PNNL-SA-160389

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A growing dependence on (precise) time

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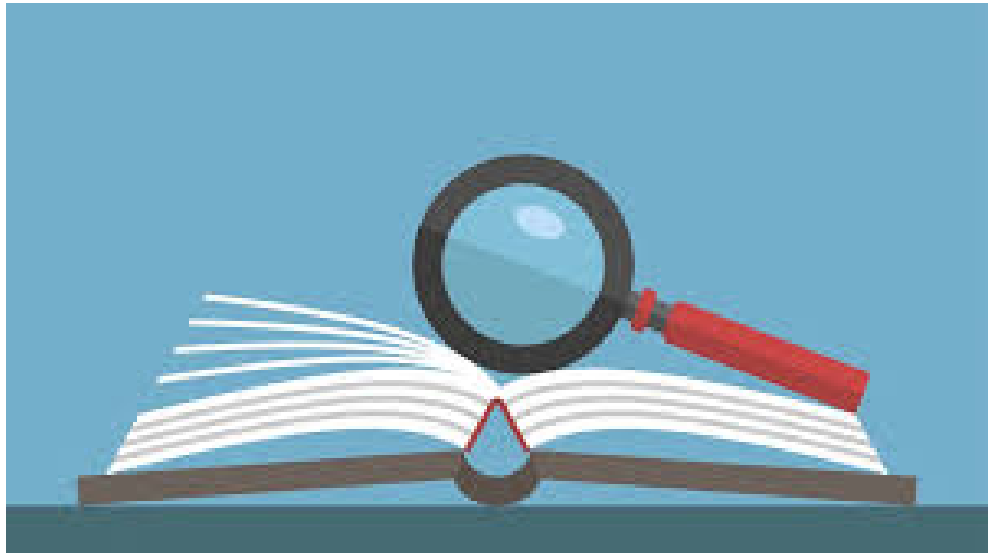
Definitions



What is 'precise time'?

- A time reference with resolution and precision appropriate for application

What about the precision part?

- Time reference is stable and will deviate from a known primary time standard (i.e. NIST atomic clock) no more than *x* over a specified period

Why does it matter?

- Near-instantaneous measurements over an area must be synchronized (i.e., PMUs)
- DFRs / Oscillography must be synchronized
- Travelling wave / LD relays must be synchronized

