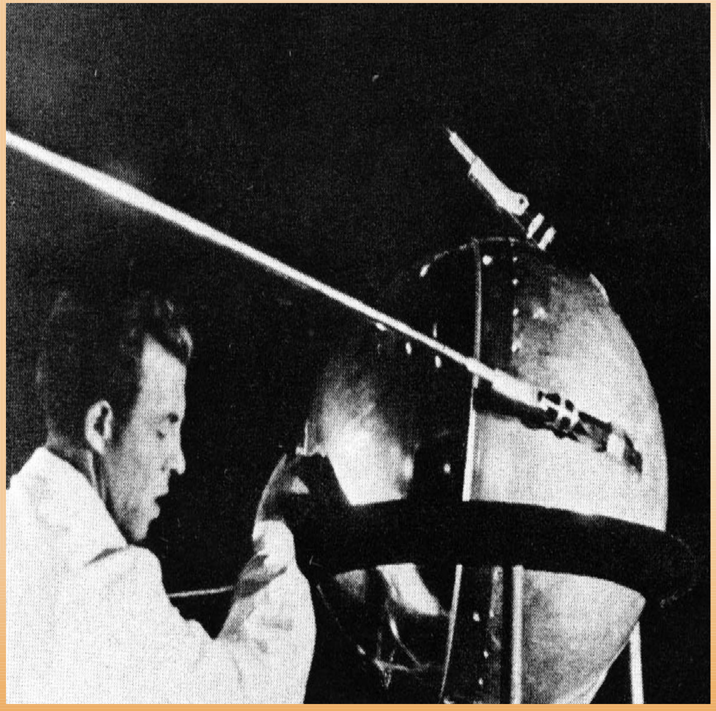
1. DARPA invented GPS.
2. Ronald Reagan declassified GPS for civilian use in 1983.
3. Global synchronized time was an unexpected consequence of GPS.
4. The U.S. government alters GPS signals during terrorist alerts.
5. The number of users today threatens to overwhelm GPS capacity.

Presentation Overview

- GPS, a technology invented in U.S. military laboratories, revolutionized war-fighting weapons, tactics and strategy.
- Contrary to common misconceptions, GPS development envisioned non-military uses from the start.
- GPS spawned complementary/competing systems worldwide and became integral to commercial, scientific and civilian activities.
- Its global impact today is greater than most people realize, and GPS has become an unseen but critical component of modern infrastructure.

24. Marty Votaw
25. Maurice Dubin
26. ?
27. Ed Manring
28. Whitney Mathews
29. ?
30.?
31. George McVey ???
18. Roger Easton
12. Luc Secretan
19. ?
20.?
21. Hans Ziegler
22. Bob Bauman
23. Milt Schach
16. Ed Rich
17. Bob Stroup
13. ?
14. John Licht
15. ?
11. George Ludwig
6. Jim Heppner
7. Jessie Mitchel
10. John Maskasky
8.Rudy Stampfl
9. Rudy Hannel
5. Vern Suomi
4.Jim Van Allen
3. Bill Stroud
1. Warren Berning
2. Homer Newell

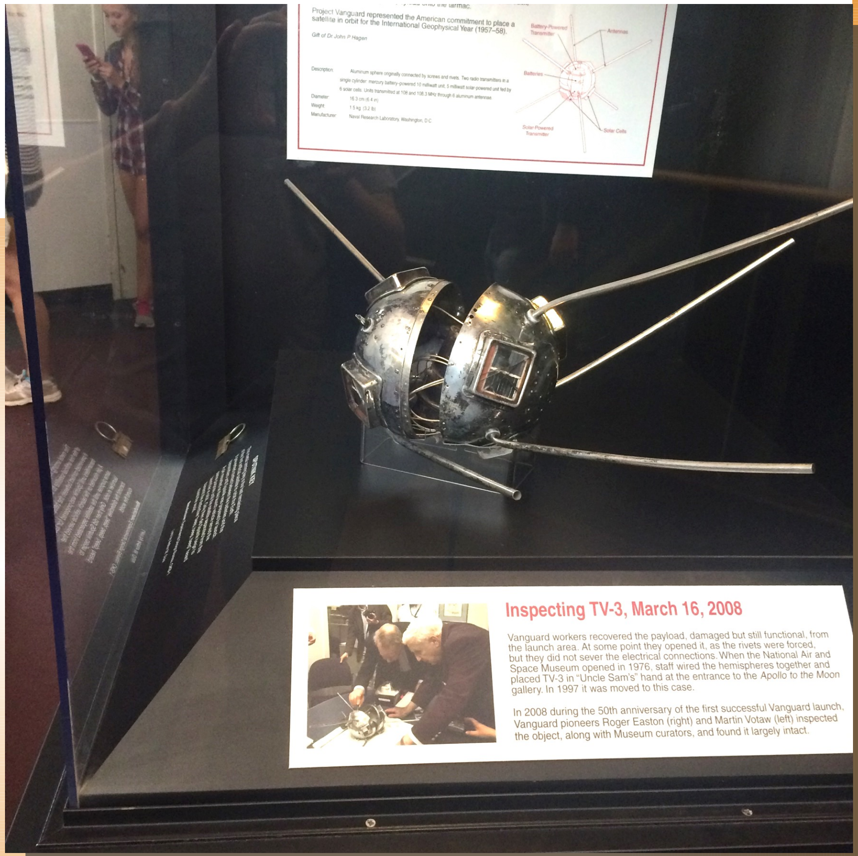
Sputniks 1 and 2



December 6, 1957

Vanguard TV-3 explodes on takeoff

Credit: U.S. Navy



Credit: Richard D. Easton

Vanguard TV-3 satellite survived.
On display at the National Air & Space Museum.

Unhappy Vanguard Rocket

Explorer 1

March 17, 1958
Vanguard 1 lifts off

Credit: NRL

Credit: Easton family photo

Vanguard I, still orbiting, is the oldest man-made object in space

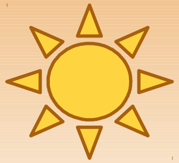
Easton children at home gathered around the Vanguard 1 satellite shortly before its launch

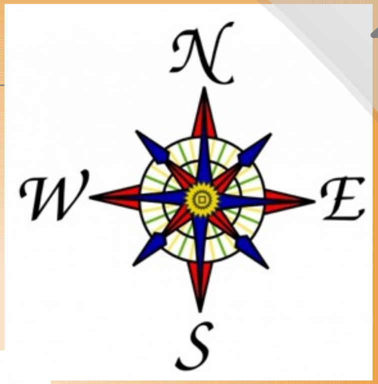
March 2008 – Vanguard 50th anniversary celebration

Vanguard TV-3 satellite reopened at National Air & Space Museum

Credit: Roger Easton Jr.

The path to satellite navigation





- **Ancient: Visual aids**

  Landmarks: rivers, mountains, coastlines, vegetation, man-made

  Celestial objects: the Sun, Moon, planets, North Star, constellations

- **Compass (200 B.C.)**

  First technology to use an **invisible** direction-finding aid

- **Navigating at sea required technological advances**

  Astrolabes, sextants, telescopes, astronomical charts

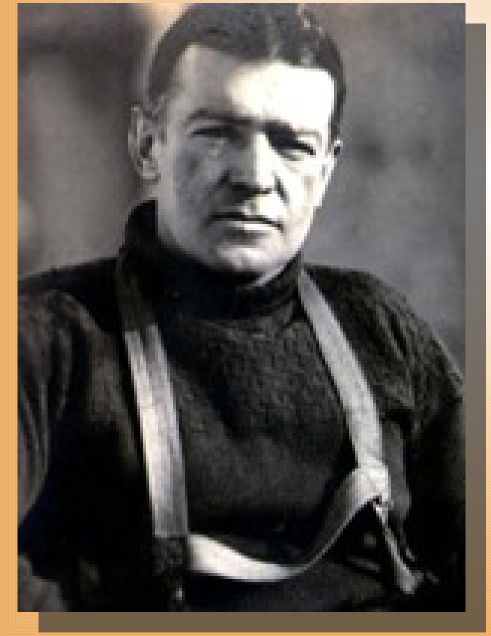
  Accurate clocks (**marine chronometer**) to solve longitude problem

- **Discovery of high-frequency electromagnetic waves (1800 A.D.)**

  Radar, radio, etc.

