Systems Integration

Case Study: The Global Positioning System

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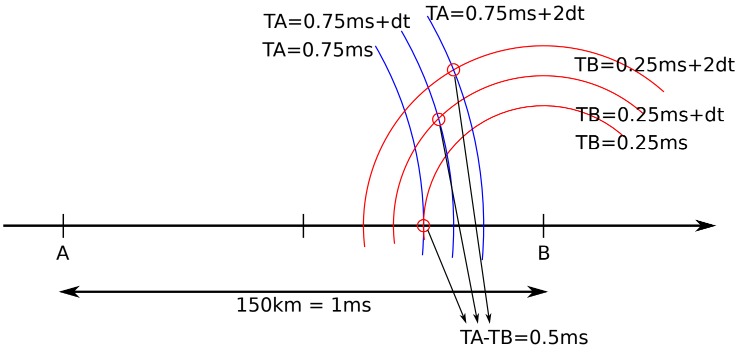
Source: A significant part is from Mark W. Maier and Eberhardt Rechtin's *The Art of Systems Engineering 3rd Ed*

The Origins of GPS

The Problem

- Position determination and navigation are fundamental to military operations
- Inertial navigation
  - Well suited to nuclear missiles
  - Short flight time (< 30 min). Accurate if launch position is accurate. Immune to external interference
- Might be a problem for navy (ships, submarines): initial position drifts in days.
- Ships: altitude known, 2D-positioning sufficient
- LORAN

LORAN. Hyperbolic navigation



The Origins of GPS /2

Weapon Delivery

- Air-delivered weapons innacurate
- Bridge
- Moving targets require pilot flying low and in direct sight
- Sensor guidance was the solution

The Origins of GPS /3

Transit (NAVSAT)

- Sputnik launch in 1957
- Doppler shifts in signal: lines of position at the receiver if transmitter position is known
- First satellite launch in 1960. Last one in 1988. Operated until 1996
- 100 m accuracy with 2 minutes of Doppler curve
- Architecture: purpose driven, clear architect and architecture, users and developers aligned
  - Provide positioning 2 decades before GPS
  - Technical advances: orbit determination, gravity models, compute and predict signal delays due to propagation in atmosphere
  - Set a precedent for commercial users

Timation and 621B

Timation

- Navy. Problem of time transfer or clock synchronization
- Timation I 1967
- Timation II 1969
- Synchronization and positioning are related (the same) problems

621B

- USAF. 3D high-precision positioning
- Delays to 3 known satellite positions
- Pseudo-random signals. Jam and interference resistant. Same frequency for all transmitters
- High-accuracy clocks in receiver

The Weekend that GPS was Architected

Revised Concept. 1973

- Measure ranges from 4 or more satellites: compute master time and position
- 21 to 24 satellites in inclined half geosynchronous orbits
- Atomic clocks on satallites. Updated from ground. Receiver computes time and position
- Pseudo-random codes. One wide and encrypted one narrow and unencrypted

Long road to success

- Basic architecture stayed invariant
- Transition from centrally-controlled to a collaborative system with no central authority

Evolution

Timeline

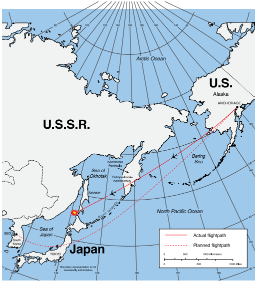
- 1960's: First satellites
- 2000's: last launches

Commercial markets

- 1984: shoot down of airliner
- Free use of the C/A signal (coarse/acquisition). Addition of clock noise to reduce accuracy ("selective availability")
- GPS Chipsets

Gulf War 1991

- Ground troops used receivers
- Precise air strikes
- GPS receivers on conventional dumb bombs



Revolution in the Second Generation

- Initial concept: Five bombs in the same hole
- Many new applications
- From specialized navigation device to universal add-on
- Time synchronization in telecommunication networks
- Moore's Law lowered receiver cost
- GPS policy lagged applications
- GPS enhancement transmitters for precise location together with SA
- 2000 SA was dropped

Architecture Interpretation

- Right idea, right time, right people
- Technically aggressive but not suicidal
- Consensus without compromise
- Architecture through invariants
- Revolution through coupled change

Right idea, Right Time, Right People

- Consensus between Navy and Air Force? Sell idea? Maintain through over a decade?
- Navy alone had not the needs for GPS
- Air Force alone was unable to sustain the program
- A significant contribution was the pseudo-random signal

Technically Aggressive, not Suicidal

- PRN signals
- Digital processing at 1 to 10 MHz was difficult. Custom hardware
- All-digital approach in 1970 lead to cheap receivers in 1990
- Half-geosynchronous orbit: fewer satellites at higher cost
- Precision clock on satellites not on receivers. Clocks have to survive a decade on satellite

Consensus without Compromise

- GPS is fusion of ideas
- Not a watered-down compromise
- Best aspects of the approaches of different stakeholders
- Simultaneous position and time determination from satellite signals alone, no auxiliary terrestrial signal, all-digital receiver, computation on receiver
- Single frequency
- But, L-band signal does not penetrate buildings and even foliage

Architecture as Invariants

- Signals unchanged
- Orbits had minimal changes
- Current satellites add new military signals
- Copy of unencrypted signal added to second frequency (direct measurement of ionospheric delay). Available to military, but not to civilian users
- Invariant signals: independent evolution of constellation and receivers
- Most receivers developed by commercial firms with no relationship with GPS program office

Revolution through Coupled Change

- Original slogan "five bombs in the same hole and cheap receivers"
- Cheap receivers, beyond original expectations
- Five bombs... not as important as thought originally
  - Low-cost receivers distributed to individual soldiers
  - Receivers cheap enough to be placed on weapons
  - Guided vs unguided weapons are similar
  - Surveyors have changed their operation
  - Ability to have globally referenced time: applications to electric power, financial and telecommunication control systems
  - Included in cell phones at a low cost. New applications