A New Generation of Atomic Clocks

Steve Peil
US Naval Observatory

Outline

- USNO Master Clock
  - Commercial clocks

- USNO Rubidium Fountains
  - 15 year milestone

- Optical Atomic Clockss
  - Commercial
  - Lab systems

Overview

USNO Precise Time

- Master Clock
  - 100 atomic clocks
  - Authoritative source of UTC

- Global customer base
  - NTP
  - GPS

- Offset of GPS Time from UTC(USNO)
  - Typically within several nanoseconds
    - Modulo 1s

clock vault

GPS satellite

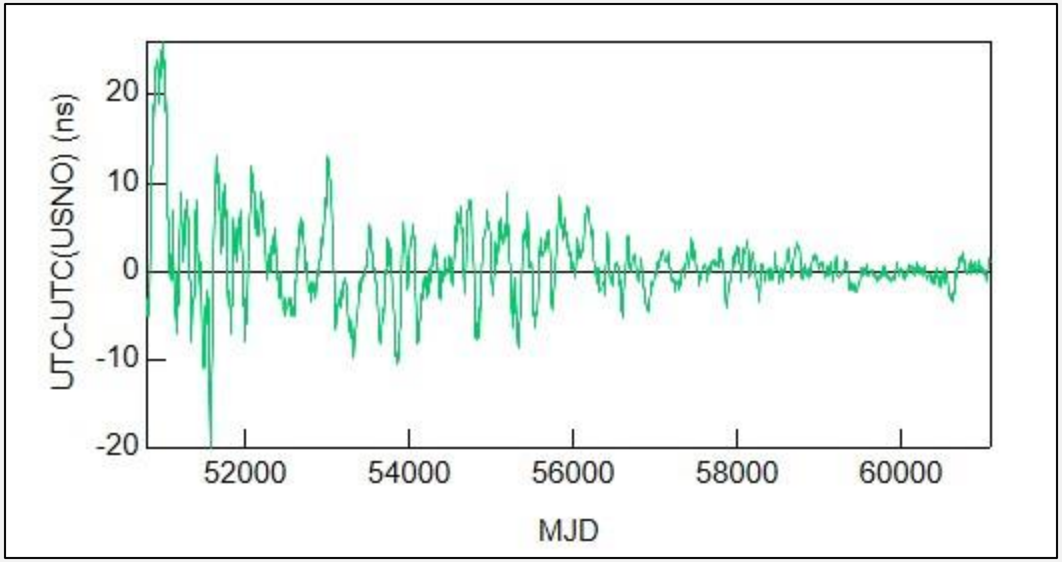
USNO Master Clock

UTC-UTC(USNO) < 2 ns

- Improvement over time

Want stable clocks for timescale

- Hydrogen Masers
  - 30+
  - Good short-term stability
  - Low (but unpredictable) drift
- Commercial Cesiums
  - 60+
  - Excellent long-term stability
- Vintage tech, mature, reliable
  - Cool atoms, higher frequency
- Rubidium Fountains
  - 6
  - Gold standard



H maser

Cs beam

Rb fountain

…not to scale …

USNO Rubidium Fountains

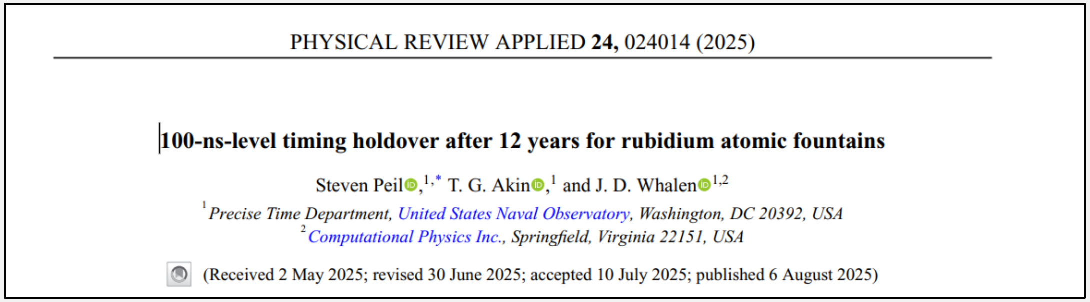
Designed, developed, built in house

Brought online March 2011

Start contributing to UTC April 2012
- Max weight
- Drift consistent with zero
- Good short-term

Key feature: **cold atoms**
- Laser technology

Holdover
- Tens of ns over 12 years …



PHYSICAL REVIEW APPLIED **24,** 024014 (2025)

100-ns-level timing holdover after 12 years for rubidium atomic fountains

Steven Peil[1,*] T. G. Akin,[1] and J. D. Whalen[1,2]

[1] *Precise Time Department, United States Naval Observatory, Washington, DC 20392, USA*
[2] *Computational Physics Inc., Springfield, Virginia 22151, USA*

(Received 2 May 2025; revised 30 June 2025; accepted 10 July 2025; published 6 August 2025)

USNO Rubidium Fountains

Designed, developed, built in house

Brought online March 2011

Start contributing to UTC April 2012

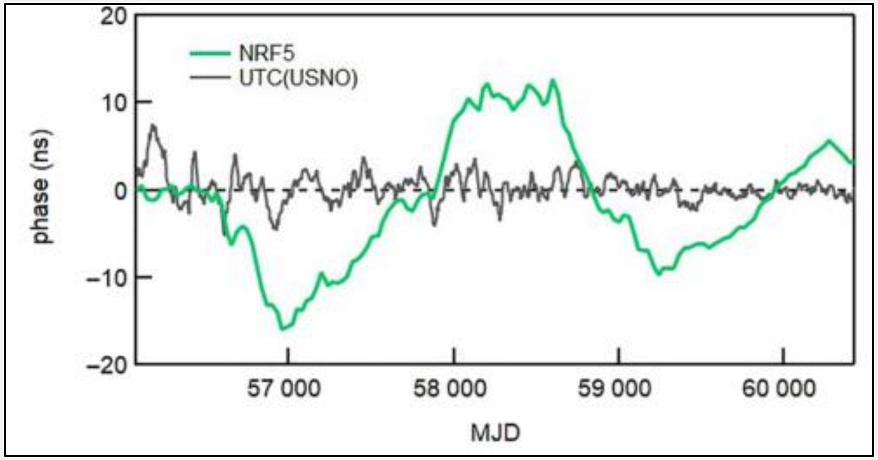
- Max weight
- Drift consistent with zero
- Good short-term

Key feature: **cold atoms**

- Laser technology

Holdover

- Tens of ns over 12 years …



Optical Clocks

Optical Frequency

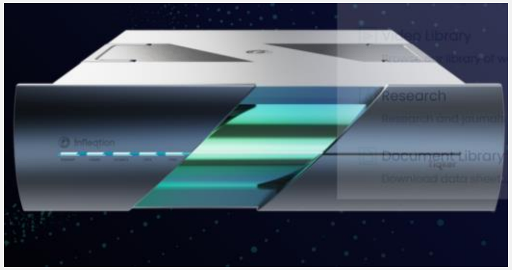
- x10^5 higher than microwave clocks
- Quality factor $Q = \frac{\nu}{\Delta\nu}$

Commercial Optical Clocks

- Optical spectroscopy, vapor cell, frequency comb
- "Low Q"
- Size of Cs, Performance of H
  - Not quite as good as H
    - Rack mount
    - Different from Cs
- Still being evaluated
  - Stability is good … reliability is under evaluation

Good laser tech (C band or 1064nm)

Vector Atomic Evergreen - Iodine



Infleqtion Tiqker - 2γ Rubidium

Vescent Miridian - Acetylene

Optical Clocks

Evergreen (30 L) → DARPA PICOSEC (5 L) → ONR MUSIC (1 L)

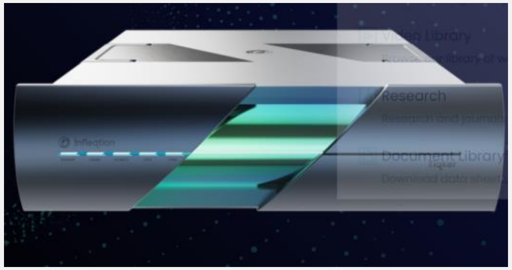
<u>Optical Frequency</u>

- x10^5 higher than microwave
- Quality factor $Q = \frac{\nu}{\Delta\nu}$

<u>Commercial Optical Clocks</u>

- Optical spectroscopy, vapor cell, frequency comb
- “Low Q”
- Size of Cs, Performance of H
  - Not quite as good as H
    - Rack mount
    - Different from Cs
- Still being evaluated
  - Stability is good … reliability is under evaluation

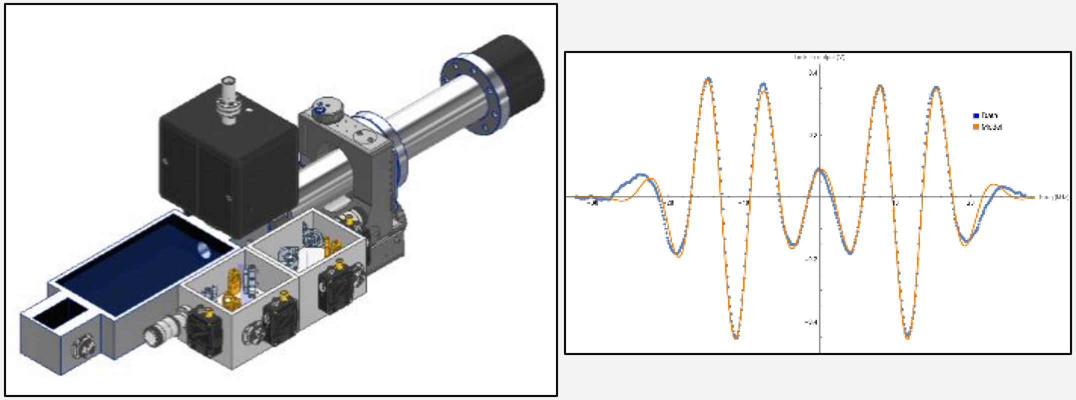
<u>Good laser tech (C band or 1064nm)</u>



Infleqtion Tiqker - 2γ Rubidium

Vescent Miridian - Acetylene

Optical Clocks


thermal Ca beam

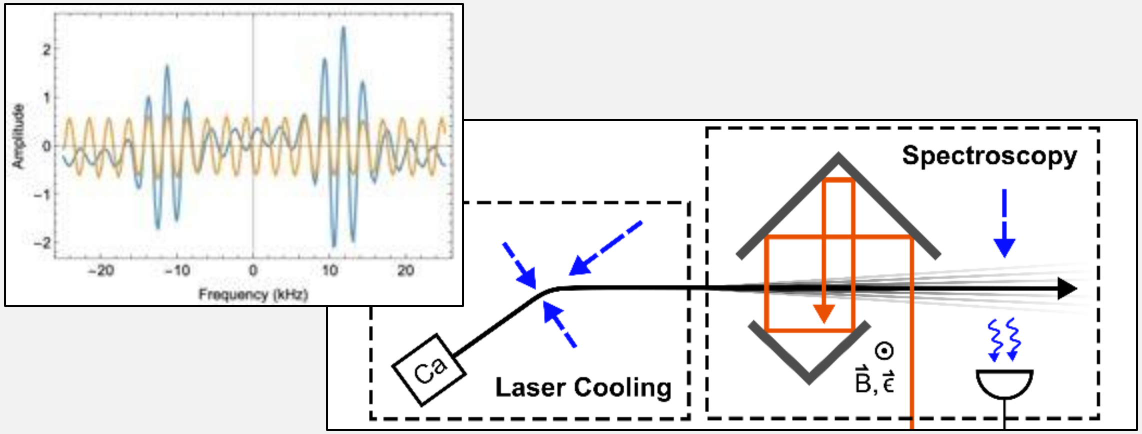


illustration of cooled Ca beam

Calcium (thermal) beam clocks

- Higher Q
    - Singly forbidden transition
    - Interaction time limited
- No laser cooling***
- Robust
    - 1 laser
    - 1 frequency comb
    - (Detection laser)
- Continuous operation

Cooled Ca beam clock

- 1 additional laser for cooling
    - Actually, 2
- 10x slower atoms

Long-term stability

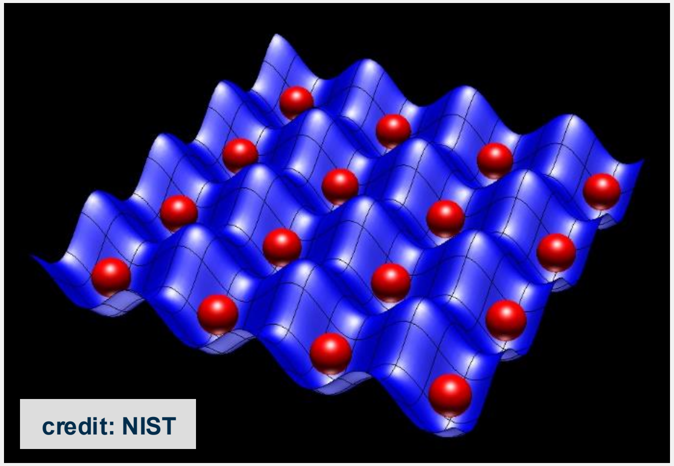
Optical Clocks

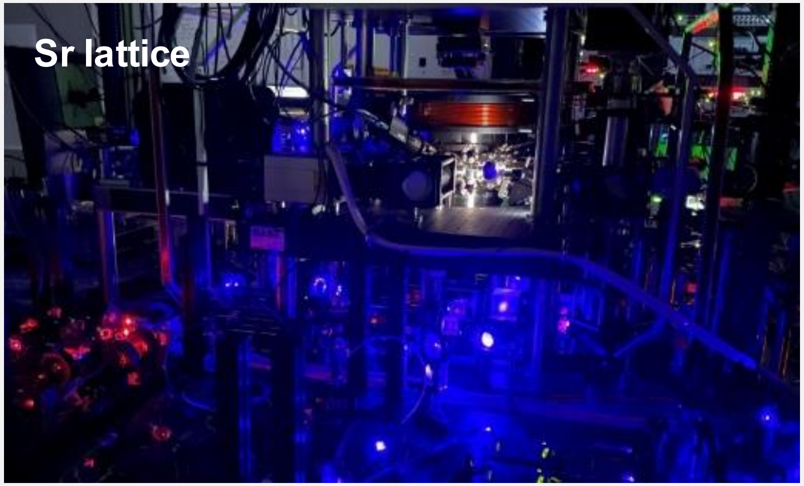
Optical Lattice Clock

- Highest Q
  - Atoms trapped in lattice sites
  - Doubly forbidden transition
- Tune trap laser to cancel shifts
- Complex
  - 8 CW lasers, frequency comb
  - Intermittent
- Pulsed operation

Optical Ion Clocks

- Fewer lasers
- Fewer “atoms”


credit: NIST



Overview of Clock Performance

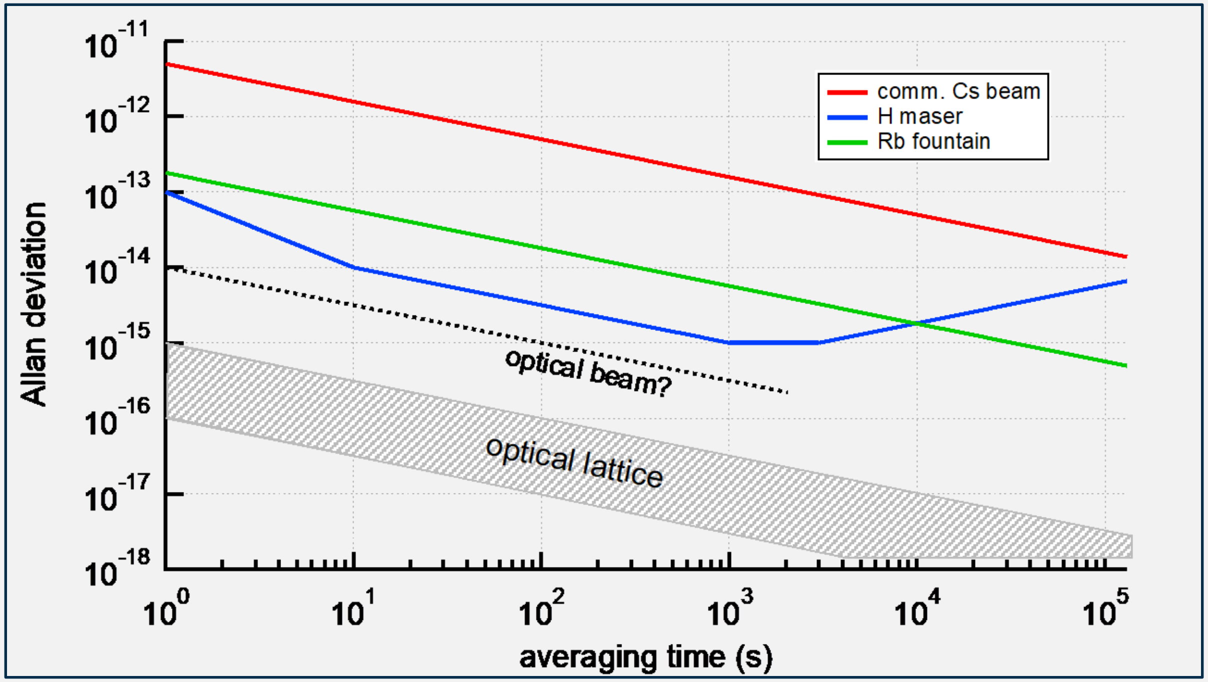
Allan Deviation – frequency instability for particular τ

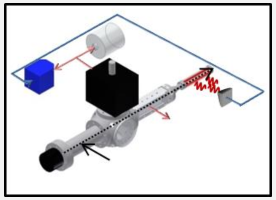
“Sigma-tau plot”

Cs beam

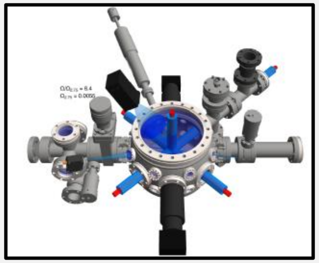
H maser

Rb fountain





Ca (optical) beam



Sr (optical) lattice

Optical Timescale

Current timescale

- 10MHz, 1PPS clock signals measured against common reference
- Masers emphasized in short-term, steered to cesiums, fountains in long-term

Optical clock – divide with frequency comb and use like microwave clock?

- Like rubidium fountains
- Beam: long-term behavior
  - Clock model?
- Lattice: intermittent operation
  - Retrace, calibration → frequency standard

All optical

- "Optical Maser"
  - Calcium beam, silicon cavity, CSO?
  - Steer to frequency standard
- Distribute, measure at optical
  - Divide steered optical with frequency comb

Clock Applications

Redefinition of the Second

- Optical transitions are recognized as secondary representations of the sec
- Redefine SI second with optical transition(s)
  - Single species and transition?
  - Average of optical transitions?
- More measurements are needed
  - Frequency ratios
  - Contributions to UTC

Relativistic Geodesy

- Use gravitational redshift of clock's frequency to map geopotential
  - 1m difference in elevation ~ 1e-16 frequency difference
  - Optical clocks achieving accuracies better than 1e-18

Key Takeaways

USNO Master Clock

- Utilizes best technology to remain within 2 ns of UTC

Commercial Clock Technology

- Needs to be supplemented with higher-stability clocks
    - Laser cooled fountain clocks
- First new commercial tech in decades shows promise

Optical Clocks

- Commercial
- Higher stability (higher Q)

A Resolution for Continuous Universal Time

Michael J. Coleman
Naval Center for Space Technology
US Naval Research Laboratory
Washington, DC

Member of the CCTF's
Task Force on Continuous UTC
Bureau International des Poids et Mesures
Sèvres, France

65th Civil GPS Service Interface Committee
Timing Subcommittee Meeting
US Department of Transportation
Monday 20 April 2026

Acknowledgement

This work is a summary of the conclusions reached and presented on behalf of the BIPM’s Task Group on Continuous UTC.

- TaskGroup is currently co-chaired by:
  - Tetsuya Ido (NICT Tokyo)
  - Patrizia Tavella (BIPM Time Department Head).
- Instantiated in 2023 following the General Conference on Weights and Measures (GCPM) Meeting in 2022.
- Main goal is to recommend a new tolerance for the offset of UT1 – UTC (DUT1) : unit chosen is 3600 seconds (1 hour).
- Recent recommendation included a date of implementation for the change: 2027 May 20.

History of UTC and the Leap Second

- Since 1972, UTC has been defined such that UTC – TAI = *n*. This puts TAI and UTC at the same rate.
- Leap seconds keep UTC aligned to the timescale UT1 determined by Earth’s rotation.
- The International Earth Rotation Service (IERS) monitors |UT1 – UTC | and directs the insertion of a leap second when this difference gets close to one second.