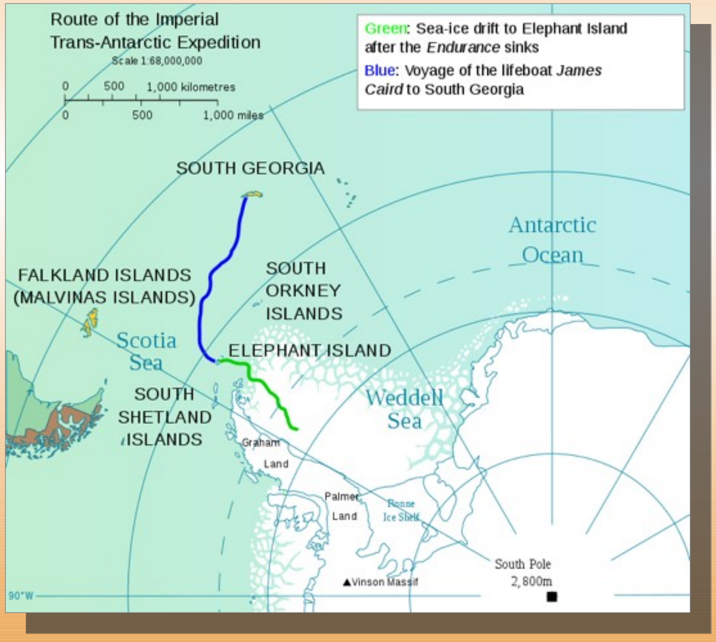
Navigation precision a century ago

Sir Ernest Shackleton
(1874-1922)



Credit: Frank Hurley, 1916,
Wikimedia Commons

1916
Voyage of *James Caird*



Credit: By Bourrichon,
Wikimedia Commons

Shackleton’s navigator, Frank Worlsey, told him that he “could not be sure of our position to ten miles.”

Foresight

"For example, the three stations in the 24-hour orbit could provide not only an interference and censorship-free global TV service for the same power as a single modern transmitter, but could also make possible a position-finding grid whereby anyone on earth could locate himself by means of a couple of dials on an instrument about the size of a watch."

— Arthur C. Clarke, letter to Andrew G. Haley, August 5, 1956

The path to satellite navigation

After the Soviet Union launched the first satellite, Sputnik, in 1957, three individuals or groups that tracked it later proposed satellite navigation systems based on:

Inverting **the tracking process**

Using receivers to track the position of satellites

↕

Using satellites to determine the position of receivers

The path to satellite navigation

"To my knowledge the idea of using passive ranging as a navigation technique was a result of a conversation between myself and Dr. Arnold Shostak of ONR [Office of Naval Research] in [April] 1964.

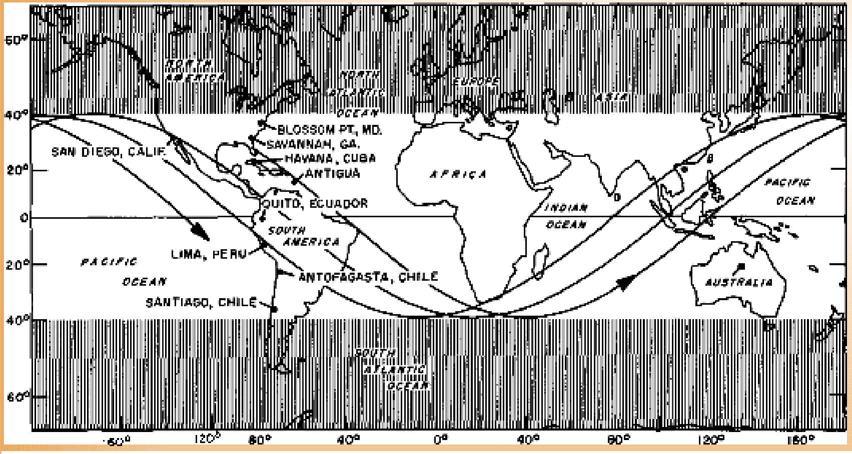
"Dr. Shostak was explaining how the hydrogen maser worked and obtained its fantastic time keeping ability. At the time I remarked that this device appeared to make passive ranging feasible. He agreed, and I spent a week working on the idea."

— from a slide presentation by Roger Easton, 1967

The path to satellite navigation

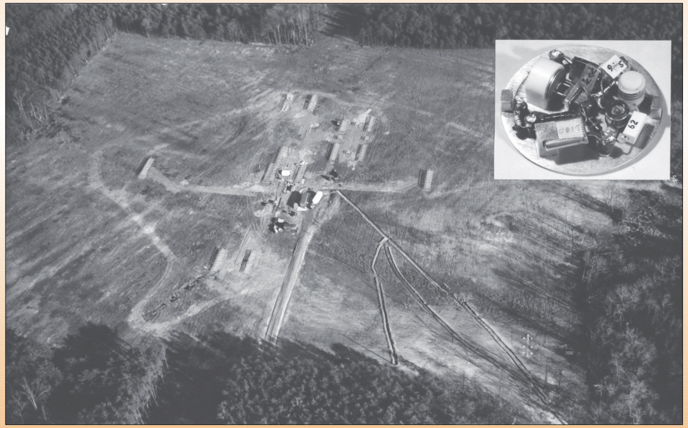
Minitrack

First satellite tracking system, designed for Vanguard Rocket Program



The network of primary Minitrack stations as of January 1957

Source: *Vanguard: A History,* NASA



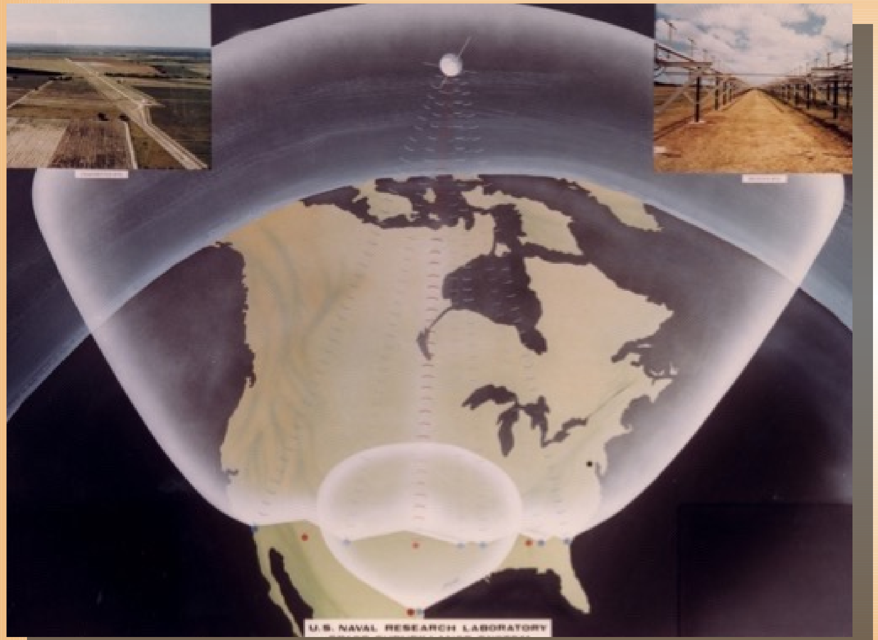
Tracking Station at Blossom Point, MD. Note the north-south and east-west antenna configuration

