The Development of the GPS System ...1964 to 1978

Chief Engineer, Design/Development of the initial GPS Satellite, Rockwell International

Hugo Fruehauf
Scientific & Technical Consultant
thfc@hugofruehauf.com, 001-714-724-7069
September. 2014

World War II

Germany: ~1.6 – 2.0M tons of Allied bombs
Euro Theater: ~2.8M – 3.1M tons
~4.4M – 5.1M tons Total

For Germany alone
~600,000 – 1M Civilian Casualties
~95% Infrastructure destroyed

- Cities of >80,000 population, ~100 cities/targets
- Bombing from ~10km altitude
- More than 10% of bombs didn’t explode

*Ref: Wikipedia and a host of other websites
Future Warfare Strategy

• Regime change, Tactical Scenarios
• Absolute minimum Collateral Damage
• Precision Targeting would be required
• Ultimate System would require:
  - Global Coverage
  - 24/7 Availability
  - Precision 3D Positioning, Navigation, and Time
  - $2\sigma$ Precision Targeting Dependability
  - Military Secure Signal (Mil-Com’I Coexistence)
  - CONUS Satellite Control & Orbital Maintenance
Earlier 2D Nav Systems & 621B Project

- Early ‘60s to ‘70s, 2D Global Navigation became reality:
  - Transit Sats, Navy, Global, ~300m
  - Loran-C Grd Sta’s, CG/Navy, Coastal, ~200m
  - Omega Grd Sta’s, CG mainly, Global, <1km

- Breakthrough mid-60s, for 3D navigation - 621B Project, USAF & Aerospace Corp.

621B Inverted Range

The time is . . . My location is

Transmitter (1) Cs Clock
The time is . . . My location is
Transmitter (2) Cs Clock
The time is . . . My location is
Transmitter (3) Cs Clock
The time is . . . My location is
Transmitter (4) Cs Clock
Further Developments; 621B & NRL

• NRL research, mid to late-60s with passive ranging:
  - Launch of Timation I & II satellites, 1967 & 1969, with other gov agencies contributing to concept validations

• Navy & USAF rivalries for control of 3D navigation programs solved by forming a Joint Program Office, headquartered at LAAFB, California (next to LAX)
  - “JPO” *(USAF-Navy)*; other services sent representatives
  - PMs: Col. Brad Parkinson (USAF) & Cmdr. Huston (USN)
  - Right hand to Brad, Cap. Gaylord Green (USAF)

• With the military and gov agencies now teamed to succeed, a GPS system began to emerge

• Gov engaged industry in 1973 to help develop a final GPS concept from available research/data and new ideas
No doubt, the most significant person that made GPS happen (then, Col. Parkinson, USAF)

- Pentagon & Capital Hill political savvy to get program funded
- Systems Design Engineering Expert
- Brilliant Program Management

Brad Parkinson, Ph.D
Stanford U, Emeritus
GPS emerged in (3) Segments

GPS program divided into (3) Segments:

(1) **Satellite Segment**
   (then) Rockwell International, Seal Beach CA

(2) **User Segment**
   (then) mainly Magnavox, Torrance CA and Rockwell-Collins, Cedar Rapids, IA

(3) **Control Segment**
   Master Control Station + Monitor Stations (MCS + MS’s)
Global Positioning System
PHASE I (VALIDATION PHASE)

DNSDP (GPS) Proposal 1974; Rockwell’s winning design

Other bidders:
- RCA,
- Philco Ford
- Grumman

Giants in the Satellite Industry – not bid:
- GE
- Hughes

- Proposal System
- Initial Gov/Mil R&D
- RFI-Industry Invt’mt & Gov?
- RFP-Mainly Industr .Invt’mt, sometimes Gov help
DNSDP - Defense Navigation Satellite Development Progr. (later renamed “GPS”)