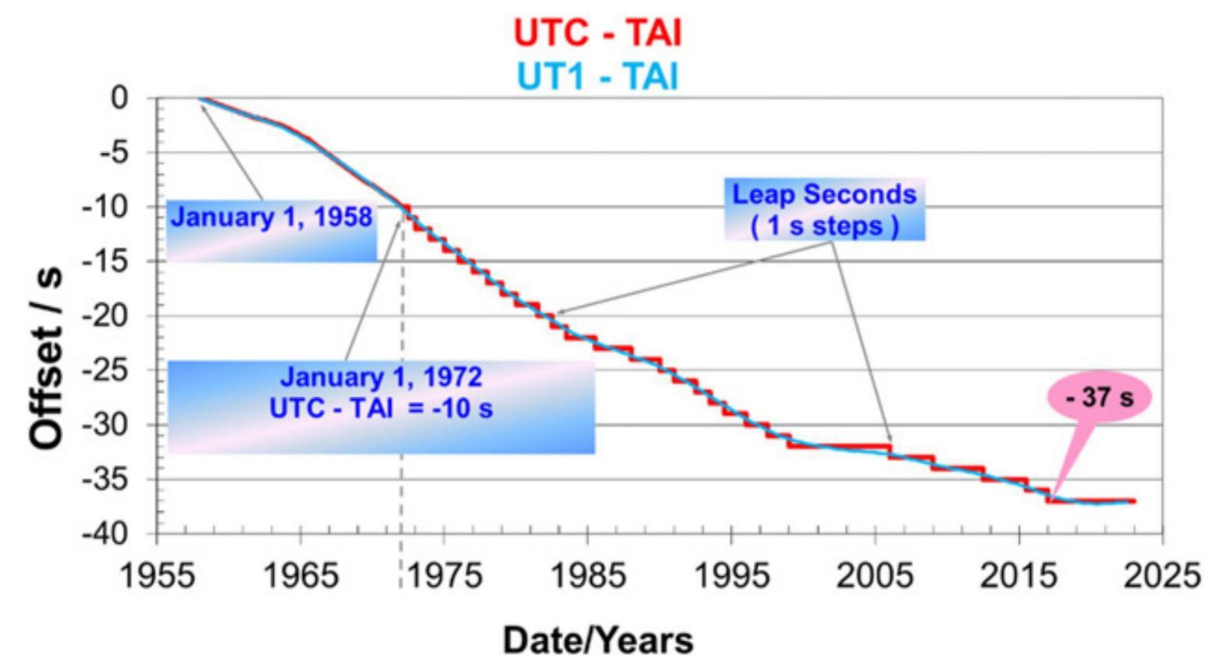
Why eliminate leap seconds ?

Risks malfunction in critical infrastructure including GNSS, telecommunications and energy transmission.

Network and GNSS operators apply different methods to handle leap seconds that do not follow any agreed standards.

Implementation of differing and uncoordinated methods threatens resilience of synchronization capabilities world wide.

Recent rotation rate observations indicate the possible need for a negative leap second- never done before!



J. Levine et. al. *Towards a Consensus on Continuous UTC.*

How is a leap second implemented?

IERS

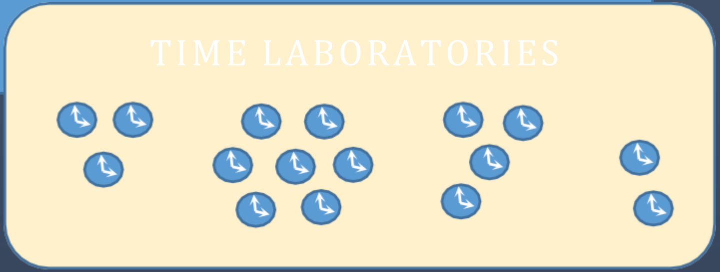
Determines the offset of UT1 – UTC routinely.

Publishes a notification that a leap second must be added to UTC when reaching the maximum tolerance is predicted in the next few months.

BIPM

Maintains UTC with contributions from National Metrological Institutes and other participating Timing Laboratories.

Coordinates additional second with Time labs at the time directed by the IERS.



Current Implementation Methods

Official UTC Labs

- TAI (Temp Atomique International) is unaffected.
- UTC timestamps are shifted at the event of the leap second

UTC Before	After
23:59:57	23:59:57
23:59:58	23:59:58
23:59:59	23:59:59
00:00:00	23:59:60
00:00:01	00:00:00
00:00:02	00:00:01

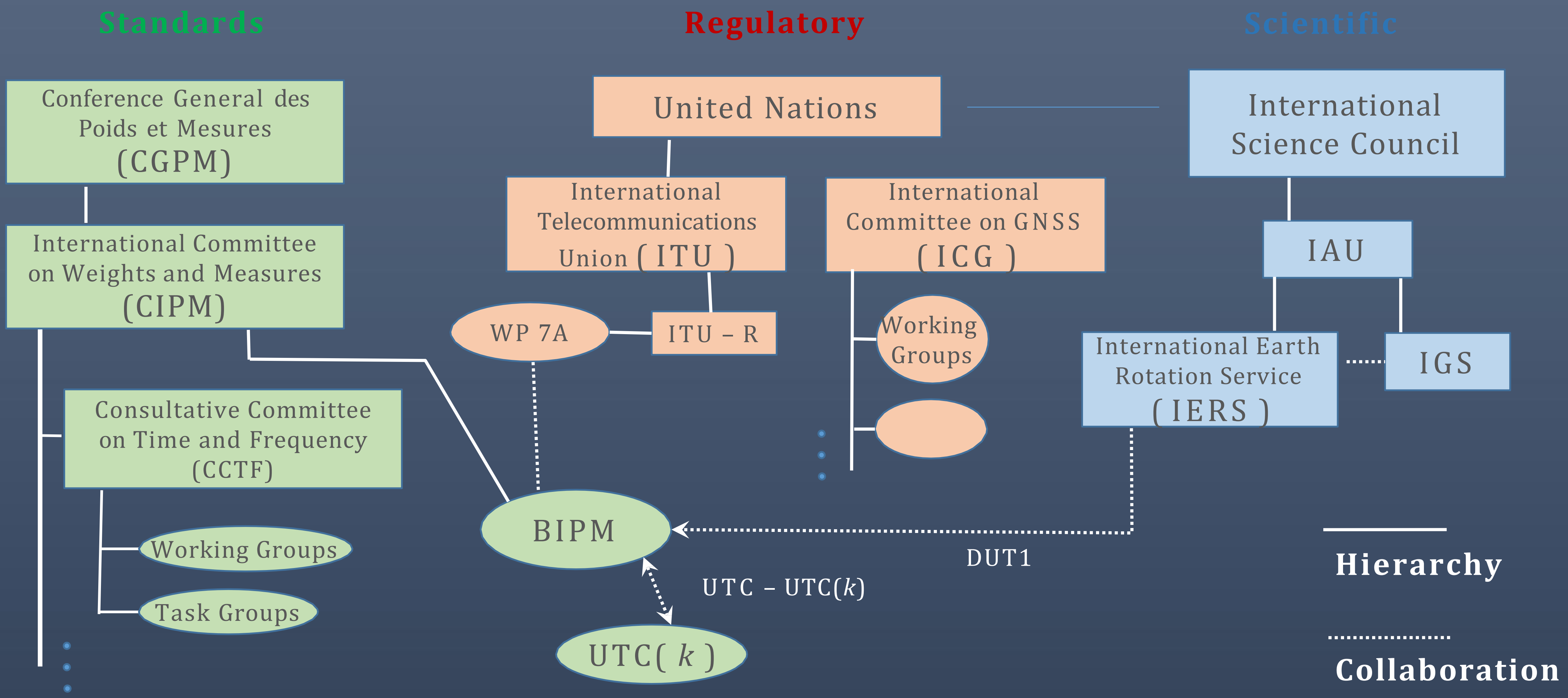
Clock Smears

- A variety of approaches smear the timestamps rate of UTC over a prescribed time around the leap event.
- The current implementations are not good since:
  - There is inconsistency between smearing approaches.
  - The realized time broadcast has a rate differing from UTC during that time.
- Google has information published on its approach to smearing its public NTP during a leap second event.

Efforts to Eliminate the Leap Second

- Because leap second pose a number of problems, efforts arose to eliminate them over the past two decades.
- Strides made in ITU–R Working Party 7A (WP7A), but no concensus had been found over the last two decades.
- Recently, at the WRC 23, a number of agreements were made including:
    - ITU–R resolved to work further with the BIPM, CIPM and CGPM to propose a new maximum tolerance for DUT1 and on the implementation of continuous UTC.
    - ITU – R and BIPM agreed on the different responsibilities: BIPM define and realize UTC, while ITU disseminate it (and DUT1) through radio signals.
- The CGPM had a reciprocating resolution at its 27th meeting in regards to finding a new maximum tolerance of DUT1.

Stake holder organizations



Standards

Conference General des Poids et Mesures (CGPM)

International Committee on Weights and Measures (CIPM)

Consultative Committee on Time and Frequency (CCTF)

Working Groups

Task Groups

BIPM

UTC(*k*)

UTC – UTC(k)

Regulatory

United Nations

International Telecommunications Union (ITU)

International Committee on GNSS (ICG)

ITU – R

WP 7A

Working Groups

Scientific

International Science Council

IAU

International Earth Rotation Service (IERS)

IGS

DUT1

Hierarchy

Collaboration

CGPM 2018 Resolution 2 (Paraphrase)

The General Conference on Weights and Measures

- **noted and recognized that**
  - International Atomic Time (TAI) is a continuous international timescale maintained by the BIPM and based on the best realizations of the SI second,
  - Universal Coordinated Time (UTC) differs from TAI only by an integral number of seconds.
  - users can derive the rotation angle of the Earth by applying to UTC the observed or predicted values of UT1 – UTC, as provided by the IERS,
  - UTC provides a means to measure time intervals and to disseminate the standard of frequency during intervals in which leap seconds do not occur,
  - traceability to UTC is obtained through local real-time realizations "UTC(k)" maintained by laboratories contributing data to the calculation of UTC, identified by "*k*"
- **recommends** that
  - all relevant unions and organizations consider these definitions and work together to develop a common understanding on reference time scales, their realization and dissemination with a view to consider the present limitation on the maximum magnitude of UT1 – UTC so as to meet the needs of the current and future user communities,
  - all relevant unions and organizations work together to improve further the accuracy of the prediction of UT1 – UTC and the method for its dissemination to satisfy the future requirements of users.

CGPM 2022 Resolution 4 (Paraphrase)

The General Conference on Weights and Measures (CGPM)

- **welcomed** the signature of a Memorandum of Understanding between the BIPM and the International Telecommunication Union (ITU), which ensures that they continue their joint work to improve global access to UTC,
- **noted that:**
  - the accepted maximum value of the difference (UT1 – UTC) has been under discussion for many years because the consequent introduction of leap seconds creates discontinuities that risk causing serious malfunctions in critical digital infrastructure,
  - operators of digital networks and GNSSs have developed and applied different methods to introduce the leap second, which do not follow any agreed standards,
  - the implementation of these different uncoordinated methods threatens the resilience of the synchronization capabilities that underpin critical national infrastructures,
  - the use of these different methods leads to confusion that puts at risk the recognition of UTC as the unique reference time scale and also the role of National Metrology Institutes (and Designated Institutes) as sources of metrological standards,
  - recent observations on the rotation rate of the Earth indicate the possible need for the first negative leap second whose insertion has never been foreseen or tested,
  - the Consultative Committee for Time and Frequency (CCTF) has conducted an extensive survey amongst metrological, scientific and technology institutions, and other stakeholders.

CGPM 2022 Resolution 4 (Paraphrase)

The General Conference on Weights and Measures

- **recognizes** that the use of UTC as the unique reference time scale for all applications, including advanced digital networks and satellite systems, calls for its clear and unambiguous specification as a continuous time scale, with a well-understood traceability chain,
- **decides** that the maximum value for the difference (UT1 – UTC) will be increased in, or before, 2035,
- **requests** that the CIPM consult with the ITU, and other organizations that may be impacted by this decision in order to
    - propose a new maximum value for the difference (UT1 – UTC) that will ensure the continuity of UTC for at least a century,
    - prepare a plan to implement by, or before, 2035 the proposed new maximum value for the difference (UT1 – UTC),
    - propose a time period for the review by the CGPM of the new maximum value following its implementation, so that it can maintain control on the applicability and acceptability of the value implemented,
    - draft a resolution including these proposals for agreement at the 28th meeting of the CGPM (2026),

This is what is now done!

Task Force on Continuous UTC

- Work with the CCTF, all UTC laboratories, GNSS providers, stakeholders, and liaison organizations to prepare a draft resolution for the CGPM 2026 containing:
  - The extended tolerance value of UT1 – UTC.
  - A procedure to align UT1 and UTC when this limit is reach.
  - The periodicity to revise this decision at the CGPM.
  - Exact date of implementation.
- Contribute to the broad communications and education, participation to the user forum.
- The group started with the following important notes:
  - Not everyone will get what exactly what is desired in their respective sectors.
  - UTC should have a known and well disseminated relationship with UT1.

What Has Been Decided ?

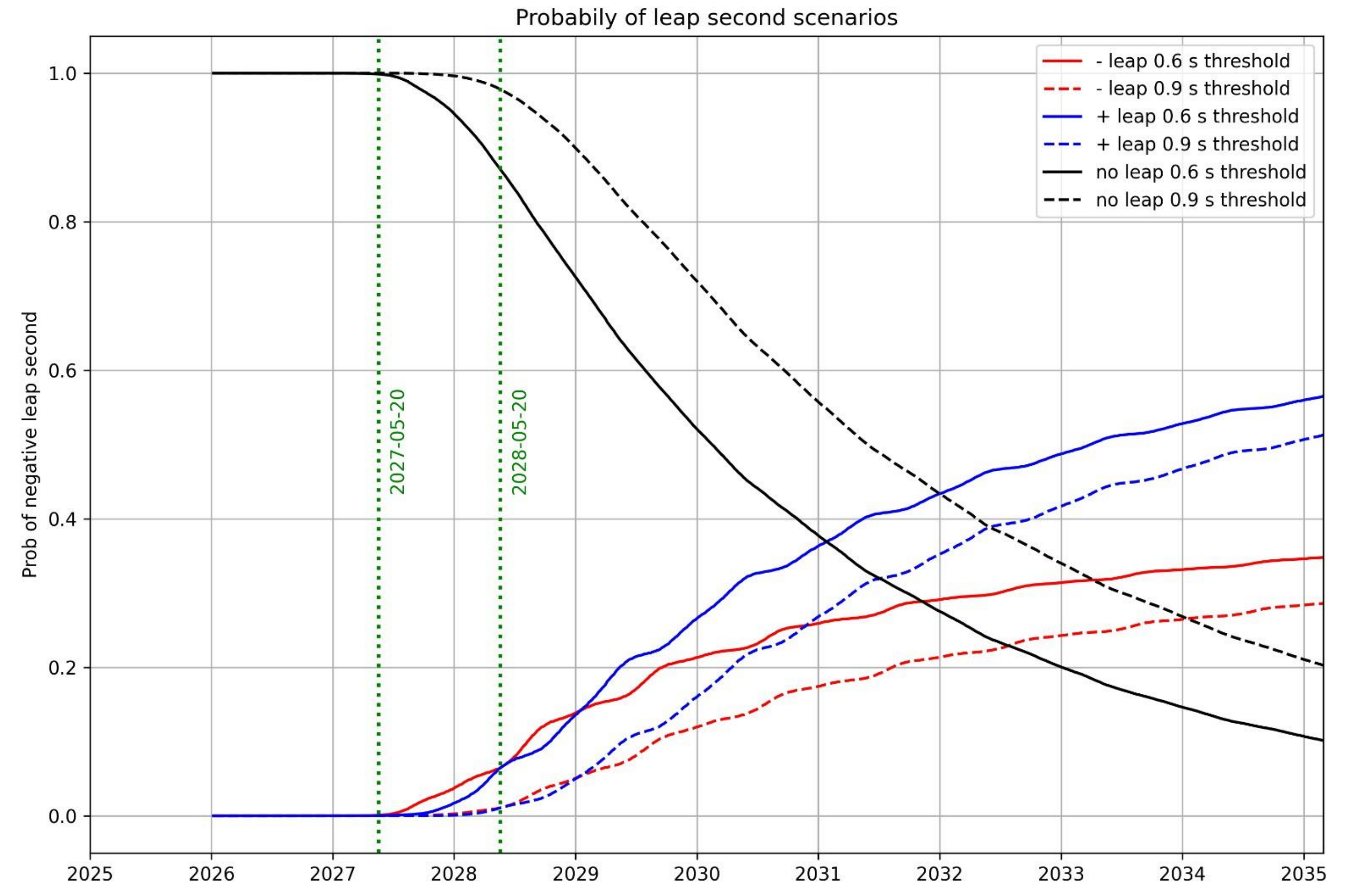
What ?

Decided that the tolerance | UT1 – UTC |should be extended to 3600 seconds (1 hour).

- Large enough to eliminate future UTC discontinuities– at least for the foreseeable future.
- When the limit is finally reached, the one hour unit limit would entail a discontinuity similar to daylight saving time change.
- Unit discontinuity is preferable (as opposed to 15 minutes, 30 minutes, etc). One minute was also entertained, but might not put off discontinuities for more than one century.

Considerations

Probability of another leap second event is growing … and it could be negative!



Chances of a near-term leap second (presented here) are based on models including:

- Slow millennial slowing of earth rotation.
- Stochastic models in earth rotation.
- Periodic terms due to seasonal and tidal effects.

Ref: P. Tavella and G. Tagliaferro, et. al. BIPM.

Decisions

When?

It was decided that the new UT1 – UTC tolerance would take effect 20 May 2027 (Thursday).

- Many agree that the probability of additional discontinuities in UTC (positive or negative) should be kept as low as possible.
- Even if the new tolerance is implemented just one year earlier, there is a high probability that actual operations will remain as present for several years.

Draft Resolution C (Paraphrase)

The General Conference on Weights and Measures (CGPM)

- **recognizing that**
  - industrial users and the synchronization needs of national critical infrastructures (among others) require UTC to be continuous with further adjustment,
  - in many countries there are differences of more than one hour between local apparent solar time and civil time,
  - Users of UT1 can find information on the value of UT1 – UTC in GNSS messages, and internet services provided by the IERS,
  - ITU–R through its WP7A is studying the possible updates of the code for transmission of UT1 – UTC by radio stations and Resolution 655 (WRC 23) resolved to establish a transition period for this implementation.
- **noting that:**
  - a negative leap second has not been tested and poses a high risk for anomalies and disruption to critical infrastructure,
  - growing influence of networked technologies, dispersed sensors, smart grids and virtual services creates an increased risk of malfunctions for additional leap second insertions,
  - further delay in taking action to make UTC a continuous timescale might cause some organizations to change their reference time to existing continuous scales such as one of the GNSS reference timescales.

Draft Resolution C (Paraphrase)

The General Conference on Weights and Measures (CGPM)

- **decides that:**
    - continuous UTC will become effective on 20 May 2027,
    - The maximum value for the difference |UT1 – UTC| will be 3,600 seconds (1 hour), ensuring the long-term continuity of UTC for several centuries.
- **requests the BIPM:**
    - to continue to collaborate with the International Telecommunication Union (ITU), International Astronomical Union (IAU), International Union of Geodesy and Geophysics (IUGG), IERS, and other organizations that may be impacted by this decision in order to
        - Inform users,
        - Continue to monitor UT1 – UTC.
        - Inform the CPGM regularly on RMO value of UT1 – UTC .
    - and to continue to work with the Regional Metrology Organizations, the NMIs, and users to promote the understanding of the importance of a continuous UTC and its prompt and efficient provision to the users.

Tolerance of UT1 – UTC changes to 1 hour.

Takes place 20 May 2027.

Requests:

Expand education and information on the change

Understand impact to users.

Draft can be found at: https://www.bipm.org/en/cgpm-2026/documents

Recollection: Questionnaire to GNSS

The task group prepared and disseminated a questionnaire to GNSS and RNSS representatives summarizing the task force goals and asking questions regarding:

- The (current and future) broadcast of DUT1 in the navigation message.
- Possible impact of changing the tolerance of DUT1 on:
    - Broadcast message format, orbit models, ground control algorithms, receiver engine firmware, reference frame, inter-component communications, etc…
- The preferred new value of the tolerance for DUT1.
- If UTC were to become continuous, would the GNSS system re-align its timescale to UTC, rather than TAI – 19, etc?

Recollection: Answers from Providers

Impacts of a new tolerance

GALILEO

- Verification that the format and processing of the DUT1 parameter with a higher value is properly handled.
- ICD: current algorithm and associated parameters format (type, number of bits…) for the new leap period adjustment will have to be checked, tested and verified, even if it is executed only once per century
- Strongly recommended that any change in tolerance is timely and clearly communicated to us so that it can be properly implemented.

GPS

- Necessitate an engineering assessment of all GPS ground and on-orbit software models that presently assume that UT1 – UTC < 1.0 second.
- Necessitate more “unconventional” time stamps to be documented during the leap interval (for example, currently using 23:59:60.xxx) in ICD.
- A large discontinuity in UTC occurring approximately once per century is likely to cause a host of problems, there will be no real (i.e., non-simulated) experience to handle it.

QZSS

- broadcast message format and ground control algorithms.

NavIC

- Change in the broadcast parameters, corresponding section in SIS ICD, and receiver firmware.

Recollection: GNSS Provider Inputs

Recommended Leap Interval:

Galileo: Preferred tolerance would be the one that minimizes the occurrences of new leap period adjustments, **therefore no limit**.

GPS: Answers vary depending on agency. Some thoughts heard:
- choose a limit that minimizes operational costs among world-wide users;
- leave the leap second alone since procedures exist and have worked for 40+ years;
- avoid a new (different) value since countless pieces of software/firmware need re-programming.

QZSS: No direct recommendation, but noted that DUT1 needs to be within 64 seconds to avoid broadcast message format and ground control algorithm changes (a value of 1 minute or less might be preferred).