Source: NRL

Roger Easton taking Minitrack data

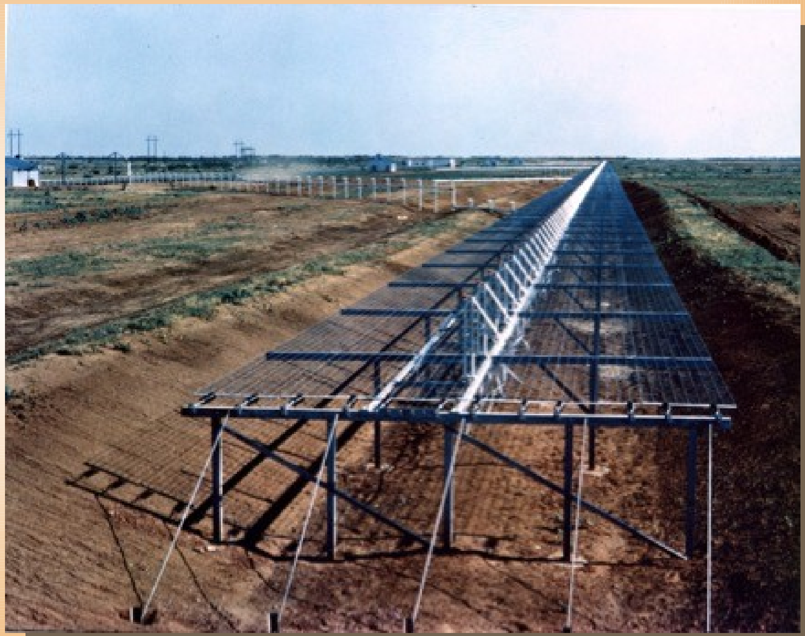
Source: NRL

The path to satellite navigation



Credit: NRL graphic

Space Surveillance System
(original space "fence" 1958 - 2013)



Credit: NRL

Tracking Station Transmitter
Lake Kickapoo Texas

The path to GPS

U.S. Pre-GPS Space-Based Navigation Proposals

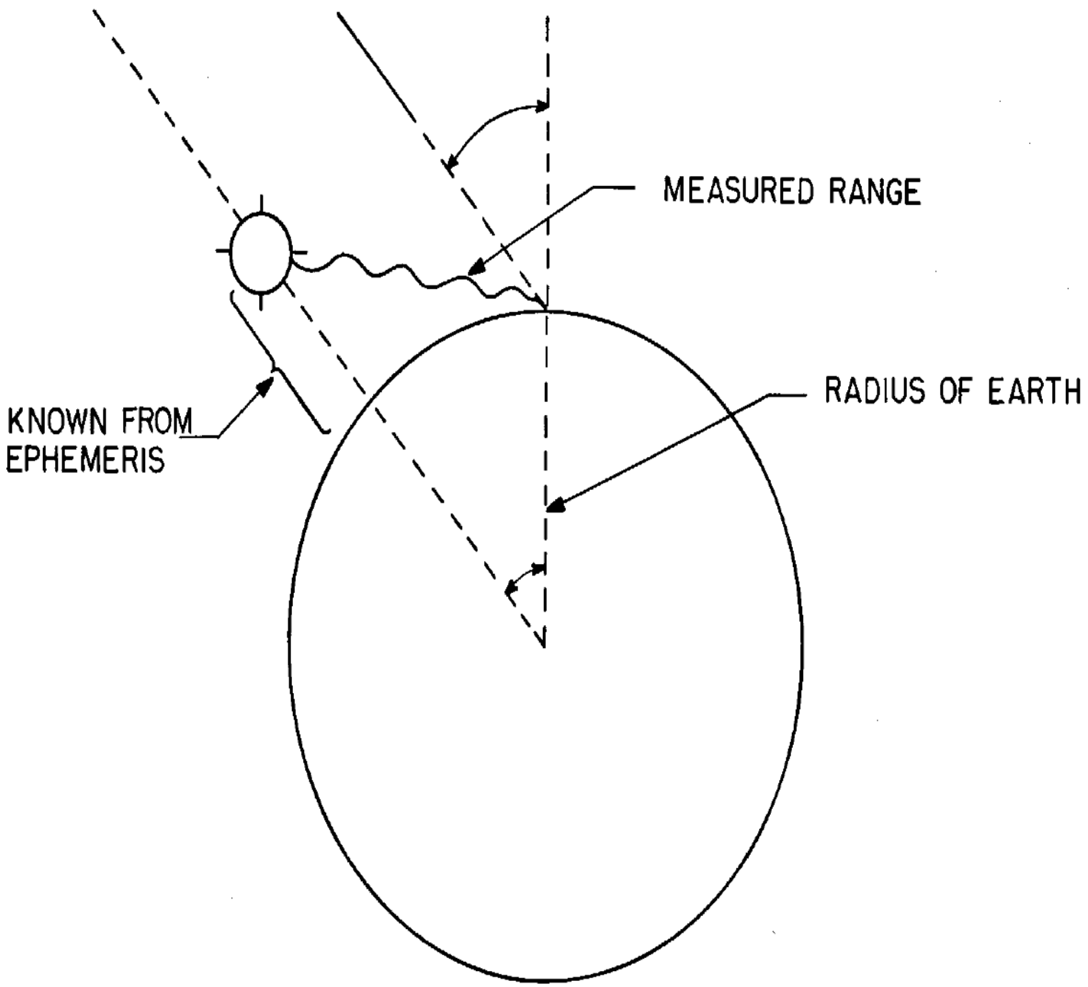
- Angle Measurement (position in sky)
  - Edward Everett Hale, "The Brick Moon," 1870
- Doppler Measurement (change in pitch of signal)
  - Lovell Lawrence Jr., "Navigation by Satellites," *Missiles and Rockets*, 1956
  - Transit, George Weiffenbach and William Guier, Applied Physics Laboratory, 1958
- Range Measurement (difference in time of arrival of signals)
  - Don Williams, Hughes Aircraft, 1959
  - SECOR (sequential correlation of range), Army, 1961
  - Roy Anderson, GE/NASA, 1963
  - Timation (time navigation), Roger Easton, Naval Research Laboratory, 1964
  - 621b, Air Force/Aerospace Corporation, 1964

1971 paper by Roger Easton

There are two very closely related ways of time dissemination today: radio and navigation. Historically, the moons of Jupiter were used to obtain the first measurements of longitude. Later, the moon was used in a navigation system in which time could be determined to about 30 miles (a little over a minute) . Time dissemination today uses the hyperbolic stations, LORAN and OMEGA, and satellites, which make possible the two-way ranging and passive ranging systems.

The satellite has four advantages: (1) well-known position; (2) line-of-sight signal, which allows the use of UHF; (3) worldwide coverage; and (4) a celestial navigation solution identical to the one used in celestial navigation for 200 years

TRANSFORM TO CELESTIAL OBSERVATION

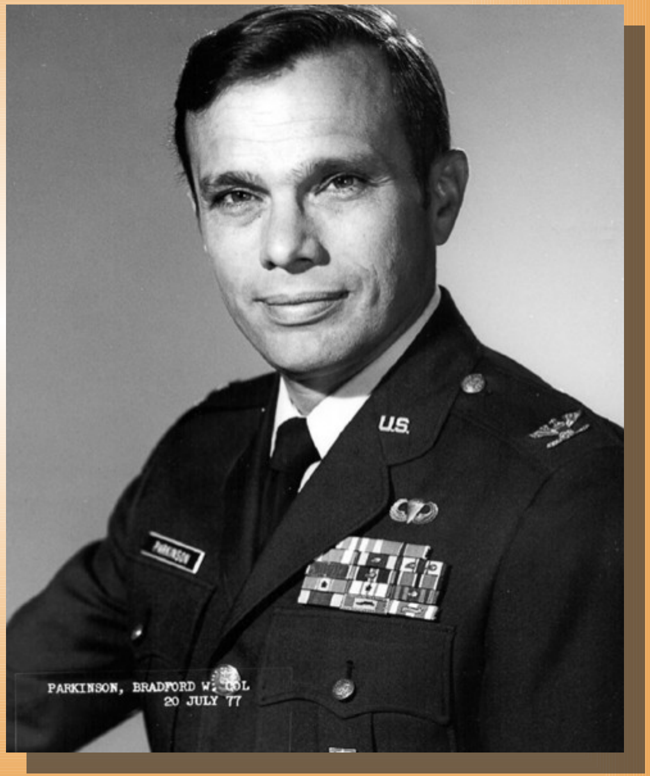


The path to GPS

The Joint Chiefs of Staff's Navigation Study Panel (1968) specified that the Defense Navigation Satellite System (replacement for Transit) provide:

- three-dimensional
- instantaneous
- worldwide fixes
- within a specified accuracy (50 feet?)