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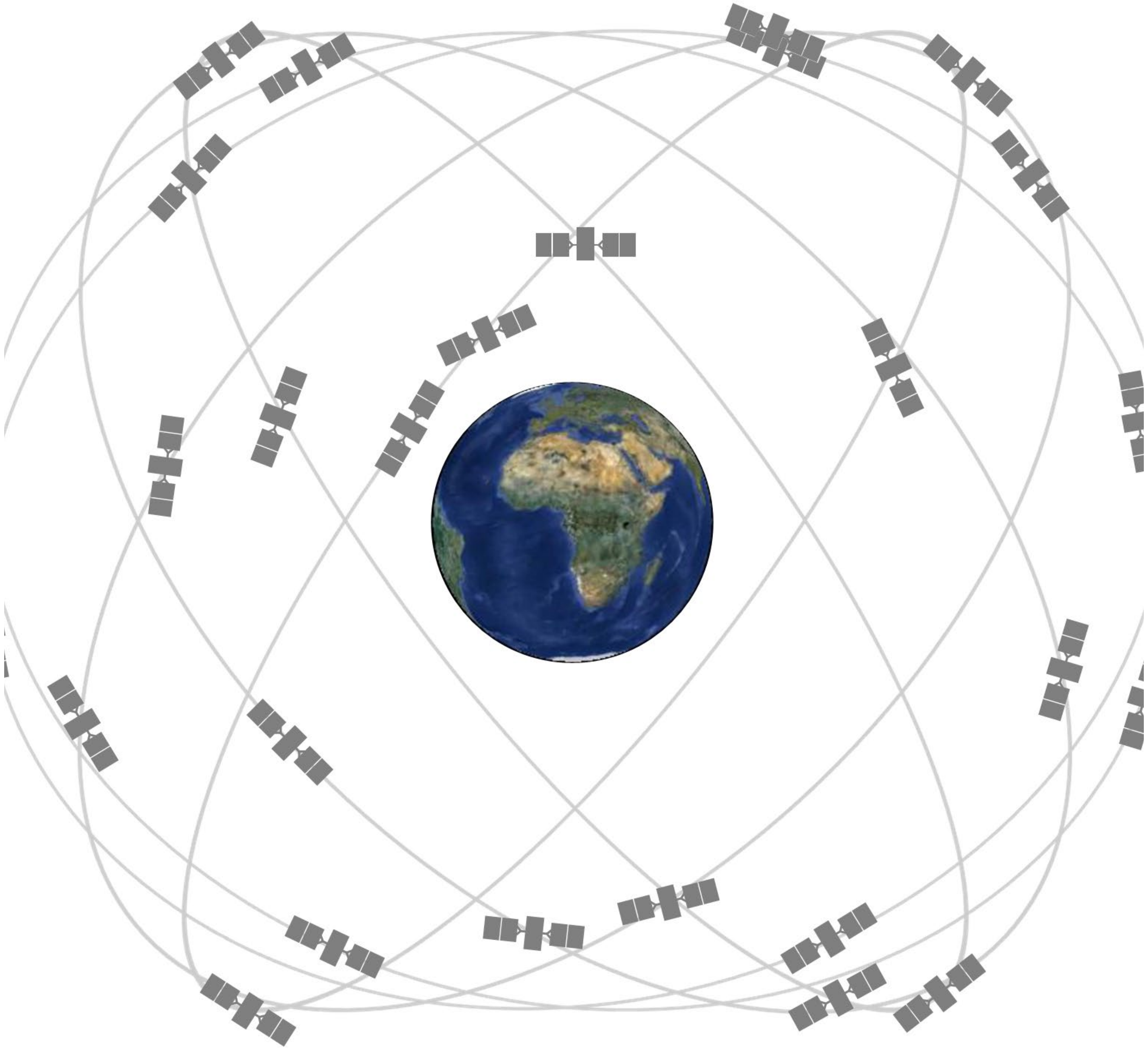
A brief history of Navstar GPS

- Project start 1973
- First SV launched 1978
- 24-SV constellation operational 1993
- 7th gen Block IIIA SVs started launching 2018 (4 operational)



What is GPS?

Per gps.gov: “A US owned utility that provides users with PNT services”