No direct recommendation from other systems.

On GNSS Time Alignment to UTC:

ALL: No.

General comments suggest that risk and cost of modifying the system time outweigh benefits of alignment to UTC.

Recollection: Questions to GNSS Receiver Manufacturers

GNSS user equipment experiences and handles leap seconds in different ways from the space and control segment. For this reason, a separate set of questions was disseminated to a large group of manufacturers.

1. Are you using, or do you plan to use a broadcast difference between UTC and UT1?
2. What affect would *any* change to the current leap second procedure have on your GNSS products? What components would be affected? Here is a list of items we have in mind that might be impacted.

   Please elaborate on the way the component(s) would be affected.
3. Assuming the tolerance does expand, which would be an acceptable or preferred tolerance for your GNSS products? Can you elaborate on the technical reasons for your answer?

Recollection: Manufacturer Inputs

Responses obtained from six different manufacturers in both the North America and Europe. Several noted that their products would likely be able to adapt to any change in the DUT1 tolerance. Other notable comments are below.

General Comment

Need for predictable leap second, well in advance (~25 years), so that there is no unforeseen change over the lifetime of our products.

Are you using, or do you plan to use a broadcast difference between UTC and UT1?

Yes, this is used, as described above, related the output of positions that are related to UTC time. The offset used is typically that between GPS Time and the current UTC, based upon the leap seconds that have been inserted since the start of GPS Time (midnight between January 5-6, 1980), which is itself a continuous timebase.

What affect would any change to the current leap second procedure have on your GNSS products?

Components affected would be related to the GNSS position output, but not related to the GNSS position calculation itself.

Assuming the tolerance does expand, which would be an acceptable or preferred tolerance for your GNSS products? Can you elaborate on the technical reasons for your answer?

If the only change is in the UT1 – UTC offset in terms of number of leap seconds, then potentially any value could be used – subject to this not impacting any form of GNSS reference time assistance solution and alteration of software and interfaces using such data.

GNSS System Impacts

Galileo

- Potentially address software interfaces that require UT1 and UTC offsets.

GPS /QZSS /BDS

- Message broadcast format allows UT1 – UTC offset of not more than 63 ns. Modifications to this broadcast need to be considered, but there is ample time to decide what approach should be taken before this offset is reached.
- Current and predicted estimates of DUT1 from on-line or GNSS are expected to satisfy needs.
- Software adjustments might then be minimal with adequate lead time.

Proposed changes to the tolerance would increase the importance of reporting from the IERS.

Perhaps a more-real time basis would be needed?

Summary

- Draft Resolution C in the CGPM, if adopted, would change the tolerance of | UT1 – UTC | to 1 hour and that change would take effect 20 May 2027. The benefit would therefore be:
    - No UTC adjustment expected for the foreseeable future of humanity.
    - Future leap seconds (positive or negative) are averted.
- Consequences /impacts:
    - Critical hardware, firmware or software updates and corrections.
    - Data format updates or modifications.
    - Broadcast message changes in either structure or definition.
- Please contact us if you are able to provide letters of support for this resolution from any particular GNSS, especially if you work closely with administrative agencies.
    - Mike Coleman michael.j.coleman134.civ@us.navy.mil

References

- J. Levine, P. Tavella and M. Milton, *Towards a Consensus on a Continuous Coordinated Universal Time*. Metrologia 60(1), November 2022.
- ITU News Magazine. *The Future of Coordinated Universal Time*, Number 2, 2023.
- Hubert, B. *Leap Seconds: Causing Bugs Even When They Don't Happen*. August 2021.
- Beard, R. *The Role of the ITU – R in Time Scale Definition and Dissemination*. Metrologia 48(4), 2011.

Relativity in Cislunar PNT and Beyond

Bijunath R. Patla, NIST Boulder
CGSIC, Washington DC
bijunath.patla@nist.gov

April 20, 2026

The Relativistic Foundation

The Death of Absolute Time

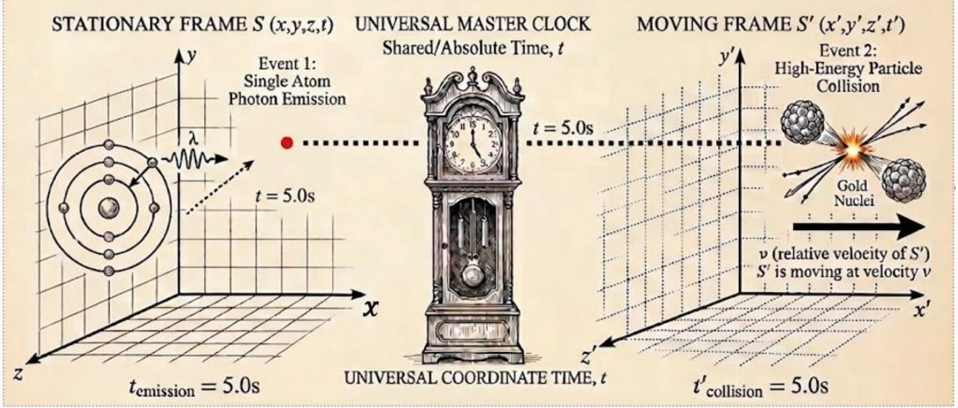


FIGURE 4.1: ABSOLUTE NEWTONIAN COORDINATE TIME (Observer Independent)

- Ideal clocks that are synchronized remain so, regardless of where and how you transport them, or who observes them.

The birth of Spacetime

- **Newtonian View:** Time is an absolute, universal parameter with a fixed rate of ss^{-1}. Valid only in an empty, static universe.
- **Einsteinian Reality:** Spacetime is coupled. Clock rates depend strictly on:
  1. **Gravitational Potential:** Deeper in a gravity well = slower clock.
  2. **Relative Motion:** Higher velocity = slower clock.
- **Metrological Reality:** Modern atomic clocks reach $10^{-13} - 10^{-19}$ stability in fractional frequency. At higher precisions, a clock's height difference of just a few mm produces measurable frequency shifts.
- **The Cislunar Problem:** Synchronizing lunar assets directly to Earth's UTC introduces escalating relativistic errors (up to $\sim 56\mu s$/day). [Ashby & Patla (2024)]

Why 56 ⍰s Matters

The Physics of Propagation

- Deep space navigation uses light-time ranging.
- Signals travel at $c \approx 299{,}792$ km/s.
- **Timing is Position:** Distance is derived from $d = c\Delta t$.

The Relativistic Drift

- Lunar clocks gain 56.02 ⍰s day^{-1} relative to Earth, resulting in accumulated position error of ~ 17 km over a day.

Mission Impacts:

- Precision Landing: Missing a 100m target zone in just 10 minutes of uncorrected drift.
- Autonomous Safety: Few nanosecond sync is required for < 1m hazard detection.
- Network Failure: Cislunar GPS (LunaNet) nodes would lose lock within hours.

Metrology vs. Kinematics: The Physical and the Grid

Proper Time (τ): The observable

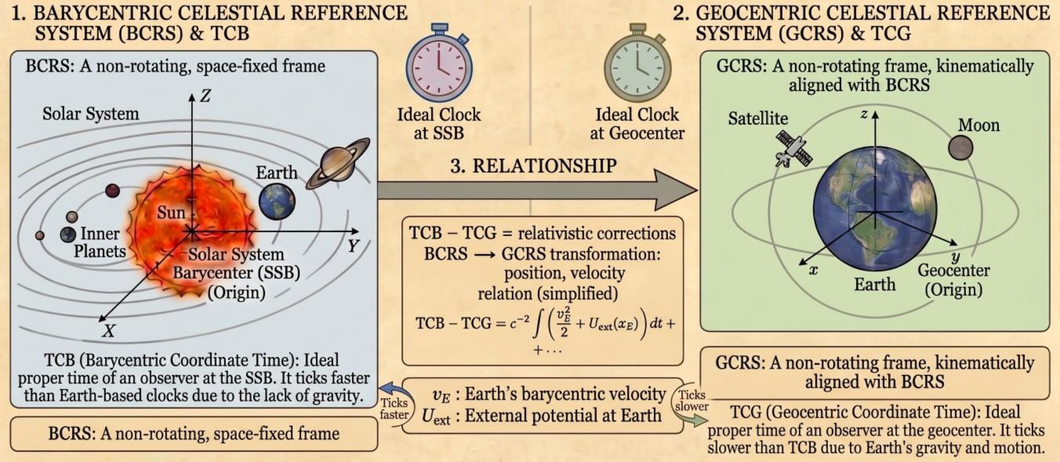
- **Direct Measurement:** The actual elapsed time realized by a clock (e.g., H-maser).
- **SI Realization:** Local hardware realize the SI second along their specific *Worldline*.
- **Invariant:** The spacetime interval $ds^2 = -c^2 d\tau^2$ is the only physical reality.

Coordinate Time (t): The Grid Parameter

- **Mathematical Definition:** A non-observable parameter used to label events in a 4D system.
- **Synchronization Tool:** Used to relate disparate observations to a shared temporal reference.
- **Derived Quantity:** Cannot be measured; it must be *computed* from τ

Earth-Based Time Frameworks

Definitions: Coordinate time



1. BARYCENTRIC CELESTIAL REFERENCE SYSTEM (BCRS) & TCB

BCRS: A non-rotating, space-fixed frame

TCB (Barycentric Coordinate Time): Ideal proper time of an observer at the SSB. It ticks faster than Earth-based clocks due to the lack of gravity.

BCRS: A non-rotating, space-fixed frame

2. GEOCENTRIC CELESTIAL REFERENCE SYSTEM (GCRS) & TCG

GCRS: A non-rotating frame, kinematically aligned with BCRS

GCRS: A non-rotating frame, kinematically aligned with BCRS

TCG (Geocentric Coordinate Time): Ideal proper time of an observer at the geocenter. It ticks slower than TCB due to Earth's gravity and motion.

3. RELATIONSHIP

TCB – TCG = relativistic corrections

BCRS ⟶ GCRS transformation: position, velocity relation (simplified)

$$\mathrm{TCB} - \mathrm{TCG} = c^{-2} \int \left(\frac{v_E^2}{2} + U_{\text{ext}}(x_E) \right) dt + \\ + \cdots$$

v_E : Earth's barycentric velocity

U_{ext} : External potential at Earth

The IAU Reference Framework (BCRS & GCRS)

To maintain synchronization, the IAU defines specific four-dimensional reference systems:

- **BCRS (Barycentric Celestial Reference System):** Centered at the Solar System Barycenter.
  - **Coordinate Time:** Barycentric Coordinate Time (TCB). Represents the “master heartbeat” of the solar system, defined outside all gravity wells ($w = 0$). It races ahead of Earth time by about +20.5 s since 1977.
- **GCRS (Geocentric Celestial Reference System):** Centered at the Earth’s center of mass.
  - **Coordinate Time:** Geocentric Coordinate Time (TCG). Defined for a clock in free fall with the geocenter, but mathematically adjusted to remove the Earth’s own gravitational mass ($w_E = 0$).

The IAU Reference Framework (BCRS & GCRS)

Source	Fractional frequency offset	Rate ms day^{-1}
Solar gravitational potential	-1×10^{-8}	-0.85
Earth orbital velocity	-5×10^{-9}	-0.42
Milky Way gravitational potential	-5×10^{-7}	-47
Velocity relative to CMB	-7.6×10^{-7}	-66

Clock rate offsets for clocks for an observer far out in the Solar System and an observer freely falling in CMBR frame

Terrestrial Time (TT) and The Relativistic Cascade

- **Physical Realization:** A physical clock at the geocenter is deep in a gravity well ($w \approx 100$ MJ/kg) and ticks slower than TCG.
- **Terrestrial Time (TT):** A theoretical scale for clocks on the **Geoid** (Earth's equipotential surface). It is realized via TAI.
- **The Transformation:** TCG provides a "mass-less" inertial baseline for the Earth-Moon system. The relationship between TT and TCG is a constant rate transformation that accounts for an accumulated drift of ~ 22 ms/year:

$$\frac{d(TT)}{d(TCG)} = 1 - L_G,$$

where $L_G = 6.969290134 \times 10^{-10} \approx 60.2$ ⍰s day^{-1}

Lunar Timekeeping & Cislunar PNT

The Lunar Celestial Reference System (LCRS)

- Established by the IAU in 2024, centered on the Moon.
- **The Ashby-Patla Formalism:** Treats the Earth and Moon symmetrically using a locally freely falling frame centered on the **Earth-Moon Barycenter**. In free fall, the Sun's massive pull is nullified into a pure tidal potential:

$$-ds^2 = -\left[1 + \frac{2\Phi_e}{c^2} + \frac{2\Phi_m}{c^2} + \frac{2\Phi_{s,tidal}}{c^2}\right](dx^0)^2 + \ldots$$

- This formalism proves that a clock on the Moon's selenoid ticks exactly $56.02\mu s/\text{day}$ faster than a clock on Earth's geoid.

Choice of coordinate time for the moon: TCL vs. TL

- **Lunar Coordinate Time (TCL):** The raw, unscaled time coordinate of the LCRS. Surface clocks naturally drift $\sim 2.71\mu s/\text{day}$ slower than TCL.
- **Lunar Time (TL):** Scaled to absorb that $2.71\mu s$ drift. Hardware clocks tick naturally at the TL rate, mimicking Earth's GPS/UTC relationship.

$$TL = TCL - L_L(TCL - T_{L0})$$

- **The Hybrid Solution:** Forcing lunar assets to constantly apply large drift corrections to match TCL is burdensome. We could use unscaled **TCL strictly for orbital dynamics**, and scaled **TL strictly for surface hardware** (requiring only "small steers" for local topography).

Pros and Cons: Theoretical vs. Practical Considerations

Metric	**TCL (Moon's CM)**	**TL (Lunar Geoid)**
Spatial/Mass Scaling	Barycentric constants remain unmodified.	Requires scaling distances and *GM* to preserve the invariance of the speed of light.
User Burden	Surface users must continuously apply a 2.71⍰*s* drift offset to hardware.	Operational ease for resource-constrained rovers (GNSS-like).
Topographical Sensitivity	Defined perfectly at the center of mass.	Defining a universal "selenoid" is ambiguous due to mascons; Moon lacks an ocean

Navigational Infrastructure & Requirements

Symbol	Lunisolar Arguments	Period (days)	Amplitude (μs)
C_1	M	27.5546	-0.4707
C_2	$2M$	13.7773	-0.0130
C_3	$3M$	9.1848	-0.0005

Major Periodic Components (excluding secular drift) [Kopeikin & Kaplan 2024]

- **Deep Cislunar (NRHO, L1):** Distant from mass anomalies. Truncation to $l = 9$ is sufficient to meet 10^{-18} stability for optical clocks.
- **Very Low Lunar Orbit (VLLO - 10 km):** Dominated by severe lunar mascons. Kinematic time dilation depresses the secular rate offset to $54.69 \mu s/\text{day}$. Requires $l_{max} \geq 300$ GRAIL-derived models.

Time transfer and Earth-Moon links

- **Shapiro delay:** Relativistic effect where light propagation slows down as it traverses the curved spacetime, or gravitational potential wells, of massive bodies
    - **Contributions:** Sun: $\sim$30 ns, Earth: $\sim$200 ps, Moon: $\sim$3 ps
- **Sagnac Effect:** Accounts for the rotation of the Earth and the velocity of moving ground stations during the signal's transit, $\sim$ 1 ps.
- **Noise:** Instrumental phase center calibration errors, precise orbit determination errors, and atmospheric interference, $\sim$ few ps.

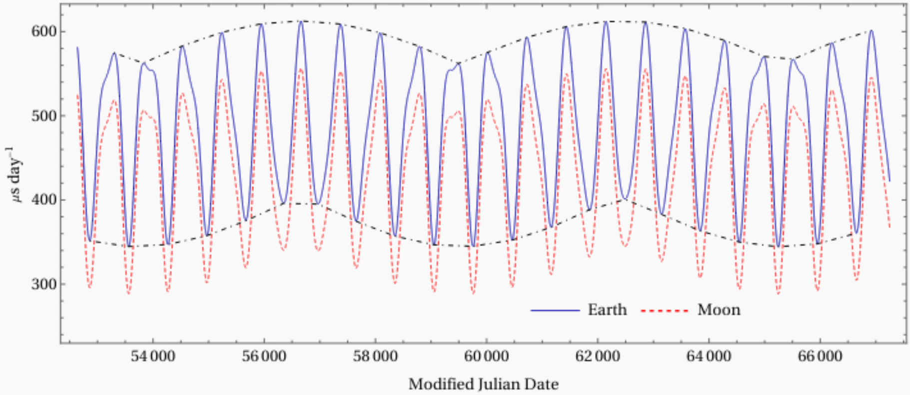
[Turyshev 2026]

Cislunar and Beyond

Mars Time [Ashby & Patla, 2026]

- The LCRS could be a blueprint for the Areocentric Celestial Reference System (ACRS).
- **Weaker Gravity:** Clocks on Mars tick $477\ \mu\text{s}\,\text{day}^{-1}$ faster than on Earth.
- **Orbital Eccentricity:** Because Mars has a highly elliptical orbit ($e = 0.093$), its clock rate fluctuates wildly as it moves closer to and further from the Sun, with an amplitude fluctuation of $\sim 227\ \mu\text{s}\,\text{day}^{-1}$.
- The amplitude envelope of the clock-rate offset between Earth and Mars, as well as between Moon and Mars, shows a modulation of about $\sim 40\ \mu\text{s}\,\text{day}^{-1}$ over a seven Martian synodic cycle.

Mars Time [Ashby & Patla, 2026]



Clock-rate offsets between a clock on Mars compared to clocks on the Earth and the Moon

Planetary Expansion, Scaling and Timescales

- If we scale space and mass coordinates to create a local Lunar Time (TL), expanding to Mars requires a new scaling constant ($L_M \approx 1.4078 \times 10^{-10}$) for Martian Time (TM).

- This creates a triple-scaling cascade across the solar system ($GM_{TT}, GM_{TL}, GM_{TM}$), and may be unavoidable for certain applications.

- The Scaling Rule: $t^* = (1-L)t \implies x^* = (1-L)x \implies M^* = (1-L)M$ to keep the physics invariant.

- Consider using scaled and unscaled versions for surface operations and deep-space navigation software.

- Mixing scaled time with unscaled mass leads to orbital residuals.