Rockwell Design Team (1973-75)
GPS Technical Challenges

- Global Coverage and 24/7 Availability
- Precision 3D Navigation and Positioning
- \(2\sigma (\sim 95\%)\) - Targeting Dependability
- Precision Timing and Synchronization
- CONUS satellite updates
- Including UTC; (604,800 s/week & 1023-0 bit Weeks + leap secs)
- Spread Spectrum Quadra-Phase C/A+P(Y) + 50 bit Data Signal Format
- C/A as acquisition-aid for long P(Y)-code Mil Signal
- Shaped Beam Antenna
- (4) Sats for 3D Nav (User RCVR w/o atomic clocks)
- Relativity Compensation
- Selective Availability (SA) – PNT accuracy of C/A
- 1,400 lbs limit for initial GPS Sats; 21 launches on Atlas-F’s
- Military control of GPS Sats and Ground Control Segment (MCS)

*Week 0 started at 00:00:00 UTC on Sun. Jan. 6\(^{th}\) 1980, and ‘rolled over’ after exhausting 1023 bits of weeks (~19.7yrs); 23:59:47 UTC, Sat. Aug. 21\(^{st}\) 1999*
GPS Biggest Risk – the Atomic Clock

- Efratom’s Ernst Jechart & co-founder Gerhard Hübner - inventors of the small (~10x10x10 cm) Rb Vapor Atomic Clock
- Werner Weidemann – Engineering
- All worked for Rohde & Schwarz – Munich Germany

Issues:
- 1st chaotic meetg
- Language
- Foreign Co.
- Very Small
- Overwhelmed
- Citizenship
- Space Knowhow (RI-Efr Team)
- Rb Confidence
- Efratom 1978
- Ernst 1991 (54)
- Werner 2008 (65)

Efratom GmbH, Munich + later Irvine, CA
GPS Rb Clock + ‘Std-alone’ OCXO

Rockwell-Efratom GPS Rb Clock

- Rb Physics Package
- 10 MHz OCXO

Satellite Clock Control

- 10.23 MHz Output
- 10.23 MHz for ‘Coherence’
  - \( x \times 145 = 1,575.42 \text{ MHz, (L1)} \)
  - \( x \times 120 = 1,227.60 \text{ MHz, (L2)} \)

The ‘saving grace’ Political Switch to isolate the Atomic side

GPS Rb Clock (case removed)
DNSDP (GPS) Proto-type Rad Hard Rb - Performance, RI-Efratom FRK-Rb, 1974, Hugo Fruehauf, Werner Weidemann, Dale Ringer, Chuck Wheatley, Norm Rudie
Today's GPS Rb Clock Stability

- $\sim 5 \times 10^{-12}$
- $1.5 \times 10^{-13}$
- $1.5 \times 10^{-13}$
- $1.5 \times 10^{-15}$

Limit of the used measurement system:

- $10^{-14}$
- $10^{-15}$

Clock stability:

- $1,000$ Sec
- $100,000$ Sec

- $10^3$ Torr vacuum
- Taken while in $10^3$ Torr vacuum

Unmodified FRK:

- Rb clock stability

Time domain stability:

- $\tau_{\text{sampling time}} (\text{S})$
GPS Blk IIF RFS Stability Performance

Chart from: “GPS Block IIF Atomic Frequency Standard Analysis”; F. Vannicola, R. Beard, etc. (NRL)
Efratom Rb Oscillator Display

(Smithsonian Institution, 1982 to 1988)
NTS-1 nearly complete, May 1974

Different names have been used for the satellites of the GPS at different stages of its development. The first to carry atomic clocks were the Navigation Technology Satellites (NTS), numbers 1 and 2, built by the Naval Research Laboratory and launched in July 1974 and in June 1977. Subsequent satellites called Navstar-1, -2, etc., have been built by Rockwell International under contract to the U.S. Air Force.

Atomic clocks on board NTS-1

Two EFRATOM Model FRK rubidium-vapor frequency standards, similar to the flight back-up exhibited here, sit on the ring-shaped instrument deck of the NTS-1 satellite. On July 14, 1974 they were launched into orbit.
# Satellite Navigation Clock History to GPS