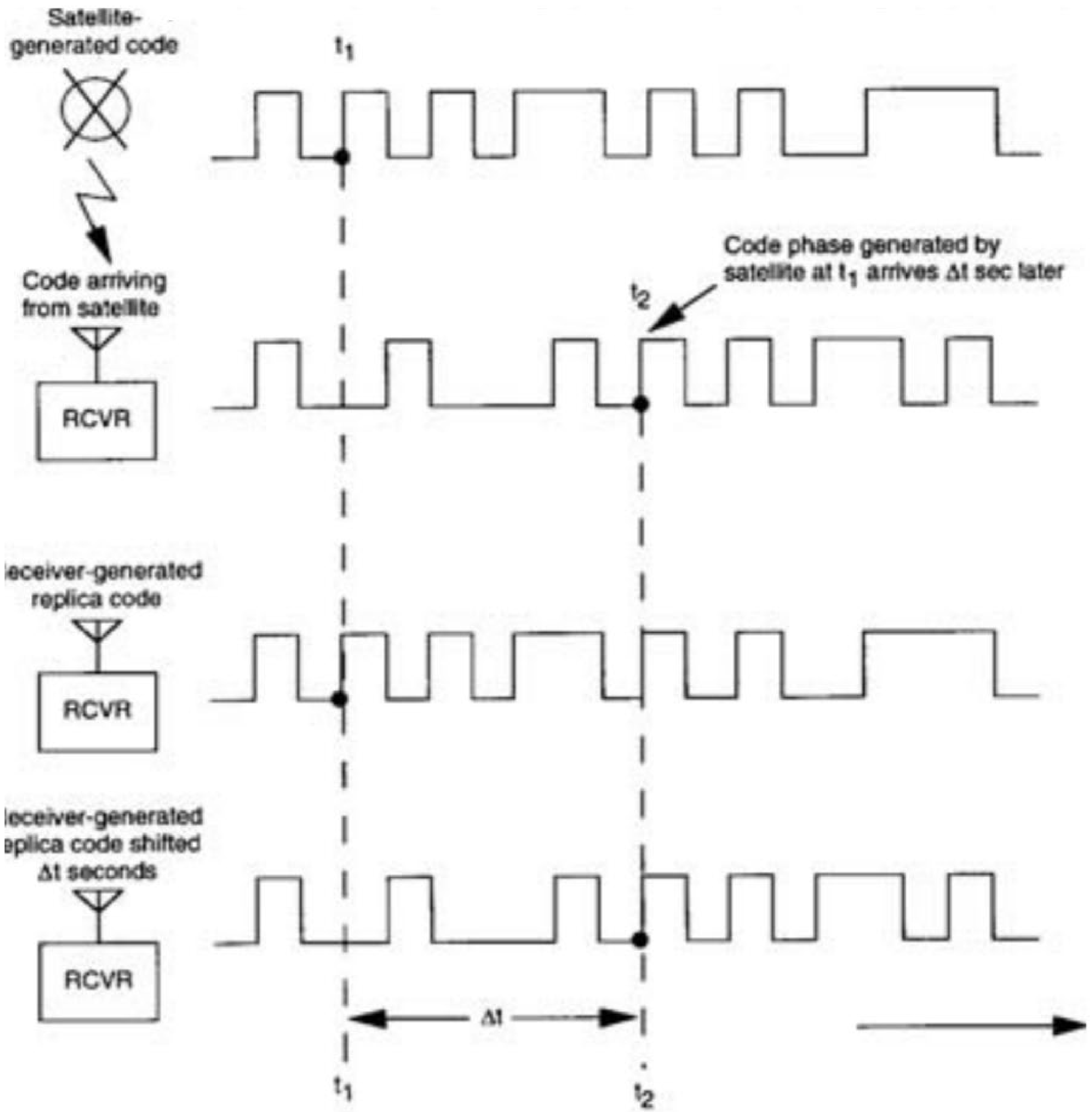
A **G**lobal **N**avigation **S**atellite **S**ystem (GNSS)

Three segments:

- Space Segment - constellation of 24 operating SVs/sats in MEO (~12,550 mi)
  - Orbital arrangement guarantees view of at least 4 sats for any terrestrial user
- Control Segment – global network of ground facilities that track sats
  - Monitor/analyze satellite performance
  - Send commands to sats (i.e., relativistic clock corrections, orbital corrections)
  - 1 Master control station, 1 alternate, 11 command & control antennas, 16 monitoring sites on every continent except Antarctica
- User segment

Principle of operation

- GPS sats carry multiple Rb / Cs clocks synchronized by Ground Segment
- Each SV continually transmits data phase-modulated on a GHz carrier:
  - C/A (coarse acquisition) 1023-bit PRN code unique to each satellite,
  - P code
  - Navigation message
    - ✓ Precise time of message sending
    - ✓ Ephemeris information
    - ✓ Ionospheric model parameters
- User/Receiver:
  - Has copy of PRNs for entire constellation
  - Grid search through PRNs, Doppler shifts, signal-time steps until match is achieved
  - PRN autocorrelation lifts received signal from ~-120db to ~90db
  - Process happens for all received sats in view simultaneously in parallel



Kaplan (ed.), *Understanding GPS: Principles and Applications*, Artech House, 1996

The math

$$R'_1 = \sqrt{(x - x_1)^2 + (y - y_1)^2 + (z - z_1)^2} + c\delta t$$

$$R'_2 = \sqrt{(x - x_2)^2 + (y - y_2)^2 + (z - z_2)^2} + c\delta t$$

$$R'_3 = \sqrt{(x - x_3)^2 + (y - y_3)^2 + (z - z_3)^2} + c\delta t$$

$$R'_4 = \sqrt{(x - x_4)^2 + (y - y_4)^2 + (z - z_4)^2} + c\delta t$$

Where R_n’ is pseudo range, (x_n,y_n,z_n) are SV positions, (x,y,z) is receiver position