A LaTeX document

IEEE 1952 Standard Project Update and application to Timing Telecom Networks

Doug Arnold, Meinberg USA

Agenda

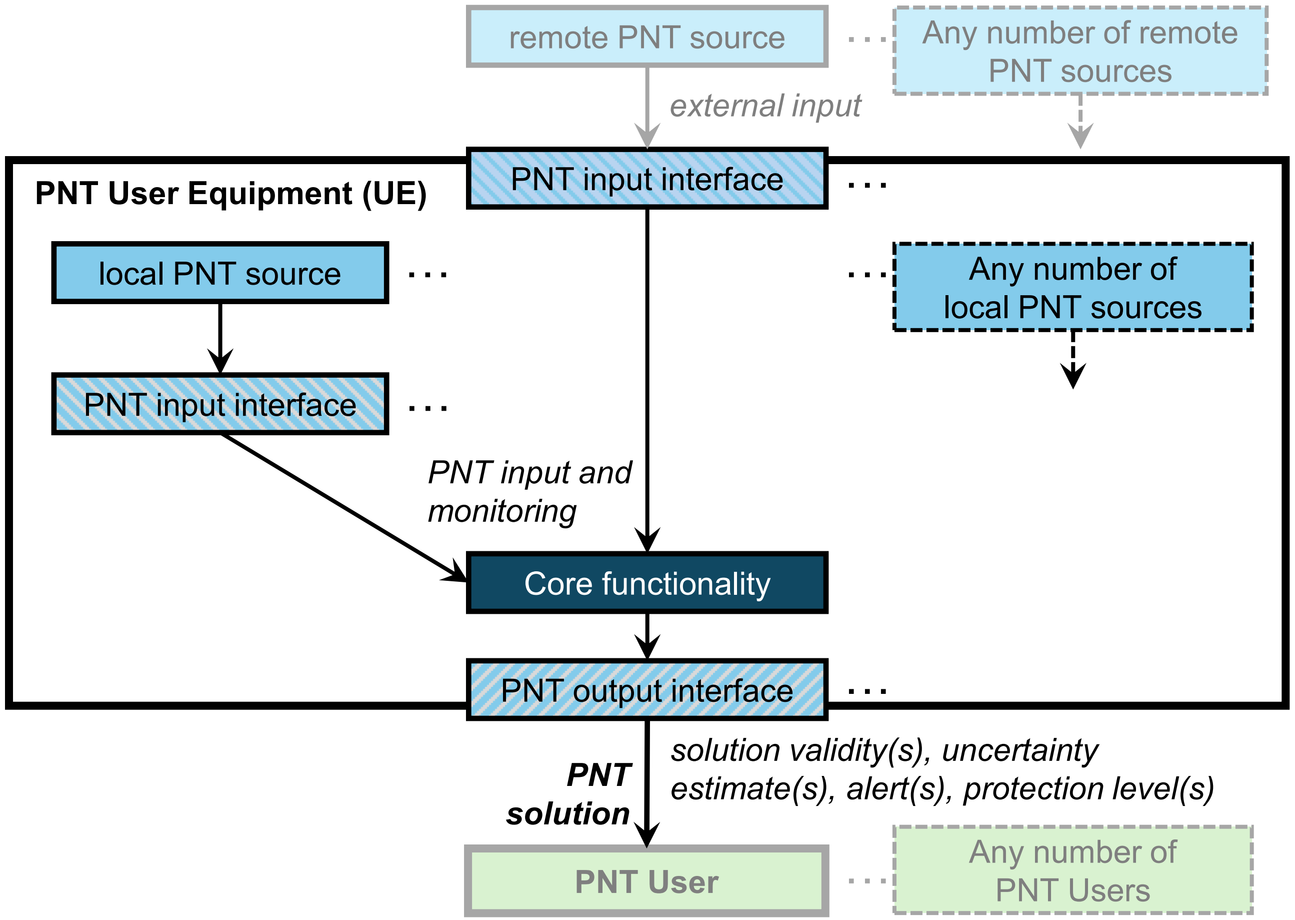
- IEEE P1952 Project
  - Scope of project
  - Current Status
- IEEE 1952 as a language for resilience
- Application to timing in telecom networks
- Summary

IEEE P1952 project

IEEE SA
STANDARDS
ASSOCIATION

- Resilient Positioning, Navigation and Timing User Equipment Working Group
- Project to create an IEEE standard
  - Standard for Resilient Positioning, Navigation and Timing User Equipment
- **In Scope**
  - Requirements on behaviors of PNT User Equipment
  - Defines levels of resilience for PNT UE
- **Out of scope**
  - Requirements on PNT source systems (e.g. GPS Constellation)
  - UE design or technologies to achieve resilience levels

PNT User Equipment



P1952 has a very broad concept of "User"

Examples of P1952 User Equipment

Equipment	**User**
GNSS receiver	PRTC vendor
PRTC	Timing architect
Timing network	Network operator

P1952 Adversity Categories

- P1952 Resilience is focused on resilience to PNT adversities

  Out of scope:
  - General reliability
  - Design flaws that do not affect PNT performance
  - Power disruptions
- PNT adversities are: natural, unintentional or malicious disturbances of the PNT input signals

- Adversity Examples for timing systems:
  - GNSS jamming/interference
  - GNSS spoofing
  - GNSS ionospheric delay variation
  - GNSS system errors

  - PTP Asymmetry
  - PTP Rogue T-GMs
  - PTP message manipulation
  - PTP delay attacks
  - Loss of SyncE

P1952 Resilience Levels

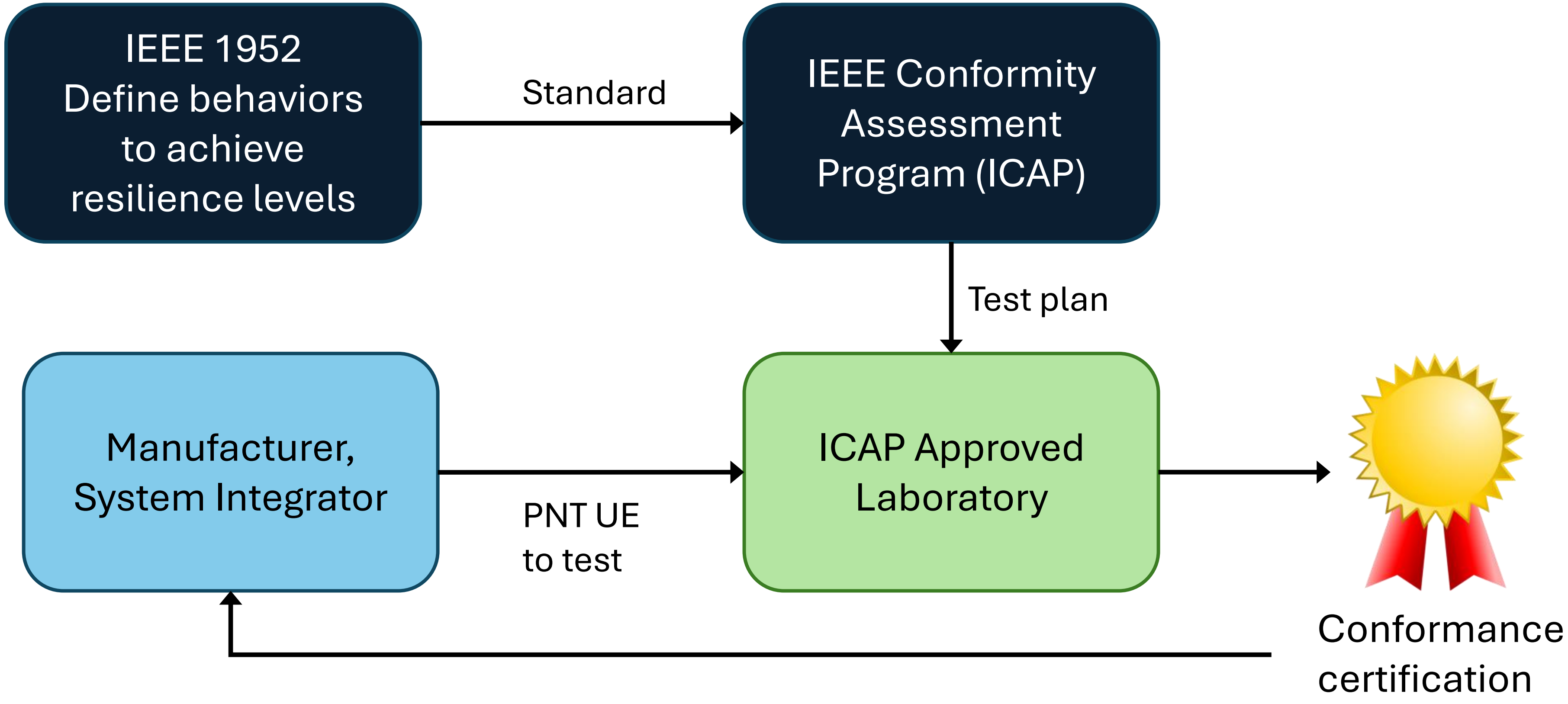
Resilience level	Description
1. Detect and alert	Detect any adversity serious enough to cause the equipment to fail to meet its PNT output performance specifications
2. Recover automatically	When the adversity is no longer happening
3. Resist	Continue to meet minimum acceptable performance requirements for some time, i.e. holdover
4. Withstand	Continue to meet minimum performance requirements in steady state
5. Verify	Verify that the received PNT information is correct

Note Each resilience level also inherits the requirements from lower levels

P1952 status

- Work in progress
- Most normative clauses close to a complete draft
- Some informative annexes still under construction
- Language defining resilience levels mostly stable
- Clause on adversities went through working group ballot
- Full document ready for working group ballot by the end of the year

Vision for helping industry



IEEE 1952
Define behaviors
to achieve
resilience levels

Standard

IEEE Conformity
Assessment
Program (ICAP)

Test plan

Manufacturer,
System Integrator

PNT UE
to test

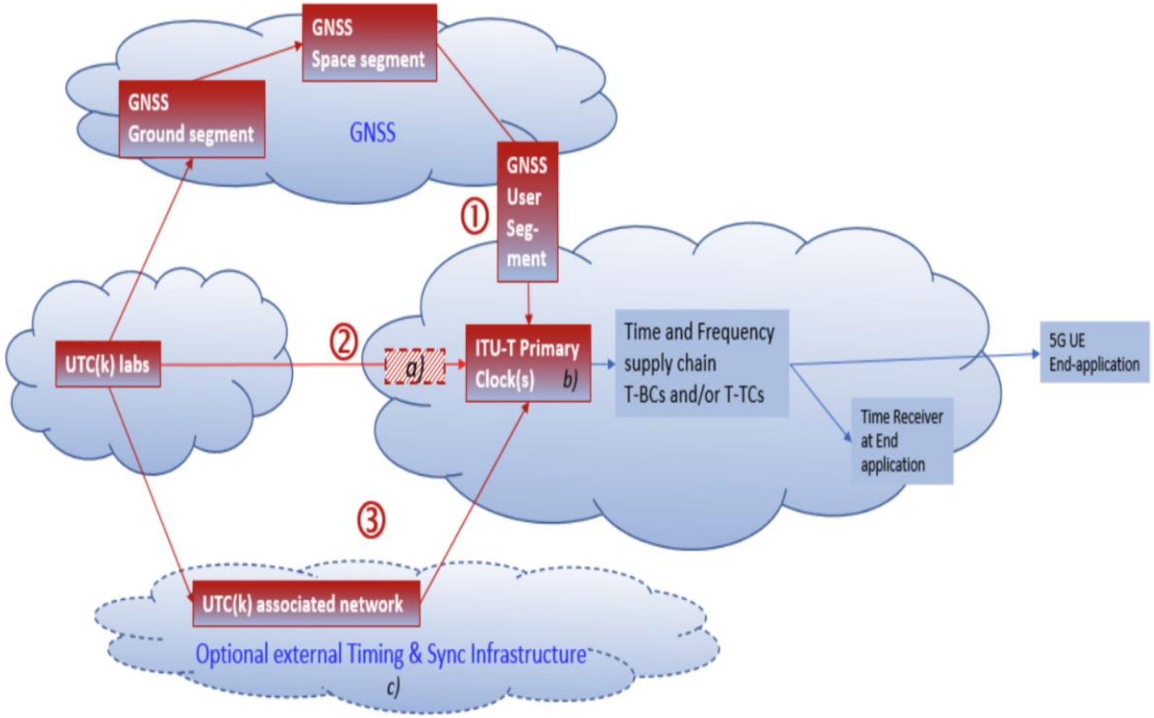
ICAP Approved
Laboratory

Conformance
certification

ITU-T defined primary clocks

Primary Source		Implementation variant number	Additional sources (external primary clocks)						
			None	external Frequency		external Phase/time			
				PRC via high-accuracy time transfer	PRC via SyncE	Phase/time via high-accuracy time transfer	via PTP-FTS profile	via PTP-APTS profile	UTC(k)
1	**PRTC (G.8272)**	1	**x**						
		2			**x**				
		3					**x**		
2	**ePRTC (G.8272.1)**	4	**x**						
		5			**x**				
		6							**x**
3	**cnPRTC (G.8272.2)**	7	**x**						
		8							**x**

Primary clocks and resilience levels



IEEE P1952 Resilience Level			Proposal	threat duration time	PRTC			ePRTC			cnPRTC	
					PRTC	PRTC with SyncE	PRTC with APTS	ePRTC	ePRTC with SyncE	ePRTC with UTC(k)	cnPRTC	cnPRTC with UTC(k)
1	**Detect** **Alert**	The ability to detect an adversity that might impact performance and generate an alert.	With the available on-board resources of the specific primary clock variants, resilience level 1 should be met without restrictions.		x	x	x	x	x	x	x	x
2	**Recover**	The ability to automatically recover and operate normally after an adversity.	With the available on-board resources of the specific primary clock variants, resilience level 2 should be met without restrictions.		x	x	x	x	x	x	x	x
3	**Resist**	The ability to operate during an adversity, perhaps with reduced performance, but still within specifications, **for a specified length of time.**	It is proposed to consider the maximul lenght of time for fulfillment of resilience level 3.	<< 1 day	x	x	x	x	x	x	x	x
				1 - 40 days	-	**based on SyncE**	**based on PTS**	x	x	x	x	x
				> 40 days	-			-	**based on PRC via SyncE**	x	(x)	x
4	**With-stand**	Withstand: The ability to operate during an adversity, perhaps with reduced performance, but still within specifications, **indefinitely**.	A indefinitely withstand can be guarantied with usage of external UTC(k) only.		-	-	-	-	-	-	-	x
5	**Verify**	The ability to determine that information from a PNT source is accurate.	A indefinitely withstand can be guarantied with usage of external UTC(k) only.		-	-	-	-	-	-	-	x

Beyond primary references

IEEE P1952 Resilience Level	Mitigation mechanism	ITU-T Recommendations	Relevant adversities
1 Detect	Monitoring	G.8275.1, Annex G	PTP asymmetry, PTP delay attacks
1 Alert	Management	Under study	All adversities
2 Recover	Under study	Under study	All adversities
3 Resist	Holdover, SyncE	G.8272, G.8272.1, G.8275.2, G.781	GNSS jamming, GNSS spoofing if detected, PTP protocol attacks if detected
4 Withstand	APTP	G.8271.2, Appendix I	GNSS jamming, GNSS spoofing if detected
4 Withstand	timeTransmitter only ports	G.8275, Annex E	PTP protocol attacks
5 Verify	APTP	G.8271.2, Appendix I	PTP asymmetry, PTP delay attacks

Possible future work for Q13/15 on resilience:

- Guidelines for GNSS receivers and antennas to mitigate jamming and spoofing.
- PTP security (this work is already started).
- Expand architecture for use of multiple time sources to support voting algorithms (this work is already started).

Summary

- IEEE 1952 Project
  - Defines Resilience levels for PNT User Equipment
  - Behaviors equipment should exhibit when PNT inputs experience adversities
  - Draft standard still under construction
  - Once published RFQ for PNT equipment may include a requirement for IEEE 1952 conformance certification at an authorized laboratory
- IEEE 1952 can also operate as a vocabulary to discuss resilience
  - Telecom timing standards group ITU-T Q13/15 created an appendix correlating 1952 resilience level behavior with mechanisms specified in ITU-T recommendations

Thank you for your attention

If you do not get your questions answered today send me email:

doug.arnold@meinberg-usa.com

April 20, 2026, 65th CGSIC Meeting

Preliminary Results from a Roadside GPS/GNSS Jammer Prevalence Assessment

Presented by

Dr. Austin Albright

Oak Ridge National Laboratory

ORNL IS MANAGED BY UT-BATTELLE LLC
FOR THE US DEPARTMENT OF ENERGY

Approved for public release
April 13, 2026. Pub ID # 256313

Acknowledgments

Lieutenant Carey Hixson, Tennessee Highway Patrol Motor Carrier + East Division

Nick Burchfield, ORNL

Nicholas Neel, ORNL

Work Sponsored by

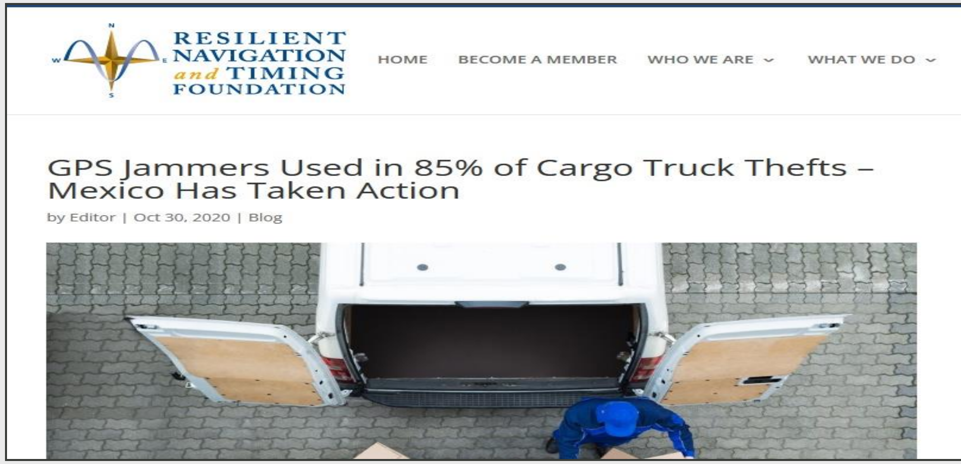
ORNL Domestic Transportation Security

OAK RIDGE National Laboratory

NNSA National Nuclear Security Administration

ORS Office of Radiological Security Eliminate and Prevent

In the US there have been “scary” stories of jammers on the roadways, but no quantitative assessment of their prevalence.



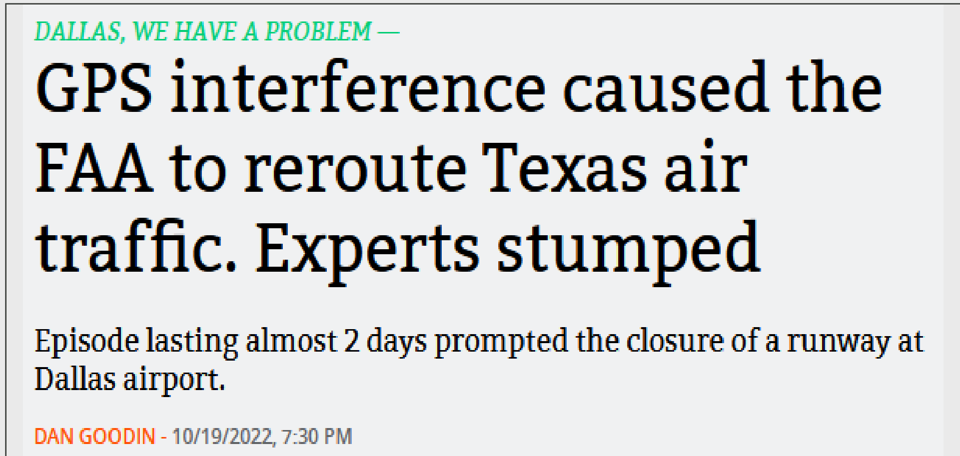
GPS Jammers Used in 85% of Cargo Truck Thefts – Mexico Has Taken Action

by Editor | Oct 30, 2020 | Blog

Truck driver has GPS jammer, accidentally jams Newark airport

An engineering firm worker in New Jersey has a GPS jammer so his bosses don't know where he is all the time. However, his route takes him close to Newark airport, and his jammer affects its satellite systems.

Chris Matyszczyk Aug. 11, 2013 8:08 a.m. PT



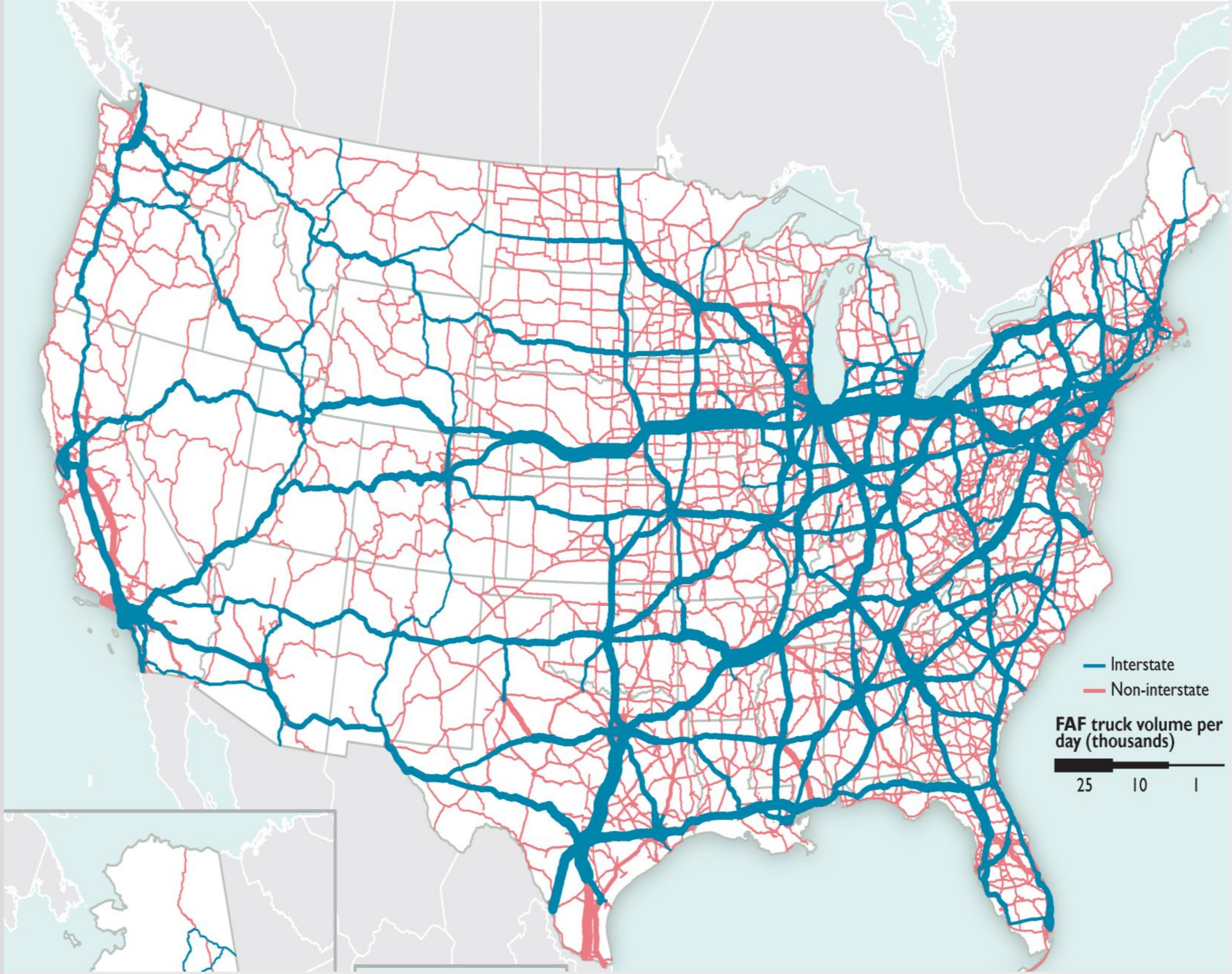
DALLAS, WE HAVE A PROBLEM —

GPS interference caused the FAA to reroute Texas air traffic. Experts stumped

Episode lasting almost 2 days prompted the closure of a runway at Dallas airport.

DAN GOODIN - 10/19/2022, 7:30 PM

Inquiring minds want to know how bad is the situation on a US Interstate? Is it bad?