*(Hugo Fruehauf, Ron Beard, Brad Parkinson; 01-13-2010)*

<table>
<thead>
<tr>
<th>Program / (Service)</th>
<th>Dates</th>
<th># of Sats / Nav Method</th>
<th>Nav Dim</th>
<th>Clocks</th>
<th>Ops Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>NNSS (Transit); (Navy-JHU/APL)</td>
<td>1964 to ~1990</td>
<td>(7) Sats; Doppler meas.</td>
<td>2D</td>
<td>(1) Quartz Oscillator</td>
<td>Was fully operational</td>
</tr>
<tr>
<td>Timation I &amp; II; (Navy- NRL)</td>
<td>1967 and 1969</td>
<td>(2) Sats; Ranging Tones</td>
<td>2D</td>
<td>(1) Quartz Oscillator</td>
<td>Experimental</td>
</tr>
<tr>
<td>Navigation Technology Satellite-1 (NTS-1) (Navy- NRL)</td>
<td>Launch July 1974</td>
<td>(1) Sat; Hazeltine 621B Transm., No Data; Ranging Tones</td>
<td>2D</td>
<td>(2) Efratom Com’l Rb’s, modified by NRL to perform in space, +(1) Quartz Osc</td>
<td>Experimental: (1) Rb operated for more than one year; (1) Rb failed early</td>
</tr>
<tr>
<td>NTS-2; (Navy-NRL); USAF/JPO provided Nav. Payload</td>
<td>Launch July 1977</td>
<td>(1) Sat; ITT Eng’g PRN Nav. Pkg. from USAF-JPO; + Rang’g Tones</td>
<td>2D</td>
<td>(2) Proto space qualified FTS Cs + (2) Quartz Osc’s</td>
<td>Although intended to be part of the initial (4) Satellite Nav testing, NTS-2 failed before nav testing began</td>
</tr>
<tr>
<td>GPS Operational Prototypes, award’d to Rockwell in 1974 by USAF-JPO, now “GPS Wing”; named GPS in Dec 1973; DNSDP* during early proposal effort</td>
<td>Devel’mt 1973-75; Rockwell Block-I launches began Feb.1978</td>
<td>(4) Sats, Production ITT PRN Nav. Pkg</td>
<td>3D</td>
<td>(3) RI-Efratom Rb’s on the 1st (3) GPS Sats; 4th Sat &amp; up, (3) RI-Efratom Rb’s + (1) 2nd gen. FTS Cs**. 1st Cs on GPS 4 failed after 12 hrs; Cs ok - GPS-5 &amp; up</td>
<td>GPS Constellation of (4) Rockwell Block-I GPS Satellites for the initial Navigation Test Program + (1) NRL NTS-2 Sat, but failed before nav testing began (see above)</td>
</tr>
</tbody>
</table>

* Defense Navigation Satellite Development Program

** Later, Block-II and -IIA flew (2) Rb and (2) Cs
GPS Technical Challenges

- Global Coverage and 24/7 Availability
- Precision 3D Navigation and Positioning
- $2\sigma (~95\%)$ - Targeting Dependability
- Precision Timing and Synchronization
- CONUS satellite updates
- Including UTC; (604,800 s/week & 1023-0 bit Weeks+ 13 leap sec)

- Spread Spectrum Quadra-Phase C/A+P(Y)+ 50 bit Data Signal Format
- C/A as acquisition-aid for long P(Y)-code Mil Signal
- Shaped Beam Antenna
- (4) Sats for 3D Nav (User RCVR w/o atomic clocks)

- Relativity Compensation
- Selective Availability (SA) – PNT accuracy of C/A
- 1,400 lbs limit for initial GPS Sats; 21 launches on Atlas-F’s
- Military control of GPS Sats and Ground Control Segment (MCS)

- Cold War Issue
  ~(-)25dB below
- Existing 2D Nav
- Commercial Mrkt
- Spoofing Problem
GPS Navigation Payload (original)

- Atomic Osc. S.A. Phase Shifter (Dither)
- Uplink Control
- Rb or C_s, 10.23 Hz

- Mult. (L1) 1575.42 MHz
- Mult. (L2) 1227.6 MHz
- Mult. (L3)

- PRN-Gen (A) C/A Code
- PRN-Gen (B) P Code

- 1.023 MCPS
- 10.23 MCPS

- 50 BPS
- 10.23 Hz

- Data
- Uplink Control

- HPA (L1)
- HPA (L2)
- HPA (L3)

- Y-Code
- 90°

- A.S. Encryp’n Device

- Helix Array Ant.