4/17/73 – Joint Program Office established with the Air Force as the lead service. Col. Brad Parkinson led it from 1973-78



Credit: U.S. Air Force

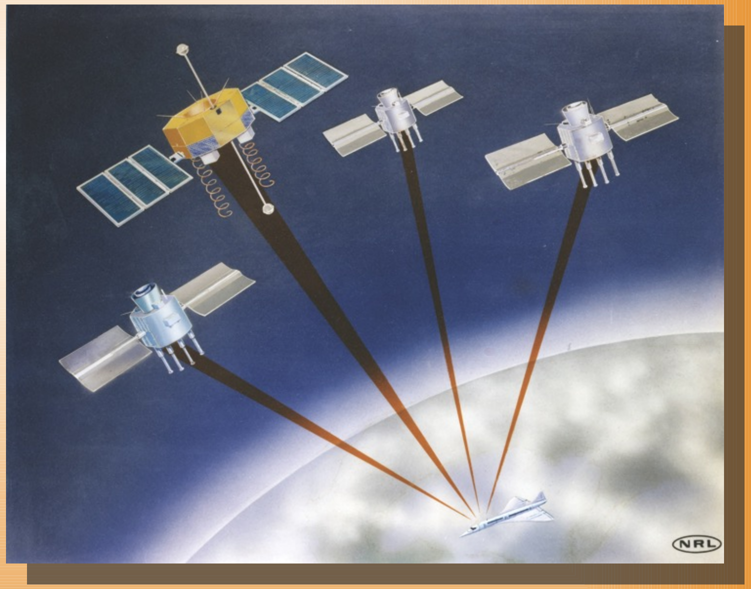
‘The Time Web’

“Precise orbiting clocks will prove to be a valuable tool in a variety of applications, by providing the entire planet earth with a single, accurate time system, enveloping the globe in a web of synchronized satellite signals.”

— Roger Easton, quoted in article, “The Time Web,” by Nathan Eberhart, *Science News*, July 13, 1974

From Timation to GPS

- **Timation III**, renamed NTS-1: First satellite launched by JPO, carried first atomic clocks to space in 1974.
- **NTS-2**, the renamed Timation IV satellite: Carried first cesium atomic clock into orbit in 1977.
- NTS-2 **plus** three later Navigation Development Satellites formed the **first GPS constellation**, successfully giving users longitude, latitude, altitude and time
- **GPS Block I,** first operational satellites
    - Launched 1978 –1985
    - 11 satellites, all retired (SVN 7 failed**)**



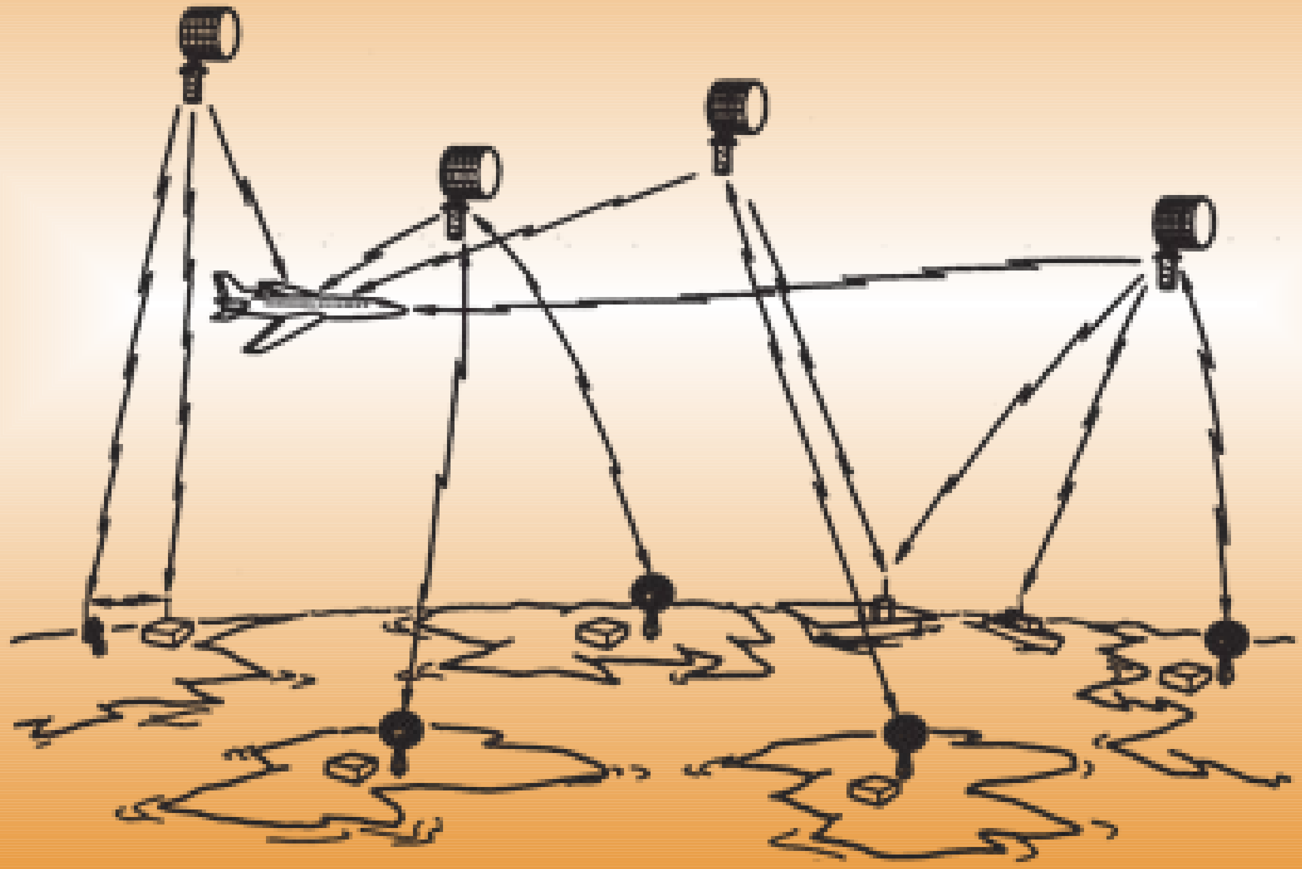
Credit: NRL graphic

Instantaneous Navigation Math (circa 1971)