Map Source: U.S. Department of Transportation, Bureau of Transportation Statistics and Federal Highway Administration, Freight Analysis Framework, version 4.5, 2019.

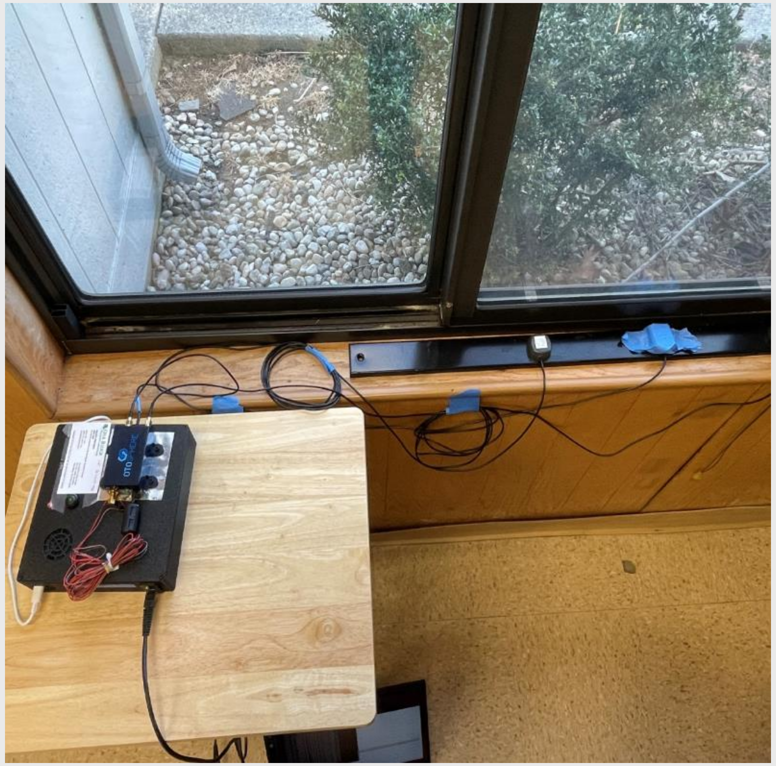
Using available, commercial, non-military, components we constructed an L1-band GNSS jammer counter

Key Components are:

- Raspberry Pi 4b
- u-Blox F9P (L1+L2 version)
- Infinidome Otosphere (gen 1)
- 2 L1 band antennas for Otosphere
- 1 L1+L2 antenna for F9P

Using commercial devices, a "counting" system was built to both test a jamming mitigator and count jammers

Full Setup



"Brains"

"Brain" consist of a Raspberry Pi, a u-Blox F9P, and an Infinidome Otosphere (gen-1) Jamming Mitigator

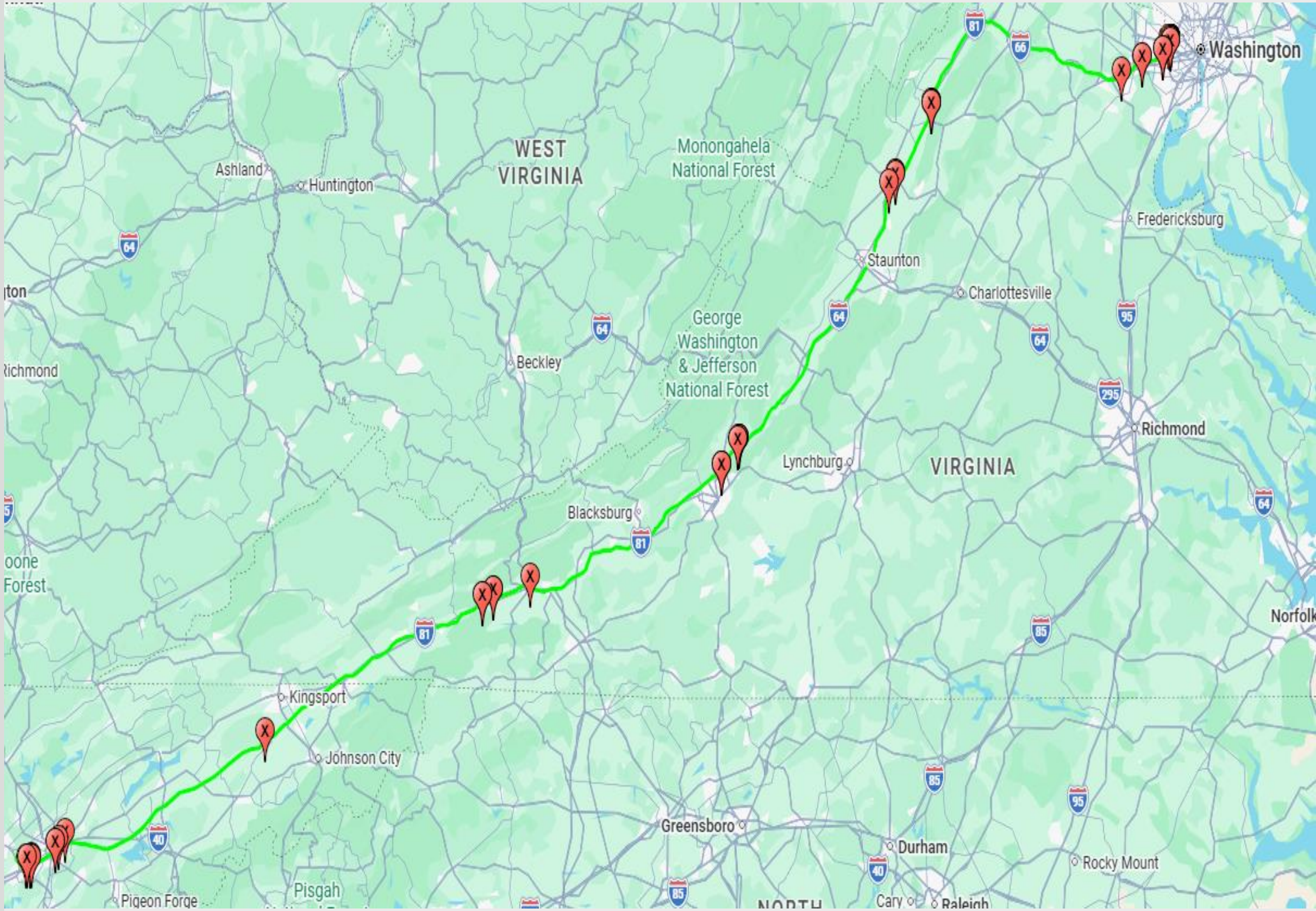
Antennas (3 total)

Two antennas (white sticker) for the Otosphere, one antenna (blue) for the u-Blox F9P

OAK RIDGE
National Laboratory

First serious attempt was made on a drive to DC…. Lessons were learned

1. Logged mitigator activations, but didn’t know what had caused them
    a) Need a means to determine cause
2. On the interstate you don’t really see a lot of different vehicles. You’re with the same “pack” except at exits
    a) Need vehicles to pass the system



OAK RIDGE National Laboratory

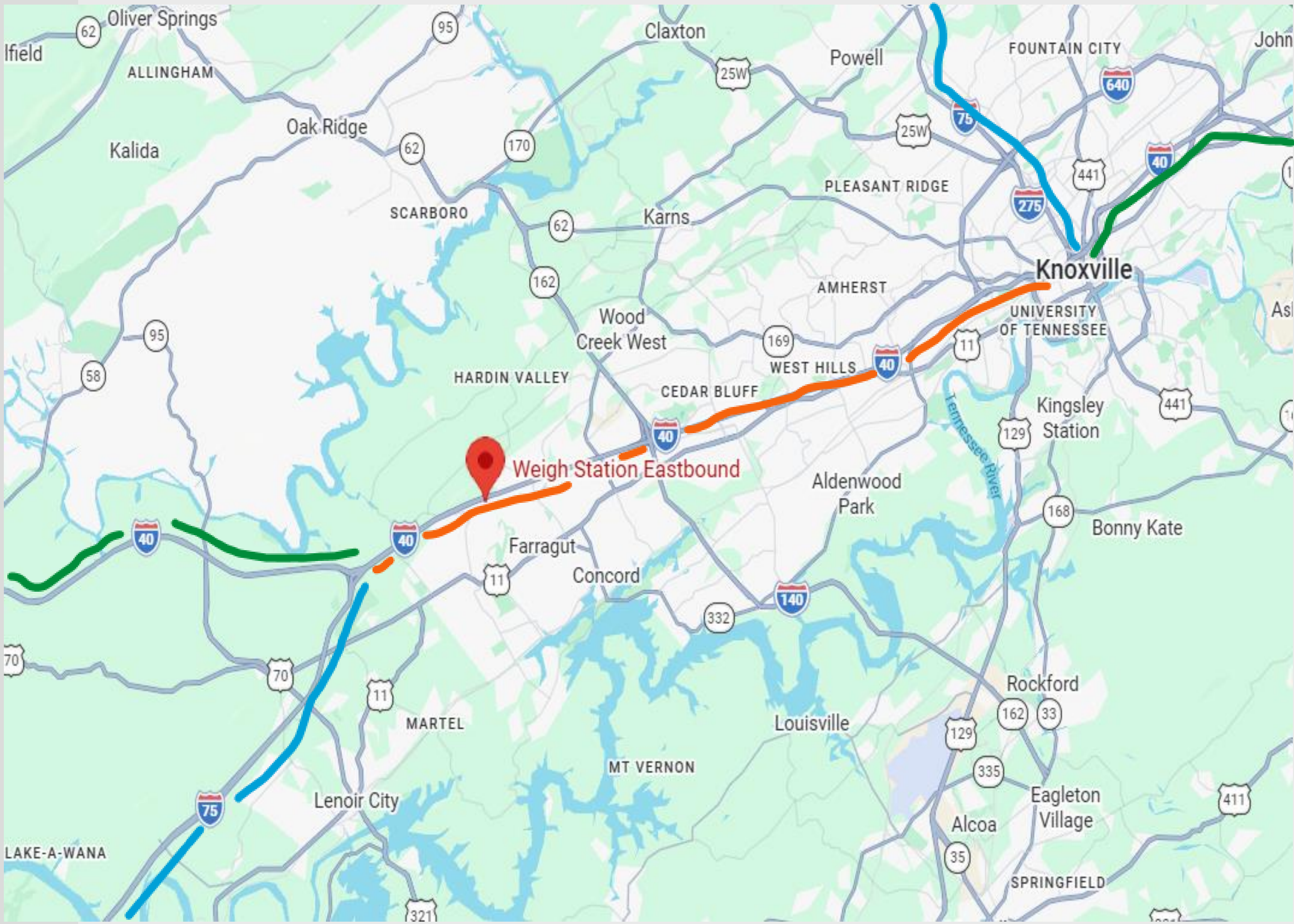
To assess jammer prevalence, we need vehicles to travel past the counter, not the counter to travel with vehicles

There exists a perfect location…

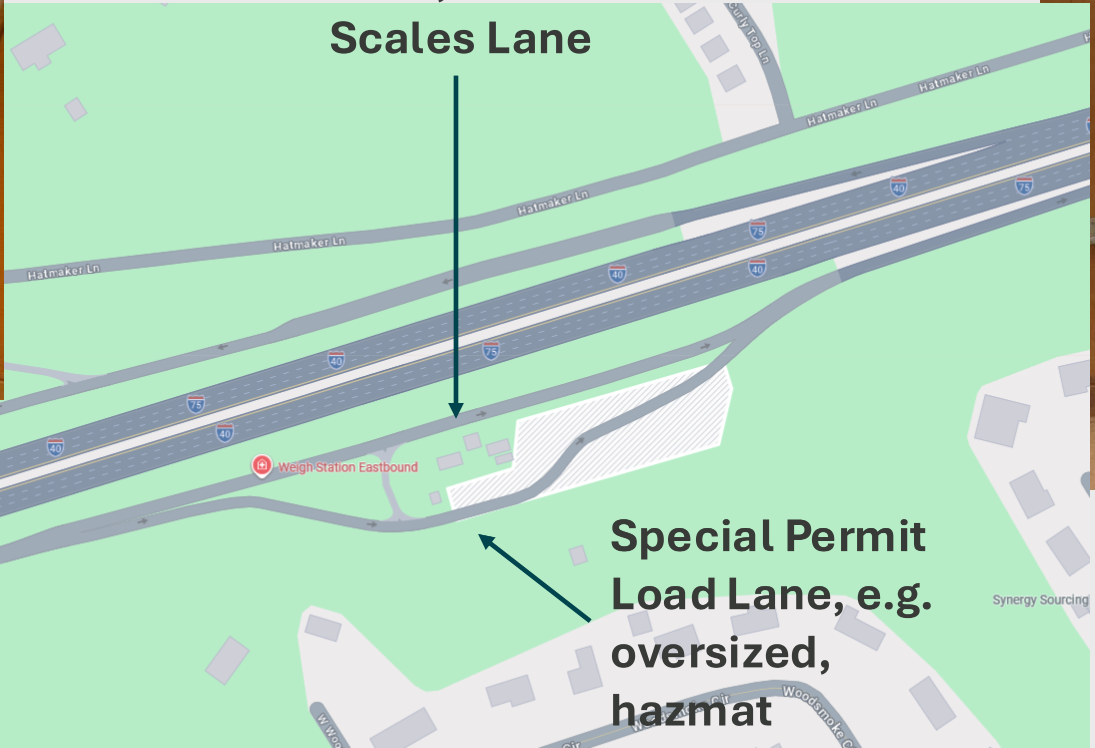
I-40 and I-75, two major US interstates merge into one in west Knox County, TN.

In the combined I-40/75 bottleneck sits a Tennessee Highway Patrol commercial vehicle weigh station.

Thousands upon thousands of vehicles pass by the weigh station everyday.



All traffic regardless of direction of travel on the Interstate will pass this location. All Eastbound commercial traffic must pass with in ~30-feet of our antennas.



2-lanes, Bypass Lane, and a Scales Lane

Special Permit Load Lane, e.g. oversized, hazmat

The data collected/logged provides two independent means of confirming the presence of an L1-band GNSS jammer

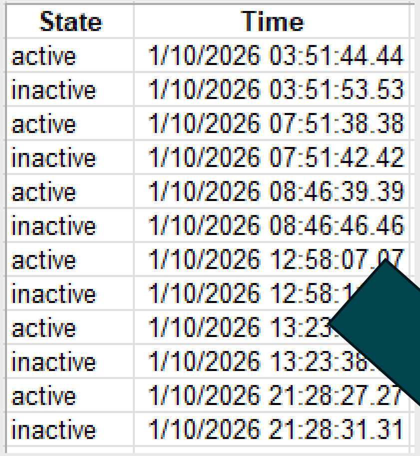
Otosphere provides:

- an “active” signal when actively mitigating
  - Used to generate a timestamped log of “on” and “off” times.

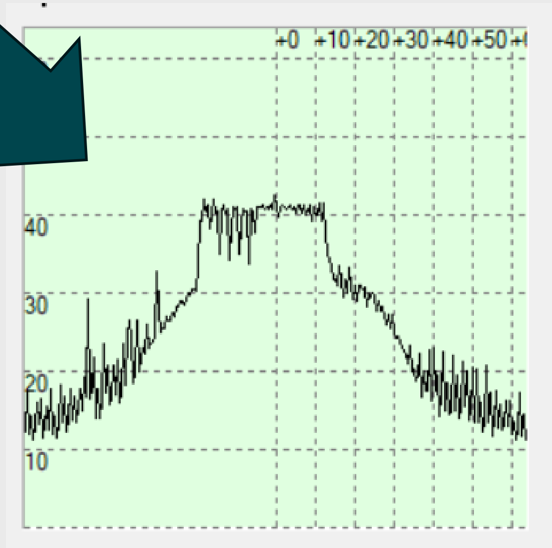
u-Blox F9P provides:

- a power spectrum snapshot once a second
- Blackbox “jamming indicator” once a second
- UTC time for logging

Activation timestamps are validated by examining the corresponding spectrum snapshots from the F9P

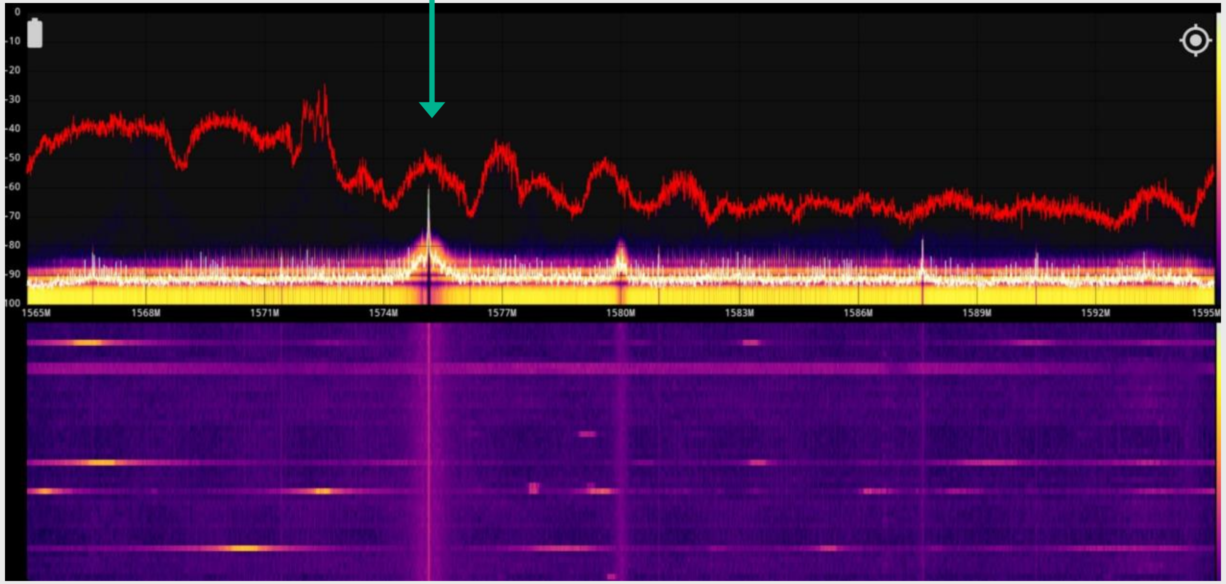


State	Time
active	1/10/2026 03:51:44.44
inactive	1/10/2026 03:51:53.53
active	1/10/2026 07:51:38.38
inactive	1/10/2026 07:51:42.42
active	1/10/2026 08:46:39.39
inactive	1/10/2026 08:46:46.46
active	1/10/2026 12:58:07.07
inactive	1/10/2026 12:58:1
active	1/10/2026 13:23
inactive	1/10/2026 13:23:38
active	1/10/2026 21:28:27.27
inactive	1/10/2026 21:28:31.31

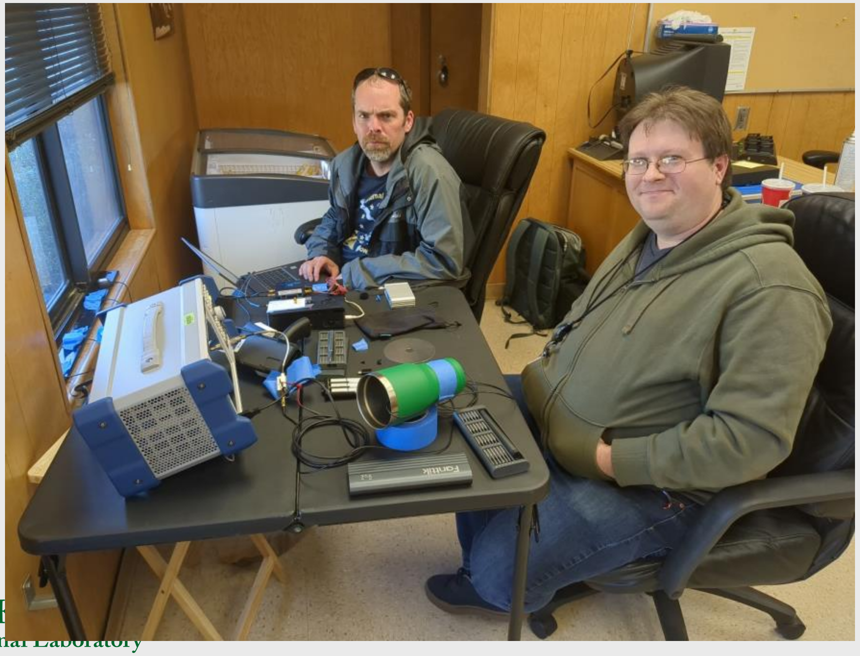


Unexpected, significant EMI present despite “protected” status of the GNSS frequency bands

- Significant persistent and intermittent EMI was and is present in the L1 band.
- Significant and persistent electromagnetic interference (EMI) was found to be present in the L2 band.