QPSK C/A, P(Y) & Data Signals (original)

Carriers (L1/L2)

Phase Shift Keying (PSK) Modulation

C/A - Code (L1)

P- Code (L1/L2)

Data (L1/L2)

(AS) Encryption
P becomes (Y)

Transmitted in Phase Quadrature (90° Out of Phase)

(SA) Degrad.
Now set to Zero

1540 Cycles per C/A-Chip

1.023 MCPS, ~290 m

10.23 MCPS, ~29 m

50 BPS

C/A Code

Y-Code

P Code

Phase Shifter (Dither)
(On All Above Signals)
**Original GPS Signals**

- **L1 1575.42 MHz**
  - Open Signal
  - C/A-Code 1.023 Mcps,
  - + 50 bps Data

- **Encrypted Signal**
  - P(Y)-Code 10.23 Mcps
  - + 50 bps Data

- **L2 1227.6 MHz**
  - Encrypted Signal
  - P(Y)-Code 10.23 Mcps
  - + 50 bps Data

- **L3 – Other Payload**
  - New signals being added to GPS SVs
    - L1C
    - L1-M
    - L2C(M&L)
    - L2-M
  - L5 - 1176.450 MHz
  - L4 - 1379.913 MHz
Shaped-Beam (12) Helix Phased Array Antenna, RHC Polarized

Received Power vs. SV Elevation Angle

*1x10^{-16} watts*
L-Band Navigation-related Frequencies
GPS, Glonass, Galileo, BeiDou, SBAS, Iridium, SAR

Note:
• Black, Blue, Light Blue, & Dark Brown signals, fully operational
• Red and Purple signals, only on a few GPS satellites
• Dark & Light Green, future Galileo signals (some Sats up now)
• Yellow, future Glonass signals
• Light Brown, future BeiDou (China Compass) signals (some Sats up now)
• White, Future GPS-III signal

WAAS, EGNOS, MSAS, GAGAN, etc. generated “L1-C/A Look-Alike” 250 bps
Space Borne Passive 3D Ranging

The Realistic GPS System

R₁ = C(Δₜ₁ + ΔT - τ₁)
R₂ = C(Δₜ₂ + ΔT - τ₂)
R₃ = C(Δₜ₃ + ΔT - τ₃)
R₄ = C(Δₜ₄ + ΔT - τ₄)

4 Equations — 4 Unknowns
Civil and Military Signal Relationships

GPS Sats

L2 P(Y) + 50 bps
L1 C/A, P(Y) + 50 bps

Mil P(Y) Code Mod. + Data
Mil P(Y) Code Mod. + Data

~6.2 x 10^{12} Chips; repeat each week
1023 Chips; repeat each ms

Real-time Ionospheric Corrections
Partial Ionospheric Corrections (Model only) until L2C is Operational

Crypto Key

P(Y) PNT
C/A PNT

PNT, Data, 1PPS

Typical GPS Receiver

Europe’s Galileo, etc..
GPS Technical Challenges

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- Existing 2D Nav
- Commercial Mrkt
- Spoofing Problem
- 1st (4) Sat testing
The Relativity Story

MAJOR GAYLORD GREEN. His innovations included design of the modified orbits that ensured daily test time at the instrumented Yuma range.

WALT MELTON, early leader of the Aerospace

ED LASSITER was the Aerospace program manager under Brad Parkinson for the latter stages of Phase 1. A skilled engineer with much flight experience, he was especially skilled at early identification and solution to

DR. MALCOLM CURRIE. As the number 3 man in the Pentagon, his support was essential to overcoming resistance from the Air Force.

Government JPO Principal Engineer

Dr. Edward Teller, Lawrence Livermore National Laboratory, CA
Relativity & Clocks Frequency

**Special Theory** - Time runs differently for observers in relative motion:

**General Theory** – Time runs differently for observers at different heights in a gravitational field

\[ \Delta t_r = t_{\text{one day}} \times \frac{\Delta f}{f} = 86,400 \times 4.46 \times 10^{-10} \]

\[ \Delta t_r = 38,621 \text{ nsec} \]

**For GPS:**

\[ \frac{\Delta f}{f} \approx -0.83 \times 10^{-10} \]

\[ \Delta f \approx 4.46475 \times 10^{-10} \text{ (nmi)} \]

GPS Orbit 10,898 nmi
(20,162.61 Km)