- Simplified – does not yet include ionospheric errors, orbital errors, multipath, or receiver noise
- 4 unknowns (x,y,z,dt) – 4 equations
- Must be solved simultaneously, for all locked sats
- Receiver sophistication: code match → carrier match → differential corrections

Vulnerability of the GPS signal

- GPS signal is extremely weak – below noise floor
- Precise position and time require continuous data from at least four sats
- Urban environments challenging for receivers – blocked views, multipath
- L-band is busy and will get busier – Ligado, LightSquared
- Coronal mass ejections can interfere with signal
- GPS can be intentionally disrupted by military exercises (upward trend)

A specific note on jamming

- Intentional GPS jamming blocks or disrupts the weak GPS signals
- Achieved by transmitting powerful noise on same frequency
- Receiver cannot ‘hear’ signals from sats anymore
- Jamming is exceptionally easy and cheap, requiring none of the sophistication that spoofing does (SDRs, modified microwaves)
- Jamming can originate from unauthorized/malevolent actors **AND** from legal military exercises

<u>Implications:</u>

- GPS cannot be relied up to be available 100% of the time
- GPS cannot be the only high-precision timing source in time-critical applications

Example GPS Testing Schedule

APPROVED GPS TESTING (UPDATED FEBRUARY 18, 2021)

TEST PERIOD APPROVED BY DEPARTMENT OF DEFENSE, EXACT DATES AND TIMES OF TESTING, DURING APPROVED PERIOD, WILL BE DETERMINED BY TEST RANGE EVENT PLANNERS AND SUBJECT TO CHANGE.

Area	Range	Date(s)	BNM/LNM
86 NM WEST OF SAN DIEGO, CA SCTTRCA GPS 21-03	154 NM	26 FEBRUARY 2021 & 27 FEBRUARY 2021	YES
WHITE SANDS MISSILE RANGE, NM WSMRNM GPS 21-04	171 NM	17 FEBRUARY 2021 & 19 FEBRUARY 2021	N/A
WHITE SANDS MISSILE RANGE, NM WSMRNM GPS 21-05	146 NM	08 FEBRUARY 2021 - 19 FEBRUARY 2021	N/A
BOISE, ID MHRC GPS 21-01	155 NM	01 FEBRUARY 2021 - 27 FEBRUARY 2021	N/A
FORT BLISS, TX FBLSTX GPS 21-01	87 NM	16 FEBRUARY 2021 - 21 FEBRUARY 2021	N/A

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What can grid operators do about it?

1. Administrative mitigation
   - Notification of GPS outages – www.gps.gov
   - Response procedures for loss of GPS timing in place and actively maintained
   - NIST offers guidance for response plan in NISTIR 8323:
     - ✓ Categories of incidents with graded approach based on timing needs
     - ✓ Timing resilience level requirements based on application criticality and impact
     - ✓ Assigned roles and responsibilities for personnel
     - ✓ Identified internal/external stakeholders
     - ✓ Information sharing policies

Mitigation

2. Technology options
   - Multi-constellation GNSS receivers – SEL-2488, Arbiter, MicroSemi
     - ✓ Issues: Foreign-operated, same frequency
   - Multi-band GNSS receivers – MicroSemi
     - ✓ Ionospheric dispersion direct measurement
     - ✓ Issues: subject to same weak signal problems (but with more redundancy)
   - Onsite backup timing sources – clocks with built-in Rb / Cs clocks or dedicated atomic clocks
     - ✓ Convenient option when purchasing new station clocks
     - ✓ Issues: depending on cost, may not offer much holdover (24 hrs)
   - Offsite (backup) timing sources – PTP fiber networks with multiple geographically separate grandmaster clocks per IEEE-1588
     - ✓ Most secure option
     - ✓ Issues: infrastructure

Conclusion

- Precise time important – but all eggs in one basket (GPS)
- GPS cannot be relied upon 100%
- Other GNSS cannot be relied upon 100%
- Best solution is likely a combination of administrative preparedness and multiple levels of technological mitigations with non-overlapping weaknesses

Questions?