1.57542 GHz,
L1C/A

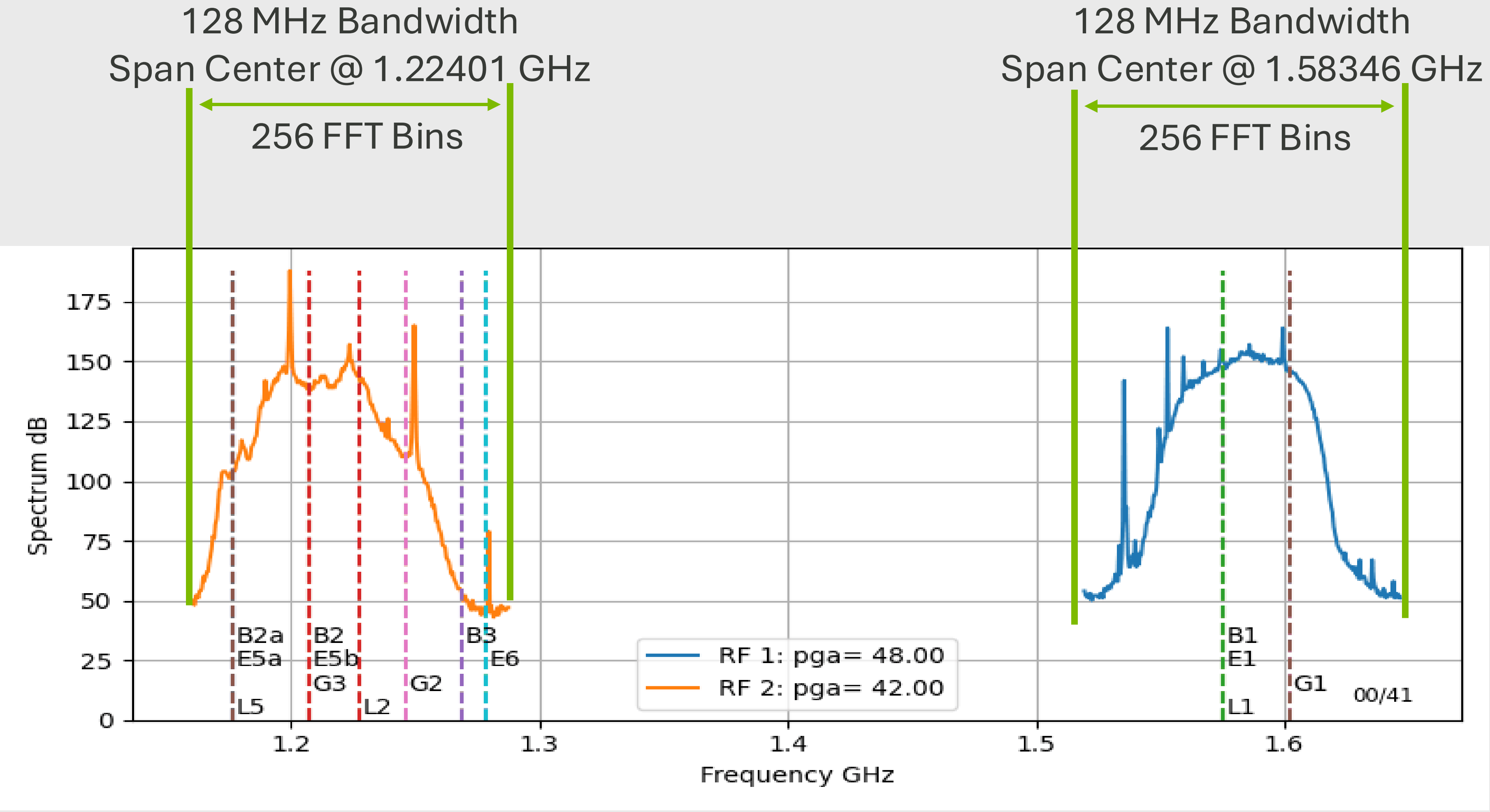


Hunting interference with a spectrum analyzer and an antenna in a metal cup. Feelings were felt

EMI requires that detections be verified with spectral snapshot to differentiate jammers from EMI

Spectral Snapshot Properties

- Passband of each band is roughly 60 MHz
- The resolution is 500 kHz per bin

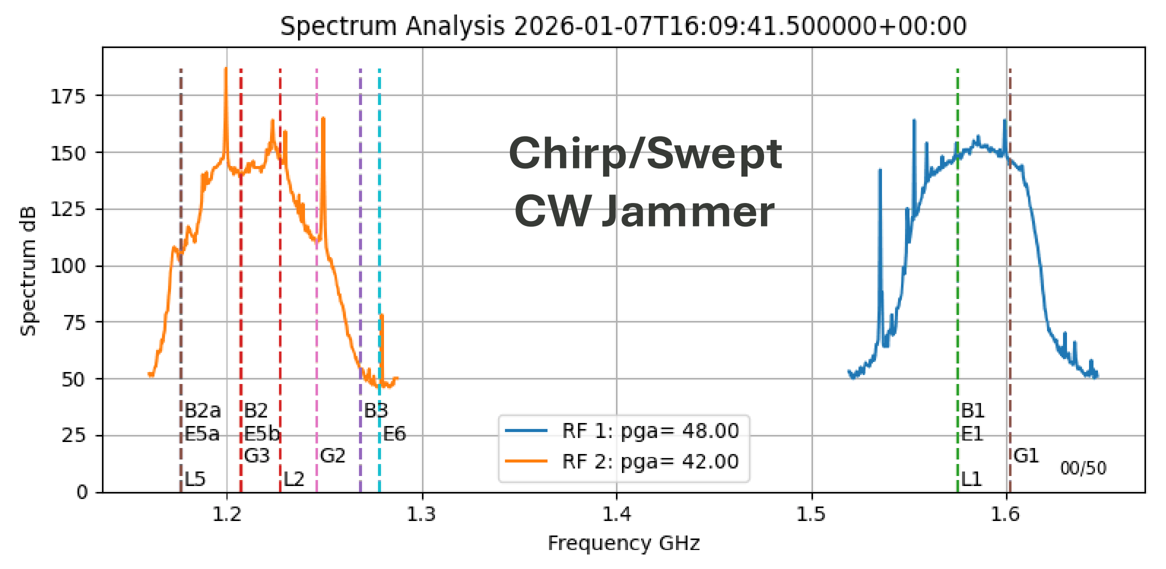


128 MHz Bandwidth
Span Center @ 1.22401 GHz
256 FFT Bins

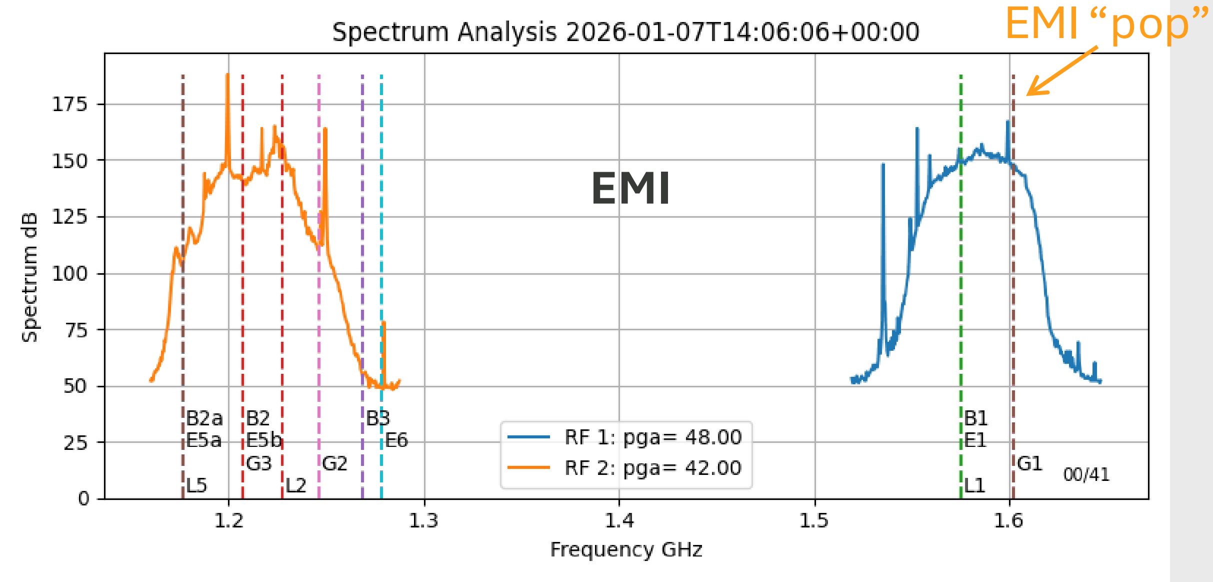
128 MHz Bandwidth
Span Center @ 1.58346 GHz
256 FFT Bins

Note: the amplitude values are in decibel but provided by u-Blox F9P unsigned values.

All mitigator activations are legitimate, but not all activations are jammers.

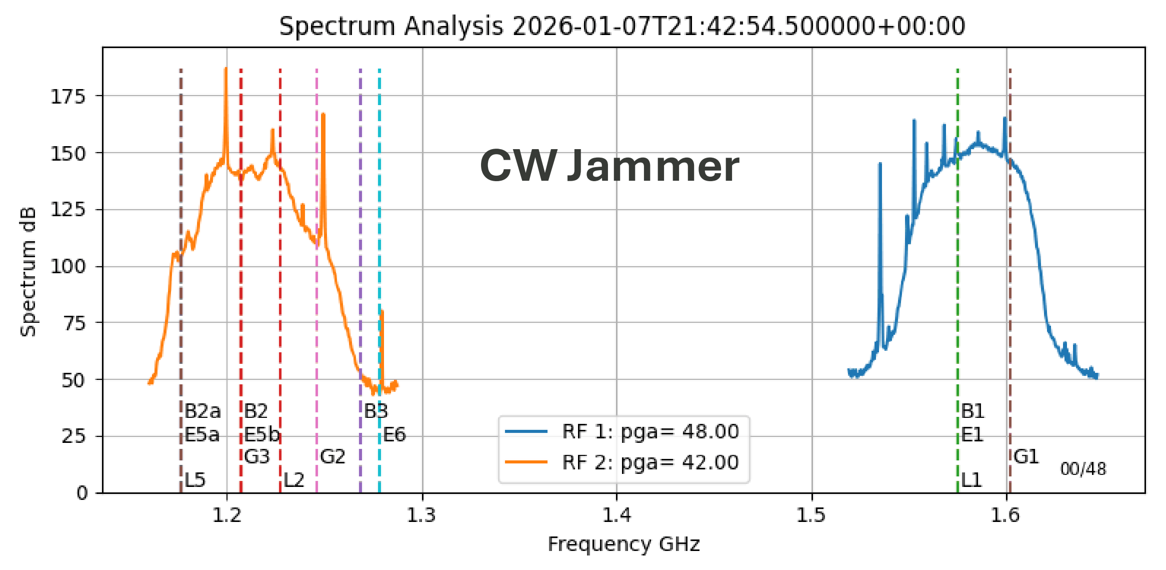

Spectrum Analysis 2026-01-07T16:09:41.500000+00:00

Chirp/Swept CW Jammer

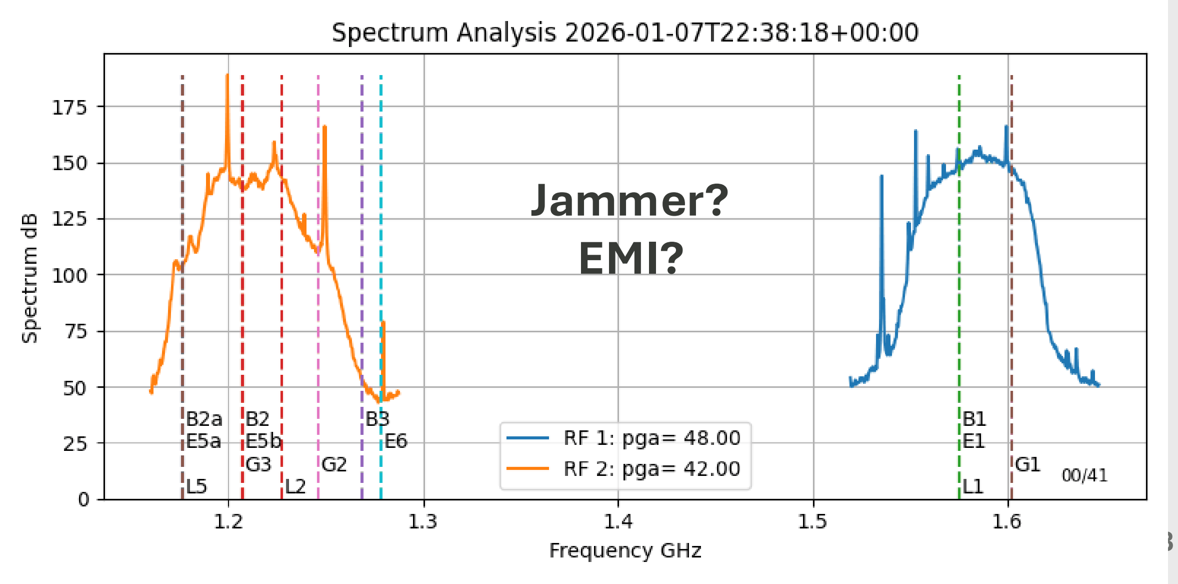

Spectrum Analysis 2026-01-07T14:06:06+00:00

EMI "pop"

EMI


Spectrum Analysis 2026-01-07T21:42:54.500000+00:00

CW Jammer

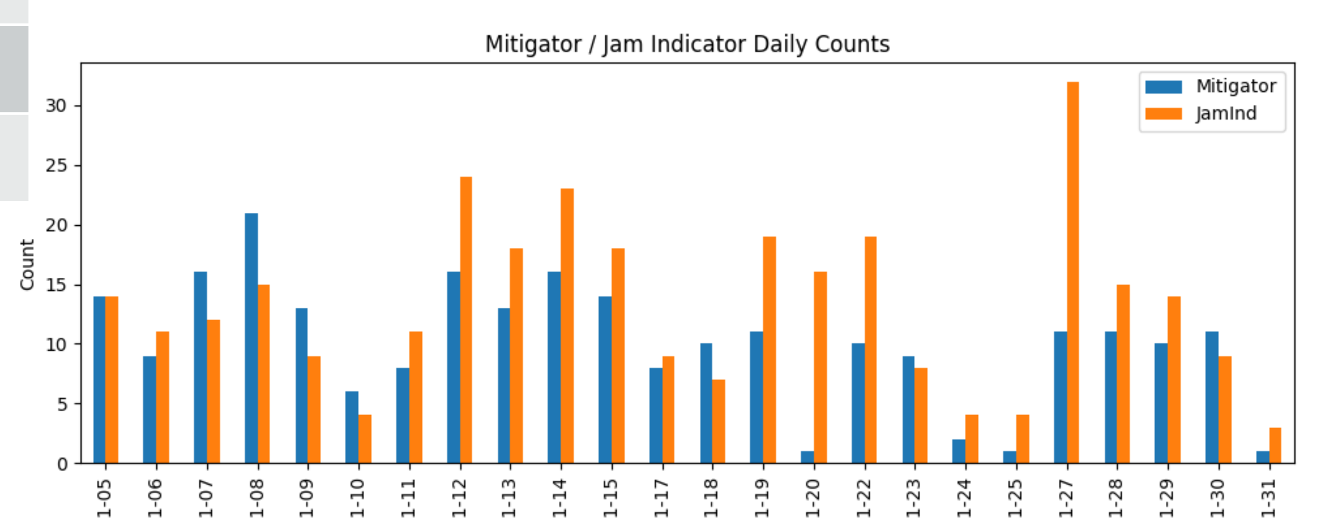

Spectrum Analysis 2026-01-07T22:38:18+00:00

Jammer?
EMI?

In January 2026, there was an average of 10 events per day detected by the L1 Jamming Mitigator

January 2026	Jamming Mitigator	GNSS Receiver Jamming Indicator
Days of Logs	27 of 31	28 of 31
Total Events	257	338
Average # Events per Day	9.52	12.1
Daily Median	10	11
Biggest Day	16	32
Slowest Day	1	2

For January 2026, there were a total of 85,232 vehicles that passed over the scales at the Eastbound weigh stations. 87,008 passed over the Westbound scales.



Oak Ridge National Laboratory

Lessons learned, hard knocks, and next steps

Equipment

- Commercial mitigator provides protection and detection
- Quantitative analysis needs spectral confirmation

EMI

- It is prolific
- It is strong

Data

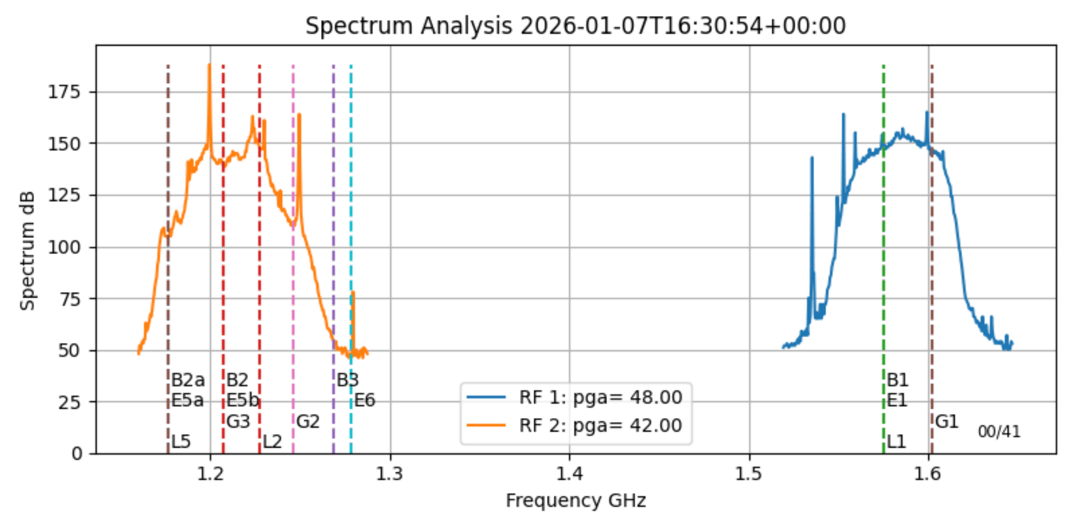
- Requires significant curation
- Form matters, volume vs value

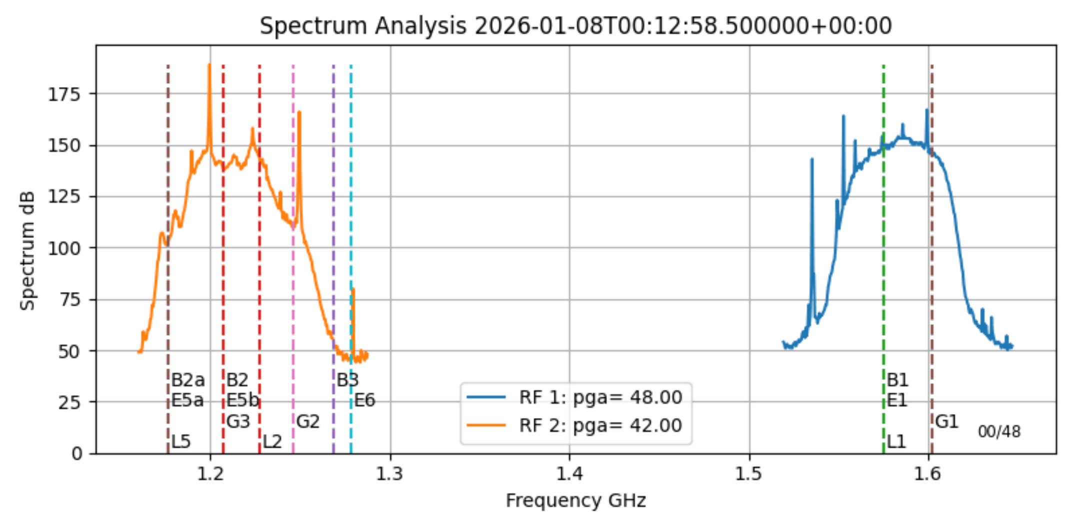
Next Steps & Open Questions:

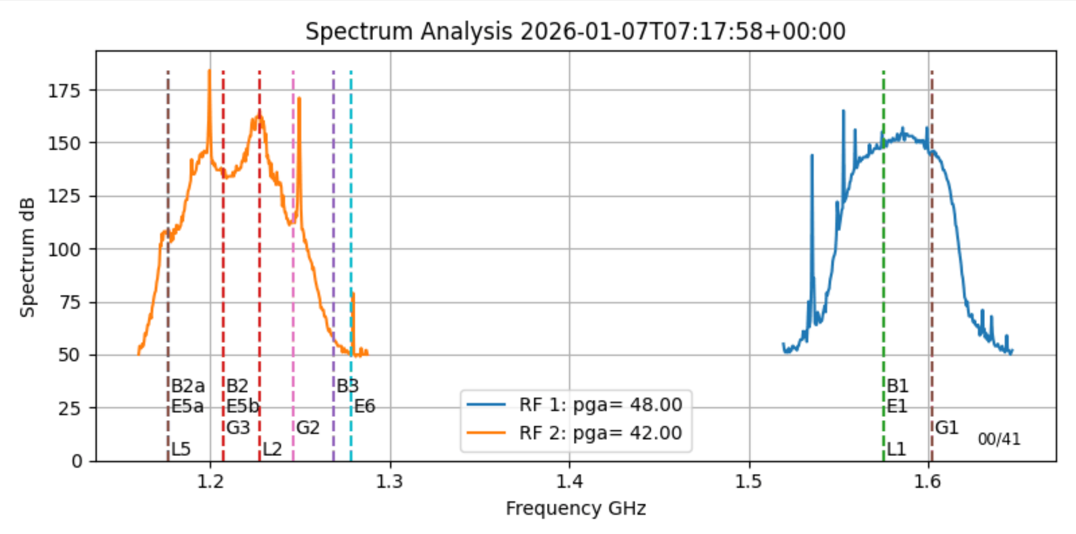
- Data curation automation… so much EMI to sift though

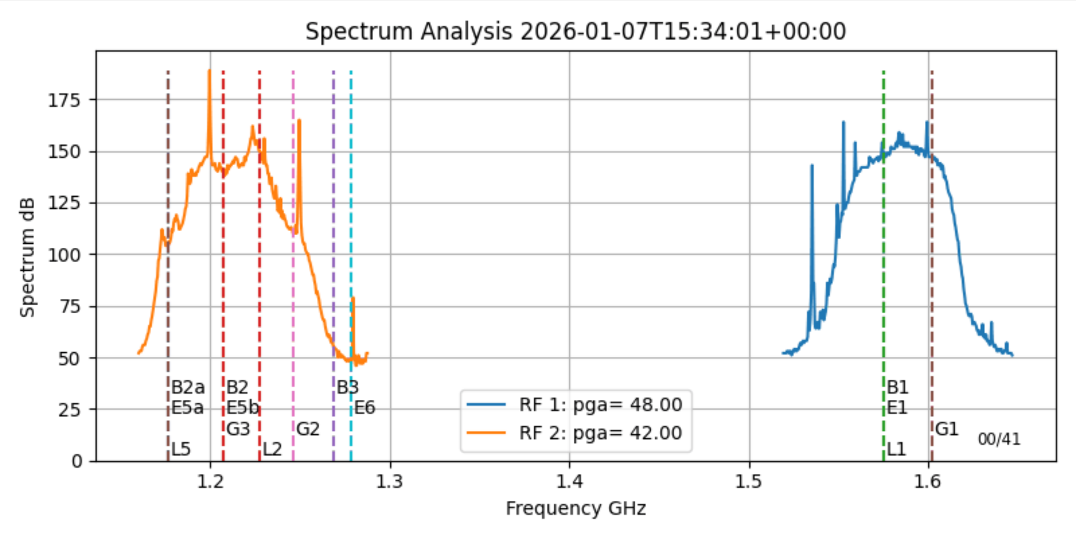
  Newer commercial, non-military jamming mitigators provide more information, e.g. signal strength of detected jammer, relative direction of detection
- Antenna orientation – what happens if pointed at roadway instead of skyward?
- Place second detector on westbound side… will detections correlate?