~38.6 microseconds; about 7 mile error per day,
GPS Technical Challenges

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- Spoofing Problem
- 1st (4) Sat testing
Initial Launches - Atlas-F’s

~1,400 lbs Lift
~ 550 lbs Apogee Motor
~ 750 lbs spacecraft

GPS Sat Orbit injection configuration

~ 11K nmi. Apogee

~ 70 nmi. Perigee
GPS Satellite (Block I) – Rockwell (RI)

Major Characteristics

- Launch mass: 1,400 lb.
- On-Orbit mass: 735 lb.
- Solar Array: 500 Watts
- Design Life: 4.7 years MMD
- Consumables: 7 years
- Clocks: (3) Rb (RI-Efratom)

All Have Been Launched
GPS Satellite (Block II, IIA) Rockwell

Major Characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Block II</th>
<th>Block IIA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch mass</td>
<td>3,660 lb.</td>
<td>4002 lb.</td>
</tr>
<tr>
<td>Solar Array</td>
<td>710 Watts</td>
<td></td>
</tr>
<tr>
<td>Design Life</td>
<td>7.3 years</td>
<td></td>
</tr>
<tr>
<td>Clocks</td>
<td>(2) Rb RI-Efratom</td>
<td>(2) Cs FTS</td>
</tr>
</tbody>
</table>

All Have Been Launched

## GPS Satellite (Block IIR) – LMSC

<table>
<thead>
<tr>
<th>Major Characteristics</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch mass</td>
<td>4,478 lb.</td>
</tr>
<tr>
<td>On-Orbit Wt</td>
<td>2,484 lb.</td>
</tr>
<tr>
<td>Solar Array</td>
<td>1,040 Watts</td>
</tr>
<tr>
<td>Design Life</td>
<td>7.5 years</td>
</tr>
<tr>
<td>Clocks*</td>
<td>(3) Rb Excelitas</td>
</tr>
</tbody>
</table>

All Have Been Launched

GPS Satellite (Block IIF) – Boeing*

* Was Rockwell International

**Major Characteristics**

- **Launch mass**: 4,634 lb.
- **On-Orbit Wt**: 3,230 lb.
- **Solar Array**: 1,900 Watts
- **Design Life**: 12 years
- **Clocks**: (2) Rb Excelitas
- ****Cs MicroSemi (Symmetricom)

GPS Technical Challenges

- Global Coverage and 24/7 Availability
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- Cold War Issue
- Existing 2D Nav
- Commercial Mrkt
- Spoofing Problem
- 1st (4) Sat testing
GPS Infrastructure

GPS Satellites

Satellite L-Band Downlinks

Satellite Control S-Band Uplinks

Monitor Station Cs Clocks (Ascension)

Monitor Station Cs Clocks (Kwajalein)

Monitor Station Cs Clocks (Diego Garcia)

Monitor Station Cs Clocks (Schriever)

GPS Master Control Station (MCS-Schriever AFB)

BIPM Paris

USNO Wash. DC

NRL
Extracting GPS Clock Error from Ephemeris (Sat Position) Error

Monitor Station Cs Clocks (Schriever)

Monitor Station Cs Clocks (Hawaii)

Monitor Station Cs Clocks (Ascension)

Monitor Station Cs Clocks (Kwajalein)

Monitor Station Cs Clocks (Diego Garcia)

GPS Satellites

Ephemeris

GPS Satellites
GPS Master Clock and BIPM

- BIPM (International Time Bureau)
- TAI (International Atomic Time)

*UTC is maintained within ~0.9 sec. of UT-1. If exceeded, ("Leap-Second")
If precision bombing was available then to destroy Germany’s war-related infrastructure:

~100 cities/target areas
(3) targets each area
(4) yrs of bombing, weekly
(1) ton bombs
(2σ) targeting accuracy

Best guess Results:

~95% of the targets destroyed
<5000 Civilian Casualties, not ~600,000 to 1M
~60K tons of bombs, not ~1.6M to 2M tons
GPS Receivers

GPS Navigation, Positioning, and UTC has become a global utility, along with:
- Water
- Energy
- Communications
- and Sanitation

GPS-related sales:
- 2013, $60B to $100B
- 2020, expect GPS/GNSS, >$1T

>1B Nav & Timing Rcvrs in use today (~7B global population)