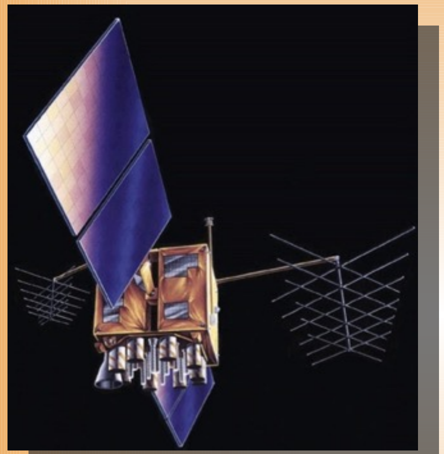
$$
\begin{bmatrix}
N & \sum_{i=1}^{N} \frac{\partial (R_c)_i}{\partial x_s} & \sum_{i=1}^{N} \frac{\partial (R_c)_i}{\partial y_s} & \sum_{i=1}^{N} \frac{\partial (R_c)_i}{\partial z_s} & 0 \\
\sum_{i=1}^{N} \frac{\partial (R_c)_i}{\partial x_s} & \sum_{i=1}^{N} \left(\frac{\partial (R_c)_i}{\partial x_s}\right)^2 & \sum_{i=1}^{N} \left(\frac{\partial (R_c)_i}{\partial x_s}\right)\left(\frac{\partial (R_c)_i}{\partial y_s}\right) & \sum_{i=1}^{N} \left(\frac{\partial (R_c)_i}{\partial x_s}\right)\left(\frac{\partial (R_c)_i}{\partial z_s}\right) & 2x_s \\
\sum_{i=1}^{N} \frac{\partial (R_c)_i}{\partial y_s} & \sum_{i=1}^{N} \left(\frac{\partial (R_c)_i}{\partial x_s}\right)\left(\frac{\partial (R_c)_i}{\partial y_s}\right) & \sum_{i=1}^{N} \left(\frac{\partial (R_c)_i}{\partial y_s}\right)^2 & \sum_{i=1}^{N} \left(\frac{\partial (R_c)_i}{\partial y_s}\right)\left(\frac{\partial (R_c)_i}{\partial z_s}\right) & 2y_s \\
\sum_{i=1}^{N} \frac{\partial (R_c)_i}{\partial z_s} & \sum_{i=1}^{N} \left(\frac{\partial (R_c)_i}{\partial x_s}\right)\left(\frac{\partial (R_c)_i}{\partial z_s}\right) & \sum_{i=1}^{N} \left(\frac{\partial (R_c)_i}{\partial y_s}\right)\left(\frac{\partial (R_c)_i}{\partial z_s}\right) & \sum_{i=1}^{N} \left(\frac{\partial (R_c)_i}{\partial z_s}\right)^2 & 2z_s \\
0 & 2x_s & 2y_s & 2z_s & 0
\end{bmatrix}
\begin{bmatrix}
\Delta K \\ \Delta x_s \\ \Delta y_s \\ \Delta z_s \\ \Delta g
\end{bmatrix}
=
\begin{bmatrix}
\sum_{i=1}^{N} (1)(O-C)_i \\
\sum_{i=1}^{N} \frac{\partial (R_c)_i}{\partial x_s} (O-C)_i \\
\sum_{i=1}^{N} \frac{\partial (R_c)_i}{\partial y_s} (O-C)_i \\
\sum_{i=1}^{N} \frac{\partial (R_c)_i}{\partial z_s} (O-C)_i \\
0
\end{bmatrix}
$$

Credit: NRL

1971 Timation Development Plan



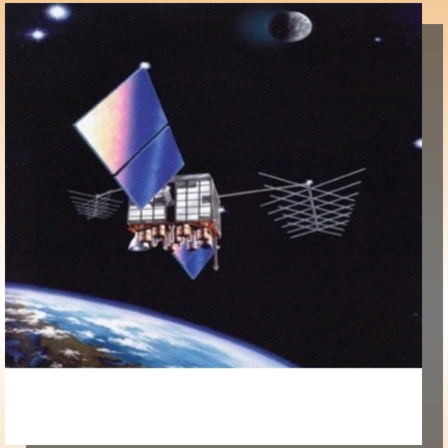
GPS satellites by type



Credit: U.S. Government, gps.gov

Block IIR

- 12 operational
- 7.5-year design life (oldest is 19 years old)
- Launched 1997-2004



Credit: U.S. Government, gps.gov

Block IIR-M

- 7 operational, 1 residual
- 7.5-year design life
- Added 2nd civil signal (L2C)
- Launched 2005-2009

Credit: U.S. Government, gps.gov

Block IIF

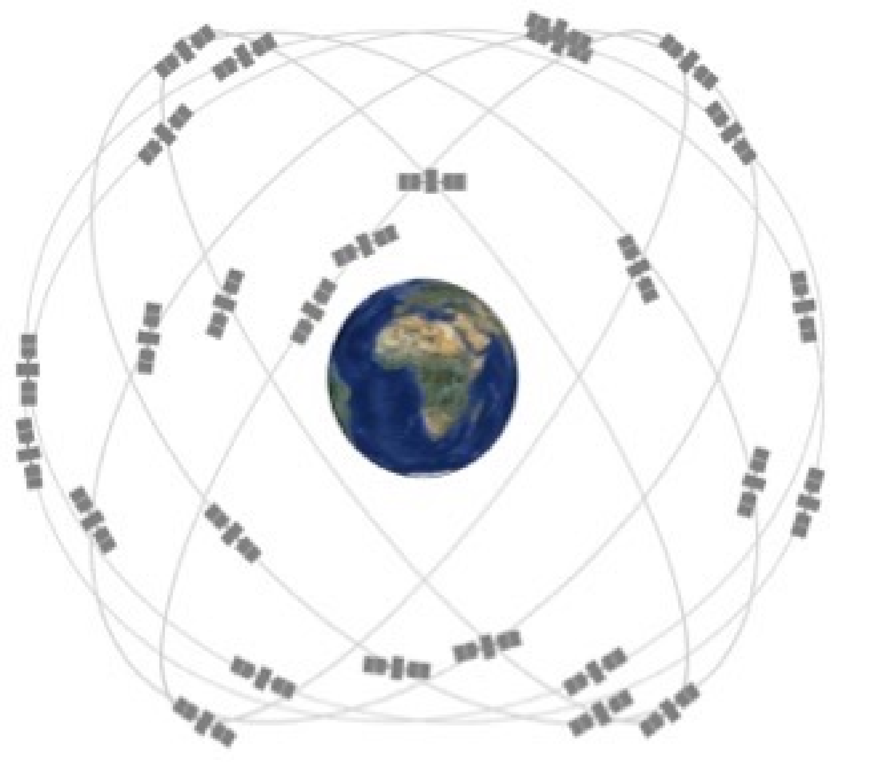
- 12 operational
- 12-year design life
- Added 3rd civil signal (L5)
- Launched 2010-2016

GPS satellites by type

GPS III

- **First launch projected for spring 2018**
- 8 Complete/in production, 2 contracted
- SV11+ incl. laser reflectors/S&R payload
- 15-year design life
- Will add fourth civilian navigation signal, the first common L1C signal
- 4 civil signals: L1 C/A, L1C, L2C, L5
- 4 military signals: L1/L2 P(Y), L1/L2M

Credit: U.S. Government, gps.gov



Credit: U.S. Government, gps.gov

GPS Constellation

2017

- 31 operational satellites (12-IIR, 7-IIR-M, 12-IIF)
- 5 residuals (IIA) (1 IIR-M, SVN49 unusable)
- Average age: 9 years   Oldest: 19+ years
- User Range Error: (Signal in Space) ≤ 0.715 m (2.3 ft.)
- Horizontal accuracy on the ground ≤ 1.891 m (6.2 ft.)
- Timing accuracy > 100 billionths/sec (1×10^{-11})