In conclusion, jammers on US roadways are not just a “scary story.” They are not rare. They are in use and traveling our roads every day.


Spectrum Analysis 2026-01-07T16:30:54+00:00


Spectrum Analysis 2026-01-08T00:12:58.500000+00:00


Spectrum Analysis 2026-01-07T07:17:58+00:00


Spectrum Analysis 2026-01-07T15:34:01+00:00

NAB® NATIONAL ASSOCIATION OF BROADCASTERS | TECHNOLOGY

Broadcast Positioning System™ (BPS™)

Tariq Mondal

NAB

What is Broadcast Positioning System (BPS)?

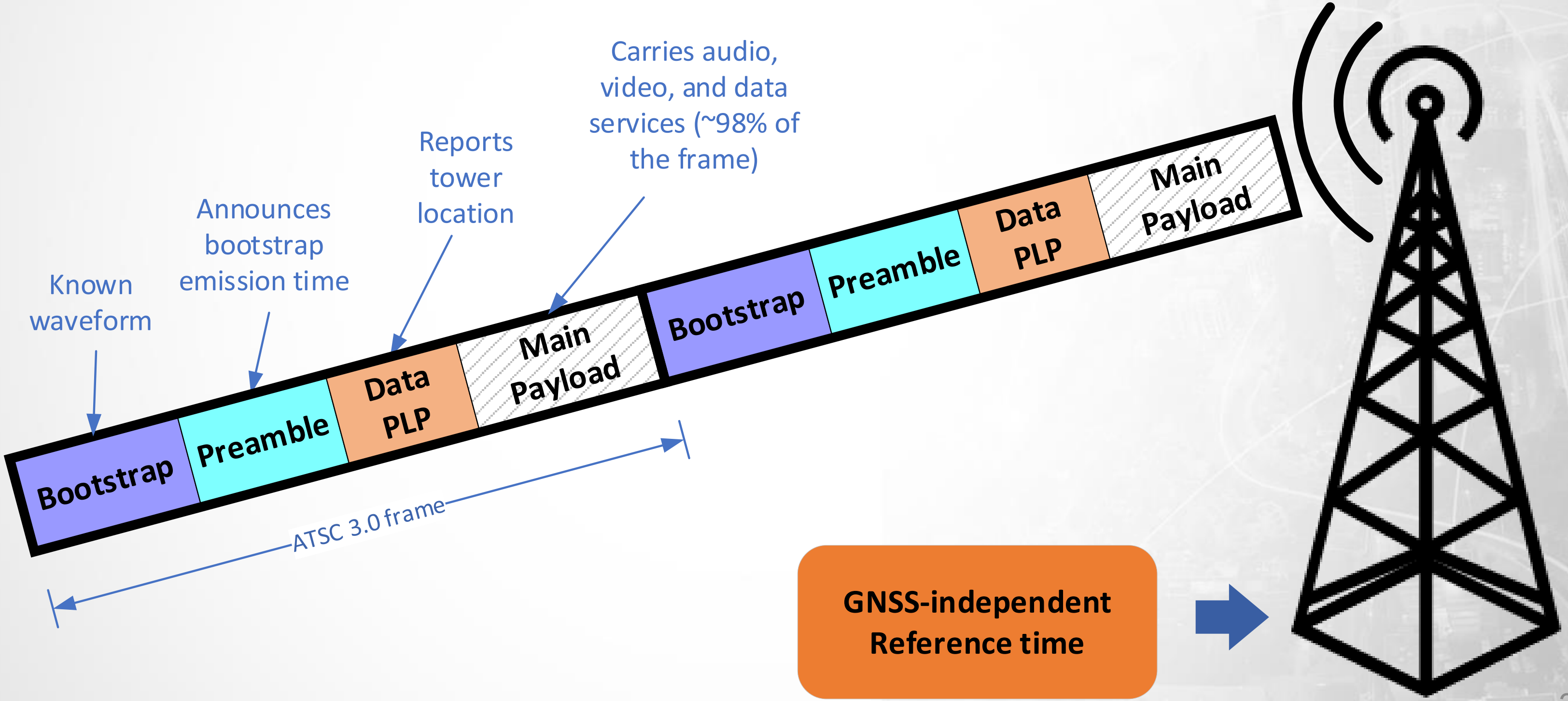
A system and method of estimating time and position at a receiver using Next Gen TV broadcast signals

Compliant with Next Gen TV (ATSC 3.0) standard currently being deployed in the US

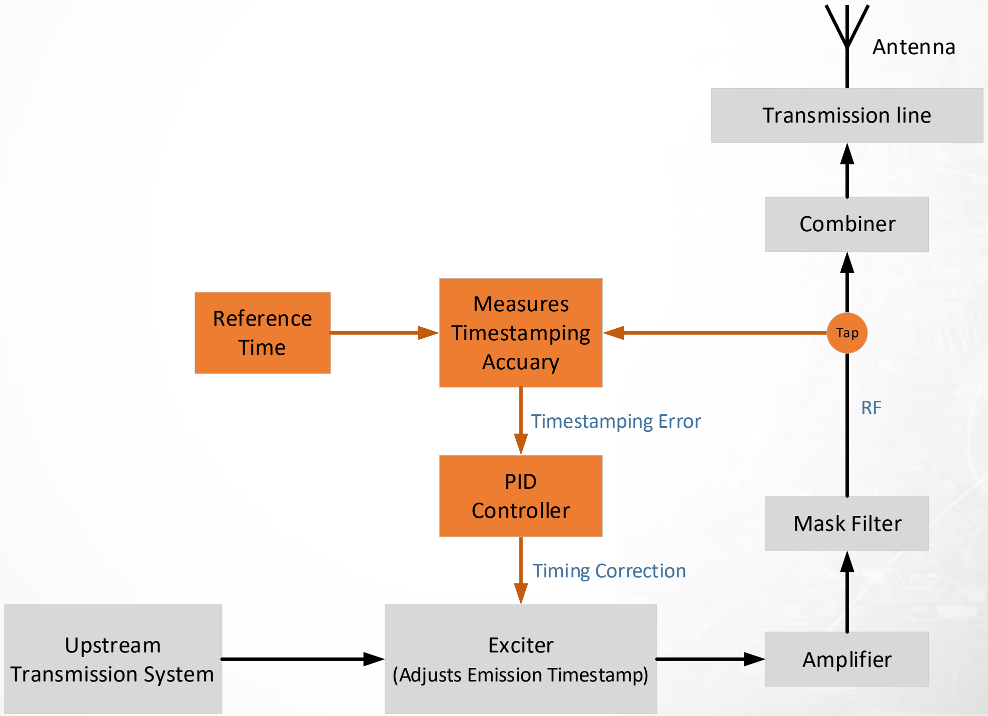
Independent and stand-alone

- GPS, Internet or cellular connectivity not required

Concept


Known waveform
Announces bootstrap emission time
Reports tower location
Carries audio, video, and data services (~98% of the frame)
Bootstrap
Preamble
Data PLP
Main Payload
Bootstrap
Preamble
Data PLP
Main Payload
ATSC 3.0 frame
GNSS-independent Reference time

Timestamp Control Loop



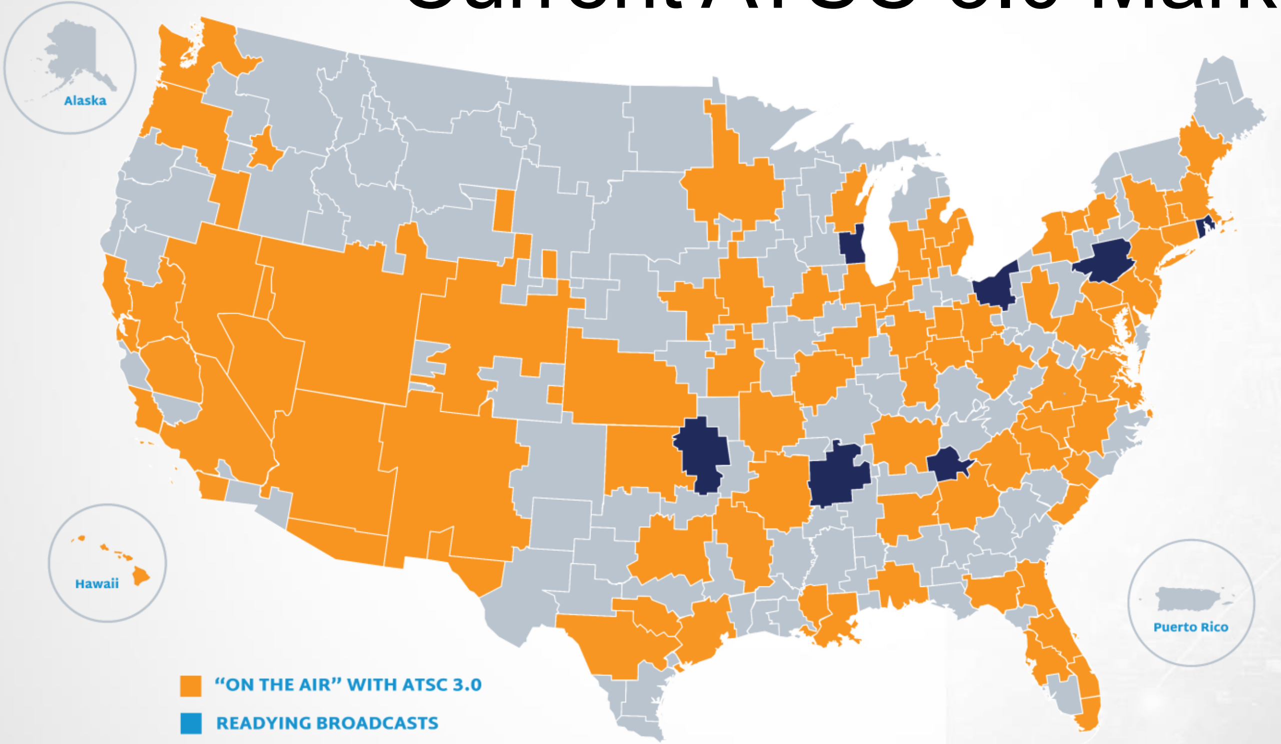
High Power with Frequency Diversity

Low VHF	High VHF	UHF
2-6 Channels	7-13 Channels	14-36 Channels
54-88 MHz Frequency	174-216 MHz Frequency	470-608 MHz Frequency

516 VHF stations, up to 100 KW

1,526 stations, 100 – 1000 KW

Current ATSC 3.0 Market Coverage



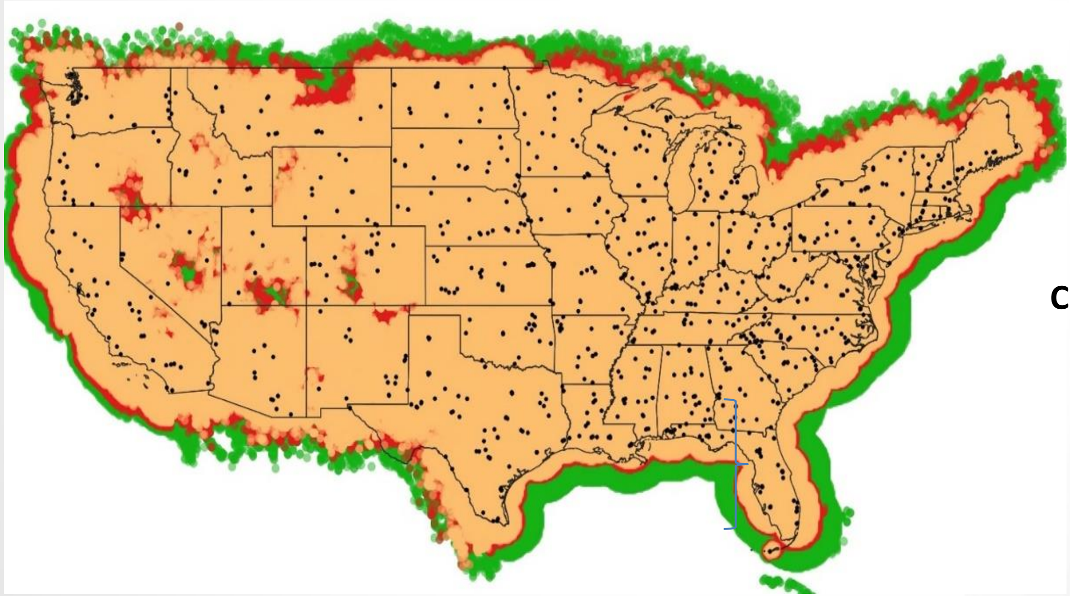
🟧 "ON THE AIR" WITH ATSC 3.0

🟦 READYING BROADCASTS

■ ANNOUNCED TARGET MARKET

Source: atsc.org

BPS (UHF & VHF) Coverage at Full Deployment



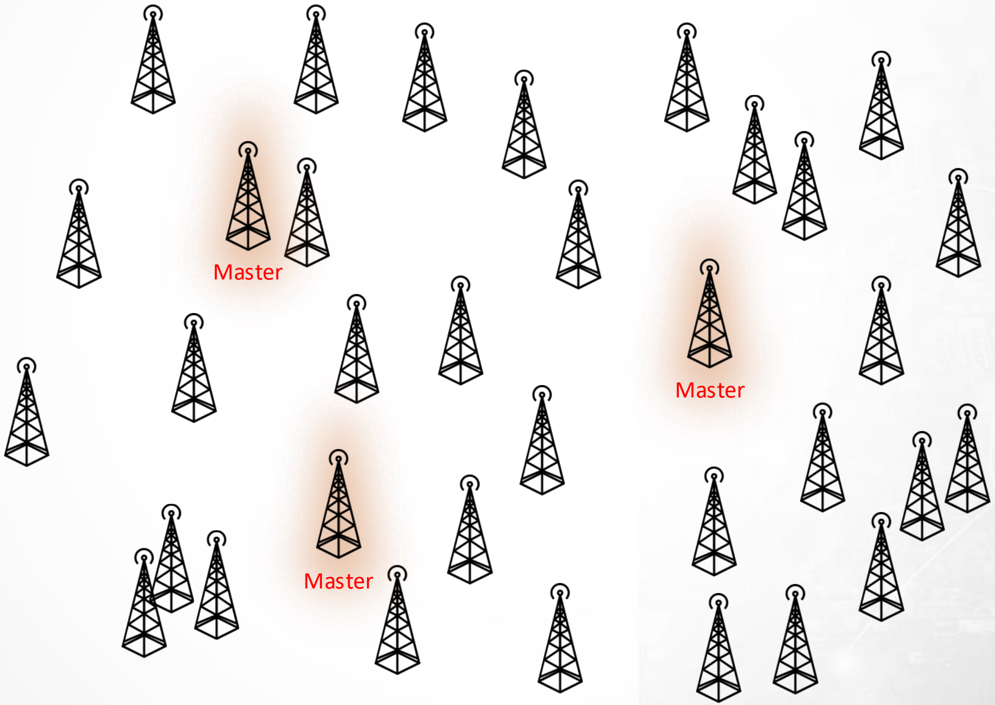
Average signal reception:

- 17 towers at 1.5 m antenna height
- 70 towers at 50m antenna height

Coverage at 1.5 m antenna height:

🟩 At demodulation threshold (-5 dB SINR)
🟥 Threshold + 10 dB
🟧 Threshold + 20 dB

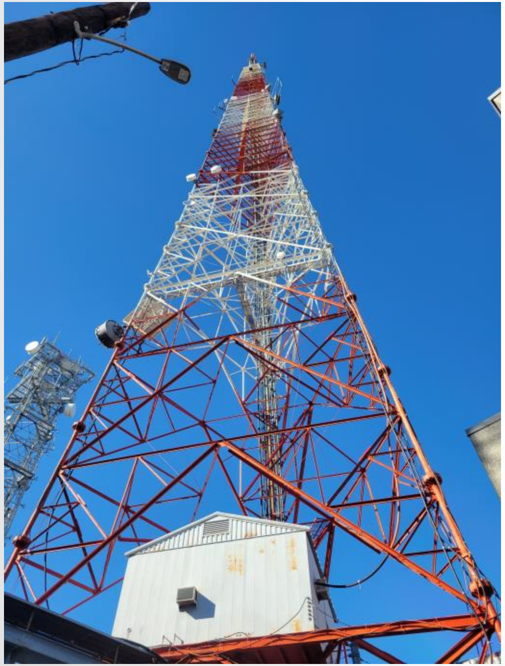
Self Synchronizing Network with Traceable Time



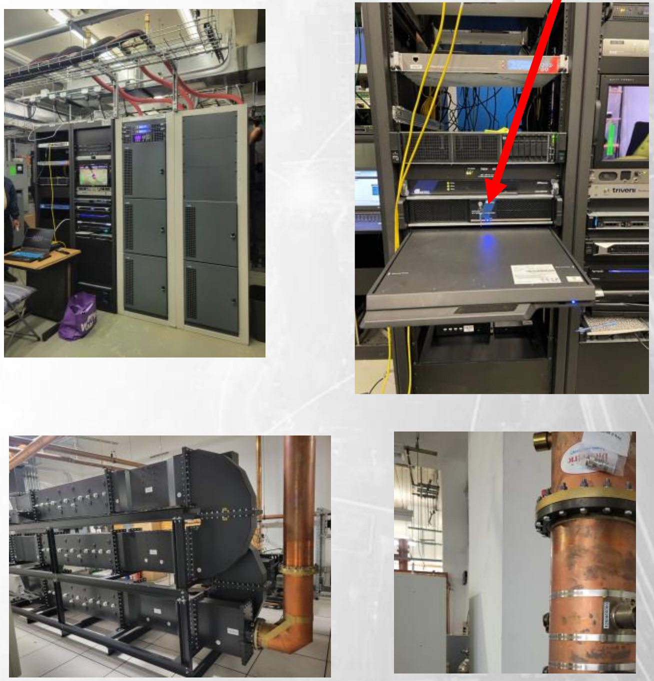
Advantages of BPS

- Infrastructure is already built
- International standard
- Passive consumer service
- Independent
- Frequency diversity
- Nationwide coverage

WHUT (Washington, DC)



Transmit Channel	33
Frequency	584 - 590 MHz
Effective Radiated Power (ERP)	**416 kW**
Antenna radiation center Height Above Average Terrain (HAAT)	254 meters