Ground Control

2 Master Control Stations (U.S.); 11 C^2 ground antennas & 16 monitoring sites (worldwide)

Users

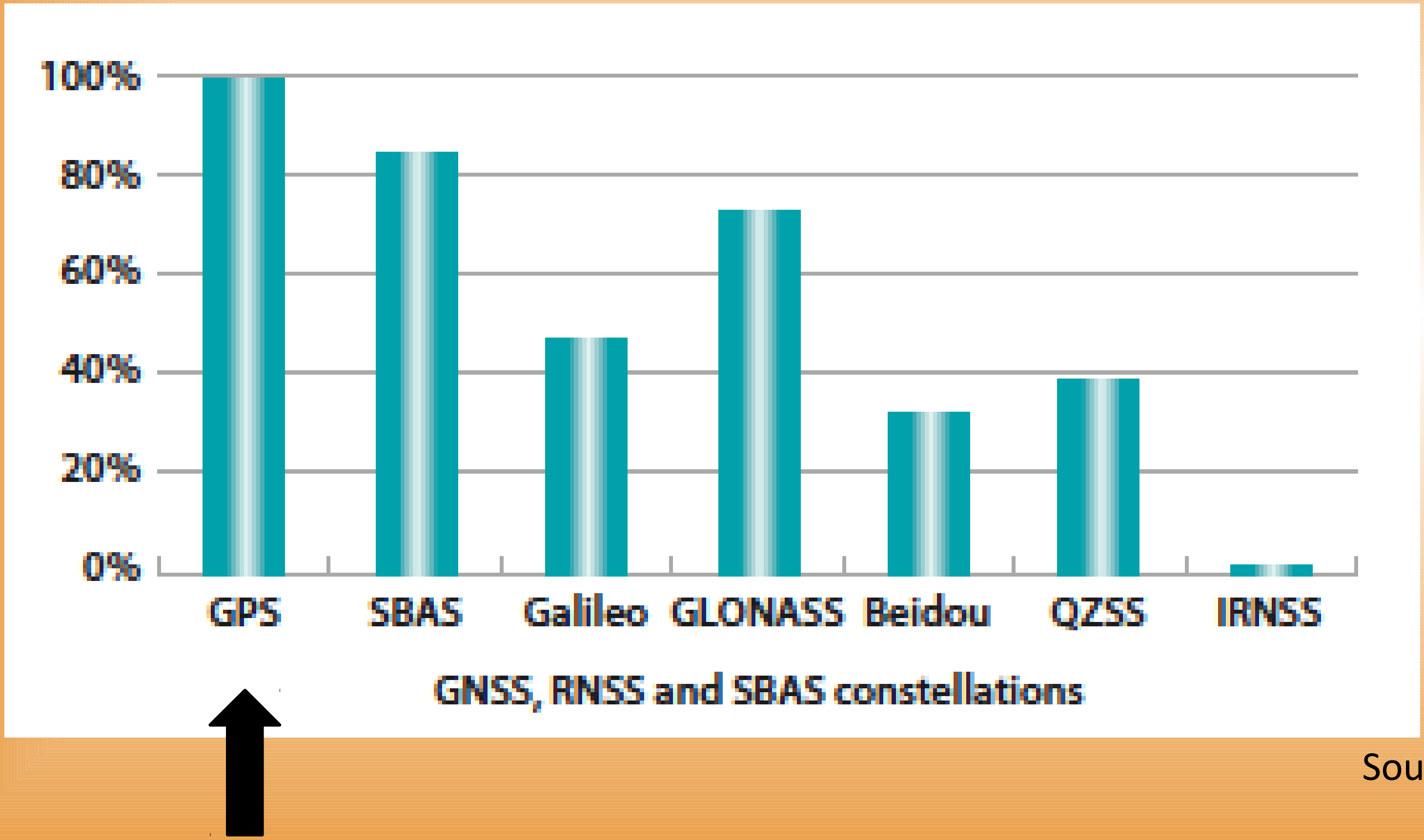
- >1 billion civilian & commercial GPS users worldwide

Other Global Navigation Satellite Systems – GNSS

Worldwide Coverage	Size	Scheduled
Russia GL ASS	25	8 more through 2017
Europe ileo	15	8 more through 2018
China Be u	23	12 more through 2018

Regional Coverage	Size	Scheduled
Japan QZ	1	2 more in 2017
India NA C (IRNSS)	7	2 backups on stand-by

Capability of GNSS receivers

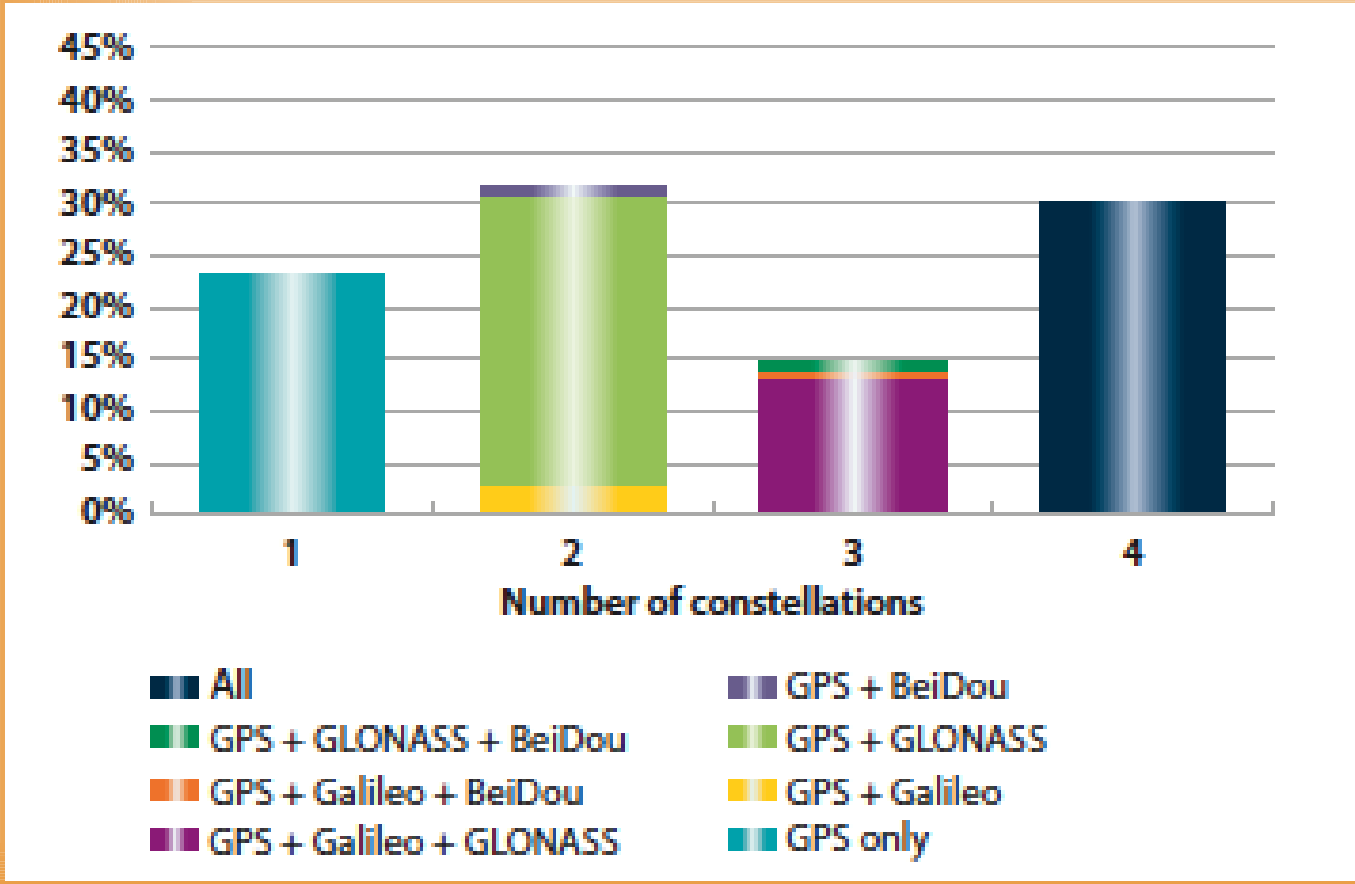


- Based on analysis of ~400 receivers, chipsets, and modules offered by top 31 global companies.
- GNSS devices in use worldwide in 2015:

  4.5 billion (est.)

Source: GNSS User Technology Report, Issue 1, copyright © European GNSS Agency, 2016, www.gsa.europa.eu

Supported constellations by receivers



Receivers supporting all four GNSS signals are growing rapidly, and now account for **30 percent** of products offered by the top 31 companies.

Source: GNSS User Technology Report, Issue 1, copyright © European GNSS Agency, 2016, www.gsa.europa.eu

Dual-use: built in from the start

"The P Signal is used by the precision military user and will resist jamming, spoofing, and multipath and will be deniable to unauthorized users by employing transmission security (TRNSEC) devices. **The C/A Signal will serve as an aid to the acquisition of the P Signal, and will also provide a navigation signal in the clear to both the military and civil user.**"

— page 30, *Navstar Global Positioning System Program Management Plan*, July 15, 1974

GPS civilian debut: land surveying, 1982

Macrometer V-1000

- 160 lbs. (plus tripod antenna, 40 lbs.)
- 22 in. wide, 26 in. deep, 26 in. high
- Used in *pairs*
- $250,000 *each*
- Recorded data for about four hours a day while 6 satellites were overhead

Soviets shoot down KAL 007, Sept. 1, 1983

"… the President has determined that the United States is prepared to make available to civilian aircraft the facilities of its Global Positioning System when it becomes operational in 1988.…"

— Larry M. Speakes, deputy press secretary, Sept. 17

Credit: By Mgarin73 – Wikimedia Commons

Challenger explosion, Jan. 28, 1986

Credit: NASA

- Grounding of Space Shuttle program set back GPS launch schedule by about two years
- Air Force developed Delta II rocket, which carried GPS II satellites into orbit from 1989 to 2009

GPS military debut: Persian Gulf War, 1990-91

August 2, 1990

- Iraq invaded Kuwait
- United States launched GPS SVN 21 bringing constellation size to 14 satellites

October 1, 1990

- United States launched GPS SVN 15

November 26, 1990

- United States launched GPS SVN 23 bringing constellation size to to 16 satellites

Ground crews made complicated adjustments to optimize the incomplete system and overcome technical problems

Map Source: Wikimedia Commons

GPS military debut: Persian Gulf War, 1990-91

Credit: U.S. Air Force

AGM-86 C/D
Conventional Air-Launched Cruise Missile (CALCM)

35 used during Persian Gulf War

Credit: U.S. Navy

AGM-84
Stand-off Land Attack Missile (SLAM)

7 used during Persian Gulf War

GPS military debut: Persian Gulf War, 1990-91

Operation Desert Storm

Source: By Jeff Dahl - Wikimedia Commons

- Receiver shortage throughout war – total of 4,490 commercial vs. 842 military
- Selective Availability turned off
- Enabled navigation across the featureless desert
- Atomic clock time used to sync helicopter attack on two targets within 20 seconds apart
- Coordinates used for dropping glow sticks at launch point for missiles
- Helped to avoid fratricide
- Improved search and rescue
- Better navigation to launch points improved effectiveness of conventional weapons

GPS military debut: Persian Gulf War, 1990-91

"GPS was used more extensively than planned and met navigation and positioning requirements….GPS should be considered for incorporation into all weapon systems and platforms."

—*Conduct of the Persian Gulf War, Final Report to Congress*,
U.S. Department of Defense, 1992

GPS reliance now

"The increasing convergence of critical infrastructure dependency on GPS services with the likelihood that threat actors will exploit their awareness of that dependency presents a growing risk to the United States."

— *National Risk Estimate, Risks to U.S. Critical Infrastructure from GPS Disruptions,* U.S. Department of Homeland Security, 2012

How did the public become reliant on a military system?

- Miniaturization, fusion of microelectronics and GPS receivers
- Decision in mid-1990s that GPS would remain under military control
- Improved accuracy, including differential augmentation (DGPS)
- Turning off Selective Availability
- Integration with consumer electronics
- Need to locate wireless 911 emergency calls
- Benefits of precise timing signals across many industries

The incredible shrinking GPS receiver…

Credit: Courtesy of Rockwell Collins

1976-77

Generalized Development Model by Rockwell Collins

Credit: Courtesy of Rockwell Collins

1980

Manpack GPS receiver by Rockwell Collins

Credit: Courtesy of Texas Instruments

1981-82

TI 4100 and antenna by Texas Instruments

The incredible shrinking GPS receiver…

Credit: U.S. Army Heritage Museum

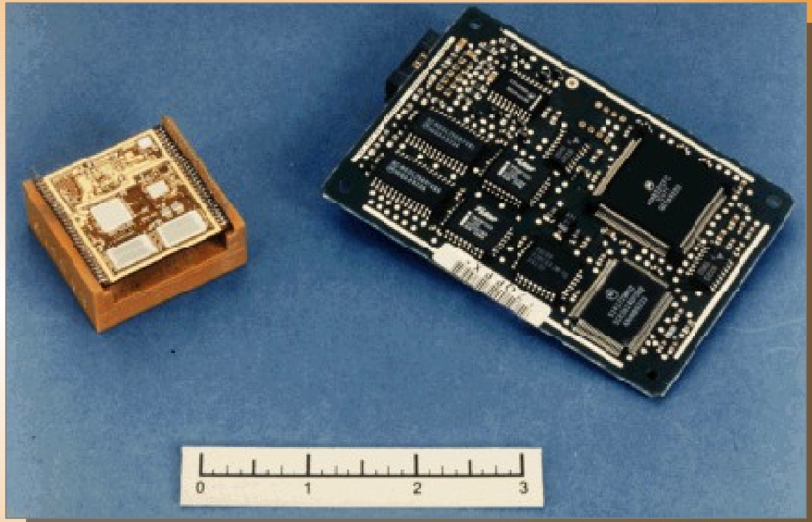
1988

Trimpack GPS receiver
by Trimble Navigation

Credit: Courtesy of Rockwell Collins

1990

Portable Lightweight GPS Receiver (PLGR AN/PSN-11)
by Rockwell Collins



Credit: U.S. Army Heritage Museum

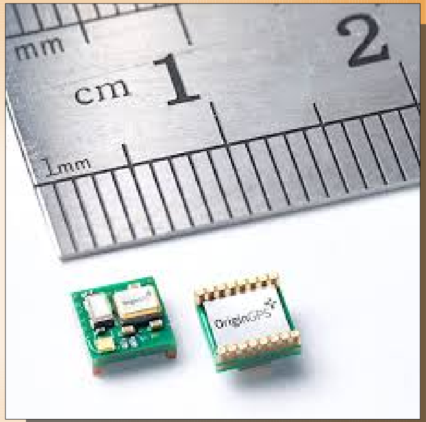
1993

Mayo Foundation/Motorola
Multi-chip Module
(pictured beside 3-inch ruler)

The incredible shrinking GPS receiver…

Credit: By Humberto Möekel – Wikimedia Commons

Credit: By Wolf Gang – Creative Commons



Credit: Courtesy OriginGPS

2007
Garmin Nüvi 200

2008
Apple iPhone 3G

2016
OriginGPS Nano Spider
(4.1mm x 4.1mm)

Civilian, scientific, and commercial activities that use GPS:

- aviation and aerospace
- trucking and shipping
- fleet management
- railroads
- fishing and boating
- surveying and mapping
- agriculture and forestry
- mining and oil exploration
- grading and construction
- environmental protection
- earthquake monitoring

- wildlife management
- recreation (golf, hiking, running)
- law enforcement (tracking stolen items, monitoring probationers, parolees)
- emergency response
- monitoring pets, children, Alzheimer's patients
- telecommunications and data systems
- banking and financial networks
- electric power grids
- location-based services

Civilian, scientific, and commercial activities that use GPS:

Monitoring physical structures

By Leica Geosystems AG
– Wikipedia

Monitoring people

By Jérémy-Günther-Heinz Jähnick
- Wikimedia Commons

Precise timing

By Yann Forget
-Wikimedia Commons

Economic Impact

- U.S. taxpayers spent roughly $40 billion on GPS through 2015, with annual expenditures approaching $1 billion
- GPS satellites, ground control stations and military receivers and are funded through military budget
- Augmentation systems funded through DOT, FAA
- Civilian receivers and applications constitute huge worldwide industry, creating jobs, direct economic benefits, and many indirect benefits

Economic Impact

"The Economic Benefits of Commercial GPS Use in the U.S. and the Costs of Potential Disruption"

- Nam D. Pham, PhD, NDP Consulting
- Commissioned by Coalition to Save Our GPS
- Reported June 2011, used data through 2010

Key Findings

- GPS provides **$68 billion to $122 billion** in economic benefits to U.S. annually
- Total **disruption** of GPS would cut U.S. gross domestic product by **$96 billion** per year

Economic Impact

”The Economic Value of GPS: Preliminary Estimate”

- Irv Leveson, PhD, Leveson Consulting
- Commissioned by National Space-Based PNT Executive Committee
- Reported June 2015, used data through 2013

Key Findings

- Conservative estimate, *excludes sectors lacking sufficient data* for confidence
- GPS provides **$37 billion to $75 billion** in economic benefits to U.S. annually
- Mid-range estimate: **$55.7 billion**

Economic Impact

"The Economic Value of GPS: Preliminary Estimate"

A few key sectors:

- **Precision Agriculture – grain**
  $10 – $18 billion

Credit: U.S. Dept. of Agriculture

Economic Impact

“The Economic Value of GPS: Preliminary Estimate”

A few key sectors:

- **Fleet Vehicle Connected Telematics**
  $8 – $16 billion

Credit: By Mariordo – Wikimedia Commons

Economic Impact

"The Economic Value of GPS: Preliminary Estimate"

A few key sectors:

- **Surveying**
  $10 – $13 billion

Credit: By Clicgauche - Wikimedia Commons

Economic Impact

”The Economic Value of GPS: Preliminary Estimate”

Other selected data points:

- 900 million mobile phones that incorporated GPS were sold worldwide in 2012
- The United States had 188 million smartphone subscribers and 263 million Internet users in 2013
- 20 percent of mobile phone users got up-to-the-minute traffic information
- U.S. Geographic Information Systems (GIS) industry estimated at $73 billion in 2011

Economic Impact

Bottom line:

- Even by conservative estimates that exclude many sectors, the *annual economic benefits in the United States alone*, are nearly equal to or exceed the total cost of GPS since its inception.

- Worldwide economic benefits of GPS (and other GNSS) are much larger.

Future Outlook

- A robust multi-GNSS, multi-PNT environment
- Greater launch capacity
- Constrained federal budgets
- Continued calls to reduce costs and redundancy
- Increased focus on resilience
- Space: “congested, contested and competitive”

Credit: U.S. Government, gps.gov

Conclusions

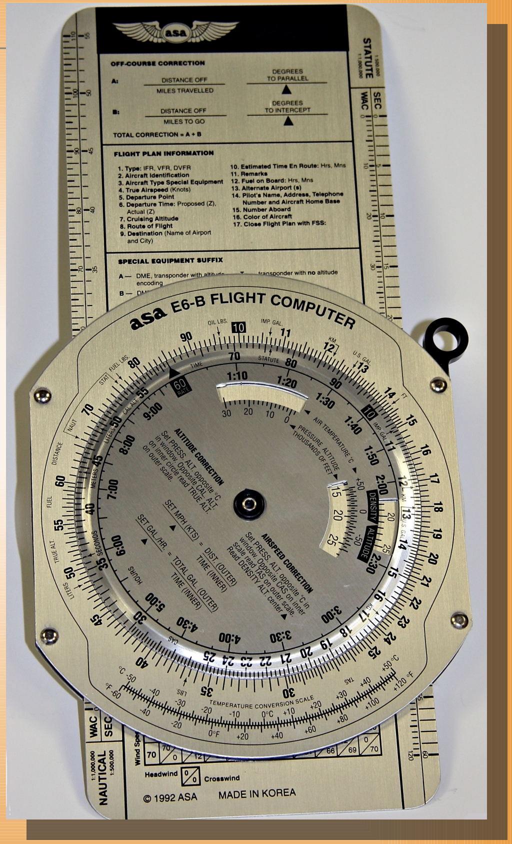
- GPS is an indispensable military asset
- GPS is a vital public utility
- Civilians cannot afford to take GPS for granted, and broader public policy engagement is needed

Credit: U.S. Government, gps.gov

New Project

Biography of Capt. Philip Van Horn Weems

- Played a major role in advancing airplane navigation during the 1920s-1940s
- Taught Lindbergh celestial navigation
- His colleague, Harold Gatty, taught Hap Arnold
- Co-patented, with Philip Dalton, the E-6B Flight computer (shown at right)
- Founded Weems & Plath, a manufacturer of nautical and weather instruments



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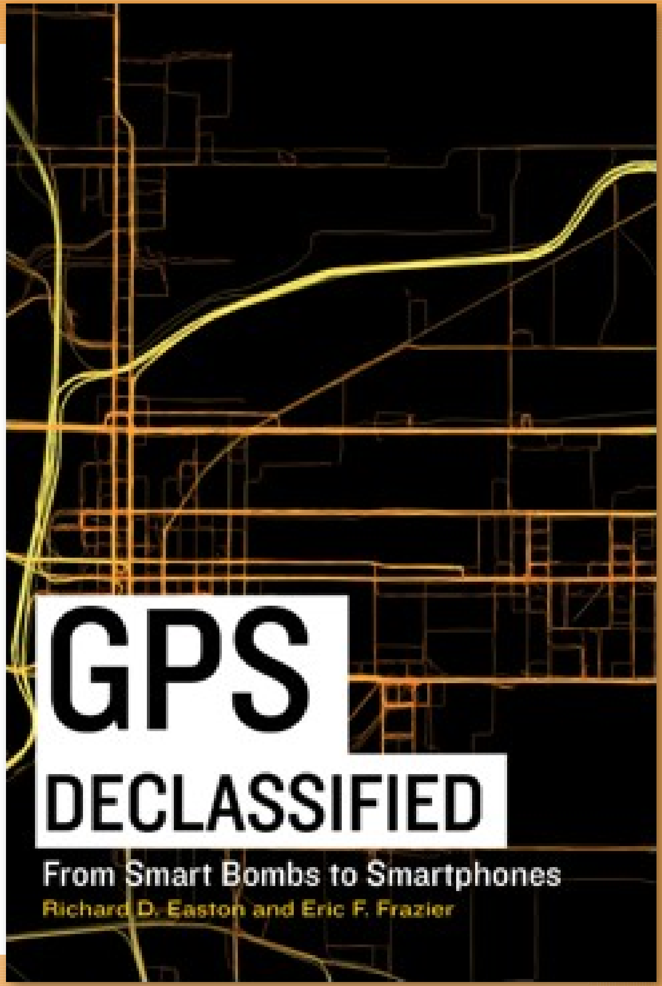
Test Your GPS IQ: True of False?

1. DARPA invented GPS.
2. Ronald Reagan declassified GPS for civilian use in 1983.
3. Global synchronized time was an unexpected consequence of GPS.
4. The U.S. government alters GPS signals during terrorist alerts.
5. The number of users today threatens to overwhelm GPS capacity.

Questions?


GPS
DECLASSIFIED
From Smart Bombs to Smartphones
Richard D. Easton and Eric F. Frazier