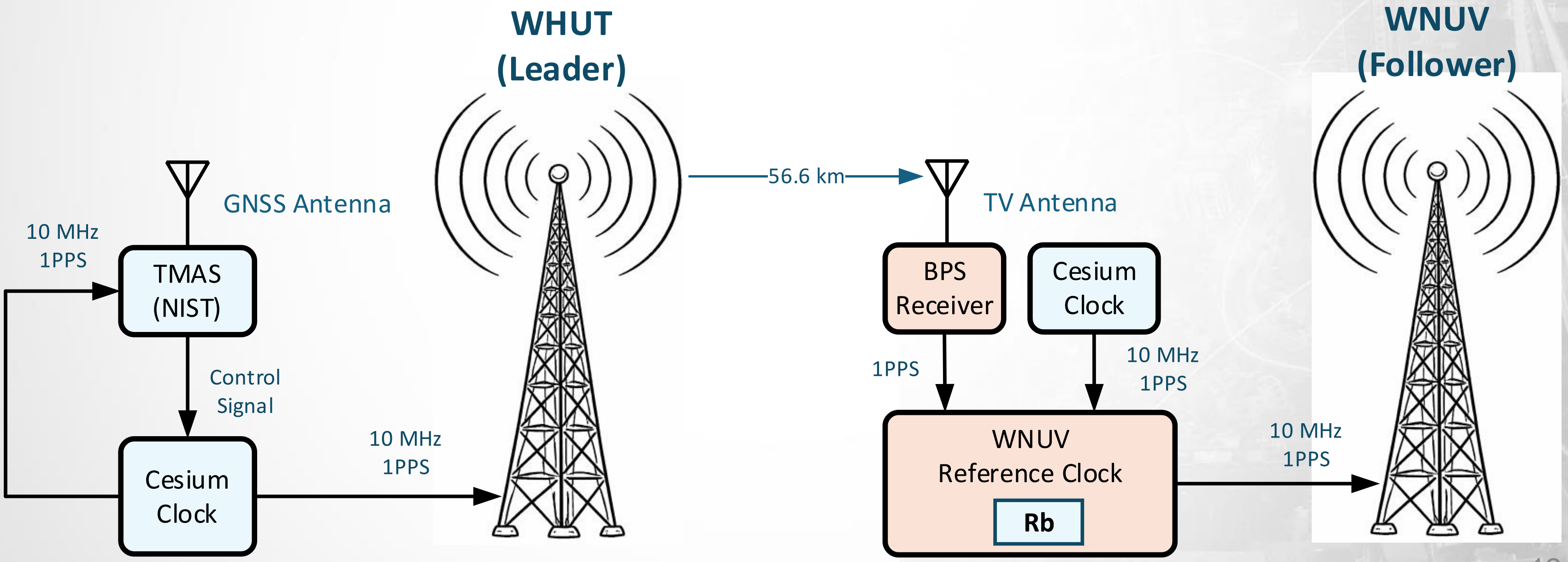


WNUV (Baltimore, Maryland)

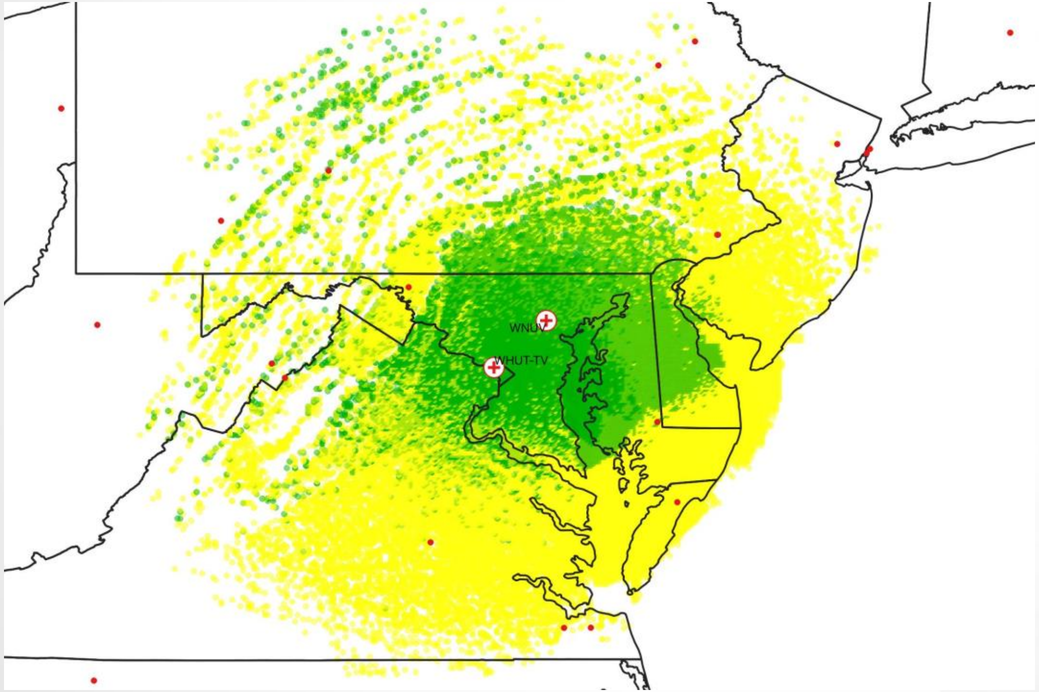
Transmit Channel	25
Frequency	536 - 542 MHz
Effective Radiated Power (ERP)	**750 kW**
Antenna radiation center Height Above Average Terrain (HAAT)	456.8 meters

Implemented Leader-Follower Network

GNSS is not directly used in the network



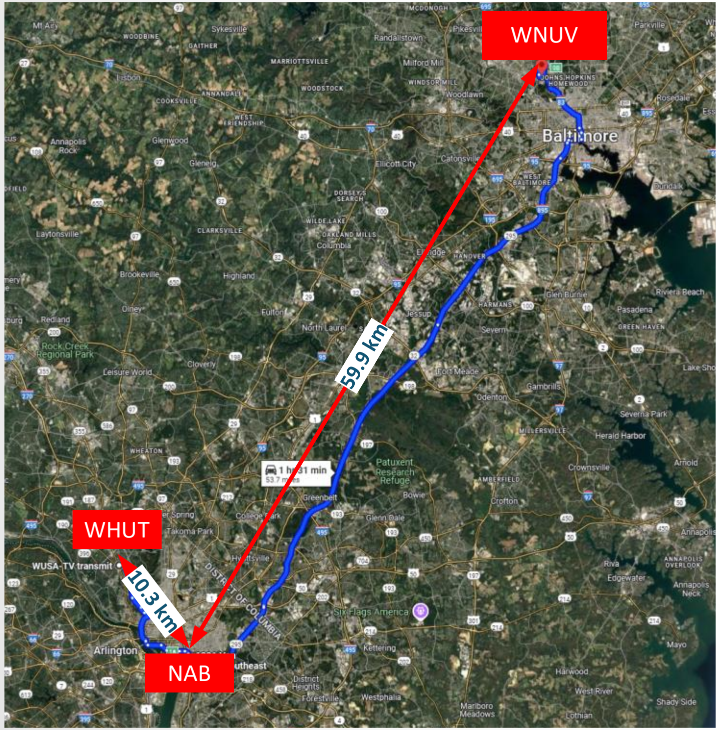
WHUT and WNUV Combined Coverage Map

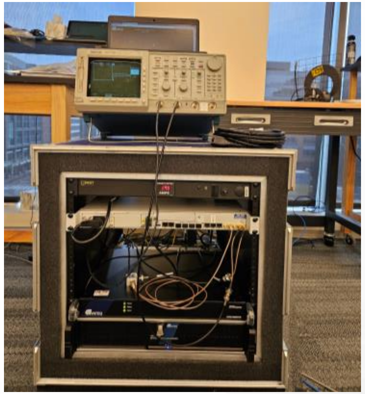


- Signal reaches to parts of Maryland, Virginia, Washington DC, Delaware, New Jersey, Pennsylvania, and West Virginia

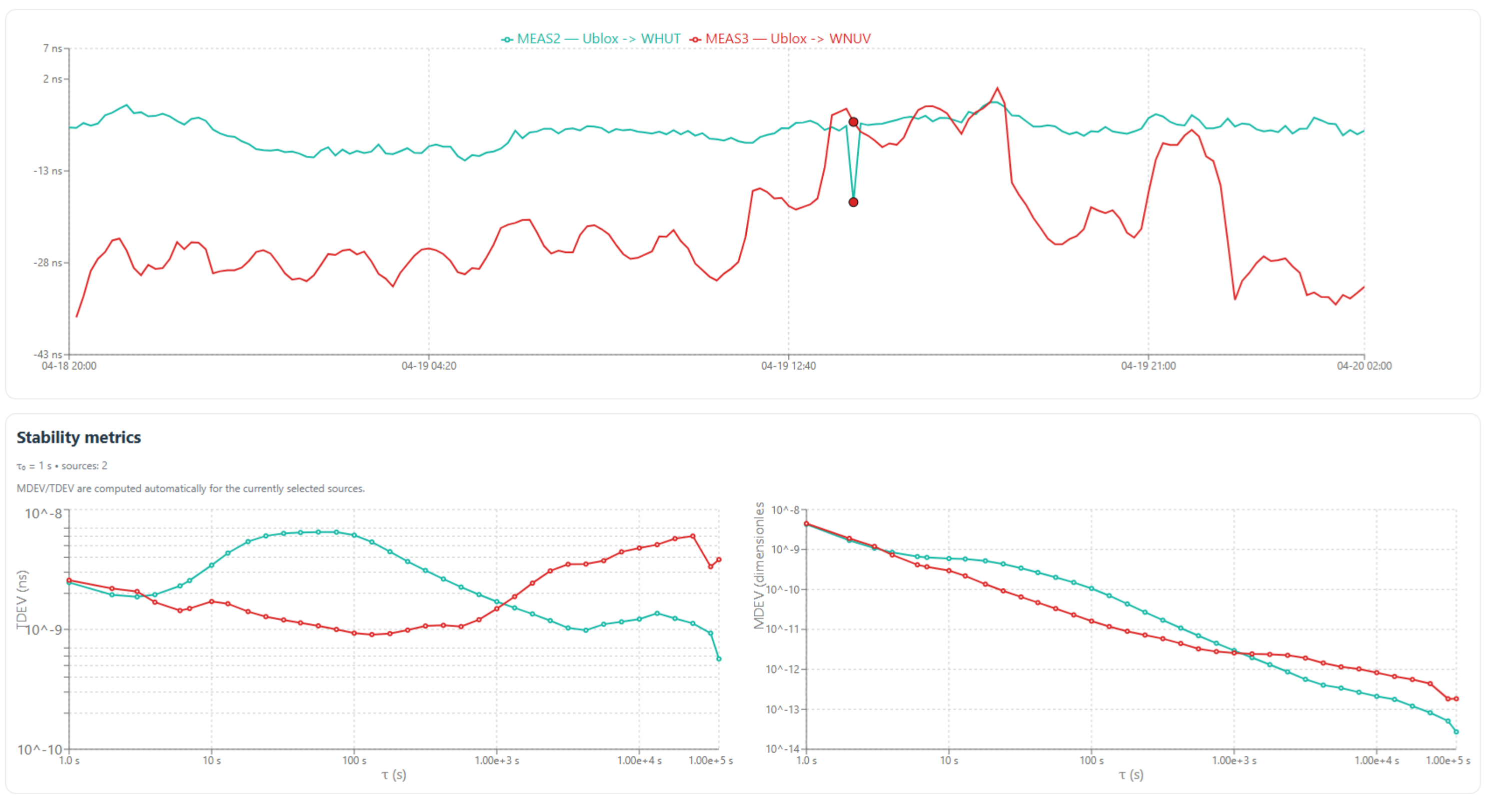
- 81,245 square-km of BPS coverage

Test and Validation at NAB Lab





Monitoring Dashboard



Stability metrics

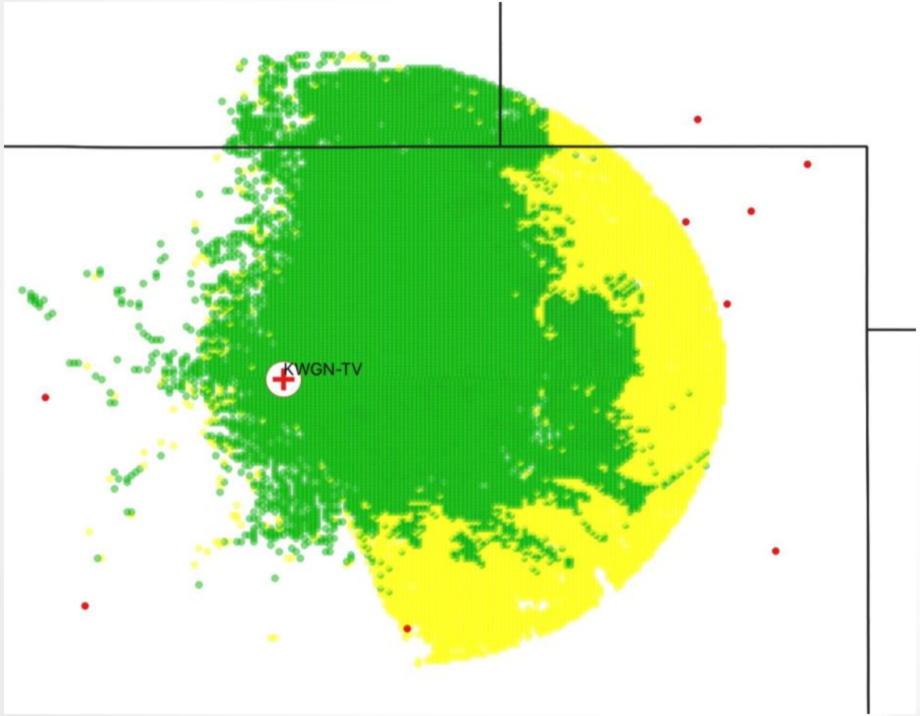
τ_0 = 1 s • sources: 2

MDEV/TDEV are computed automatically for the currently selected sources.

KWGN (Denver, Colorado)

Transmit Channel	34
Frequency	590 - 596 MHz
Effective Radiated Power (ERP)	**1000 kW**
Antenna radiation center Height Above Average Terrain (HAAT)	336 meters

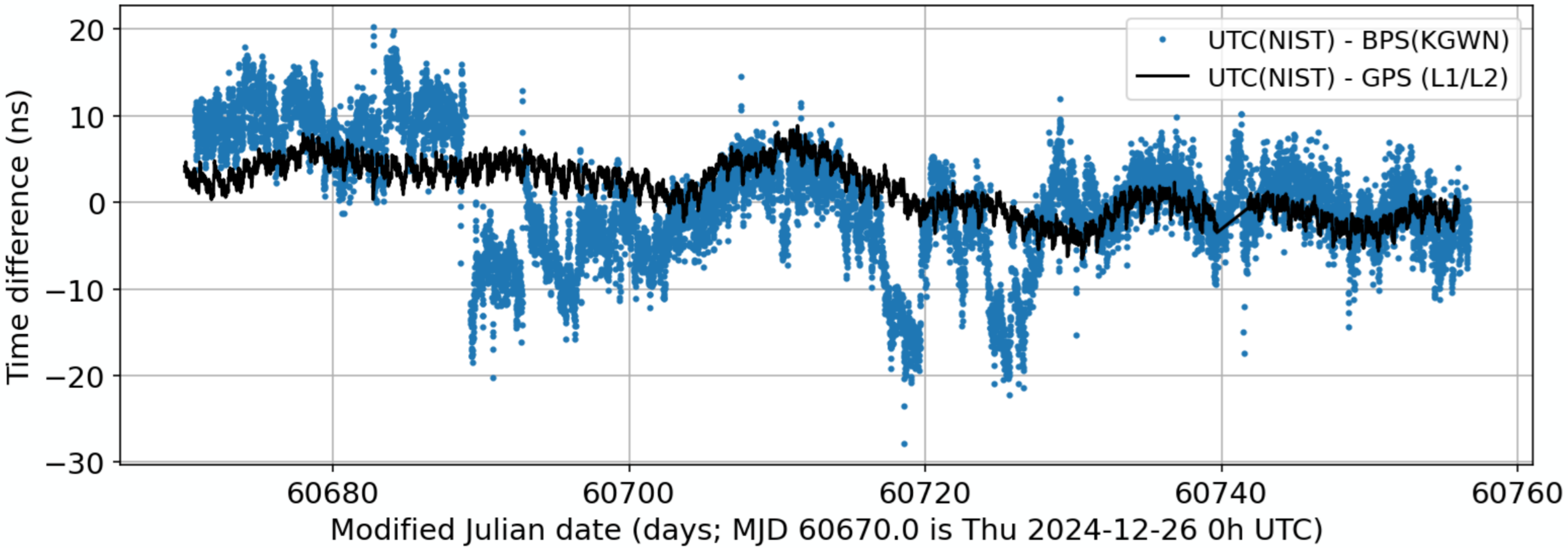
KWGN Coverage



- Signal reaches to parts of Colorado, Wyoming and Nebraska
- 75,858 square-km of BPS coverage

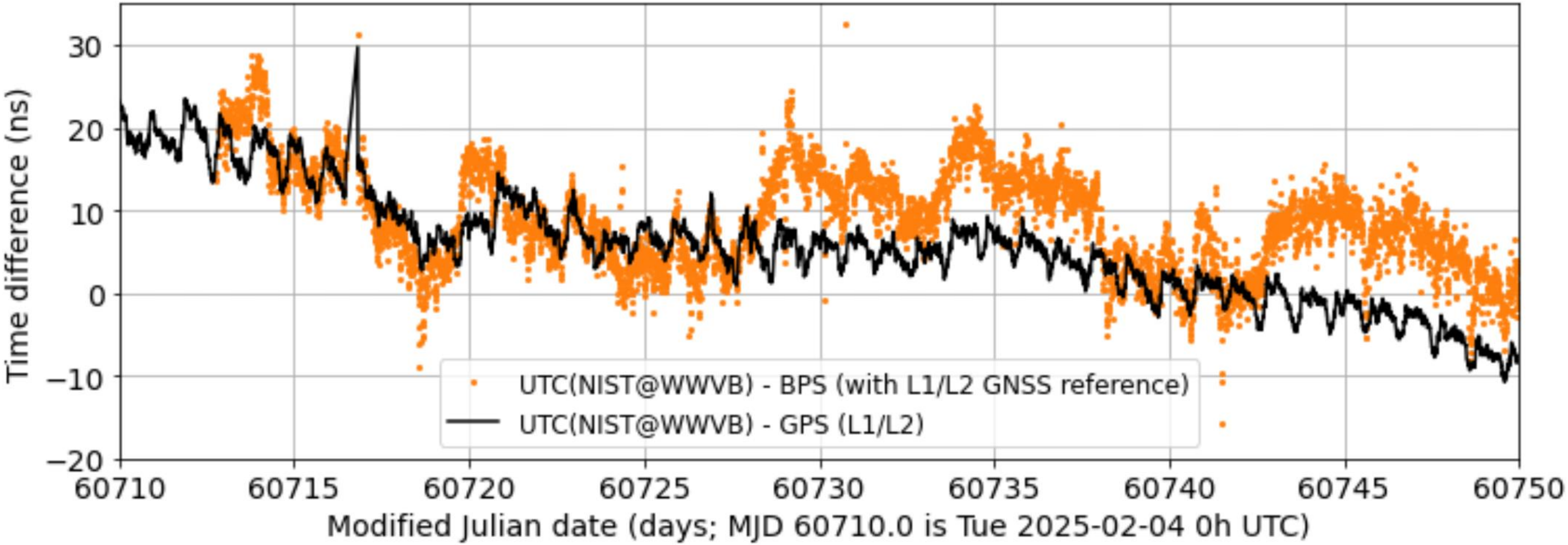
30 km NLOS Performance (NIST)

Example: 86 days, UTC(NIST) - BPS(KWGN)

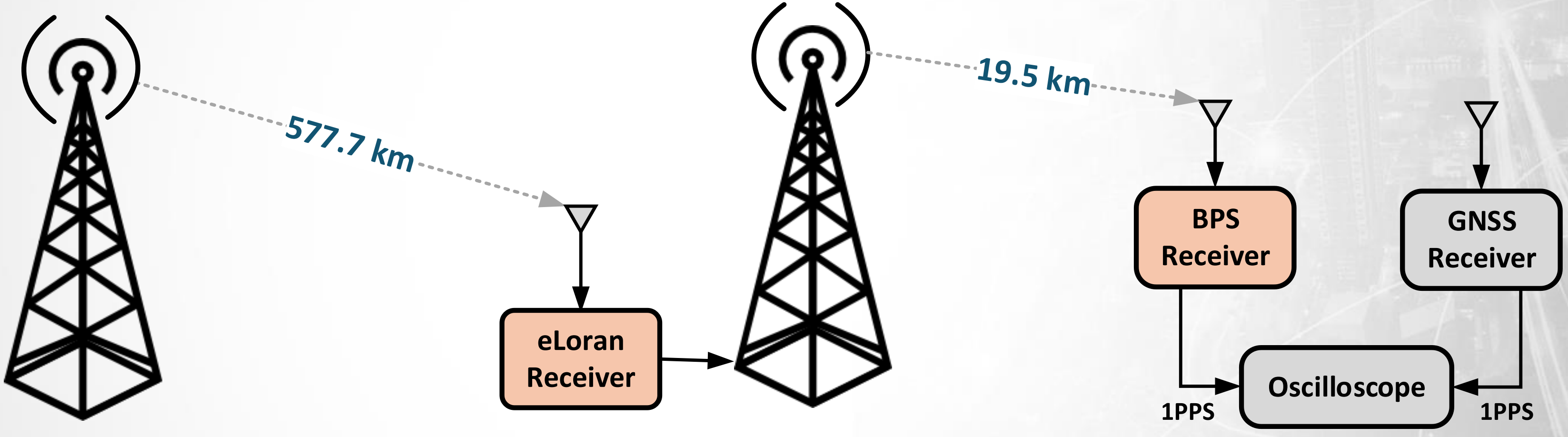


106 km LOS Performance (NIST)

Example: 40 days, UTC(NIST@WWVB) - BPS(KWGN)



Live BPS+eLORAN Survivability Demo



577.7 km

19.5 km

eLoran Receiver

BPS Receiver

GNSS Receiver

Oscilloscope

1PPS

1PPS

eLoran Transmitter at Fallon, Nevada

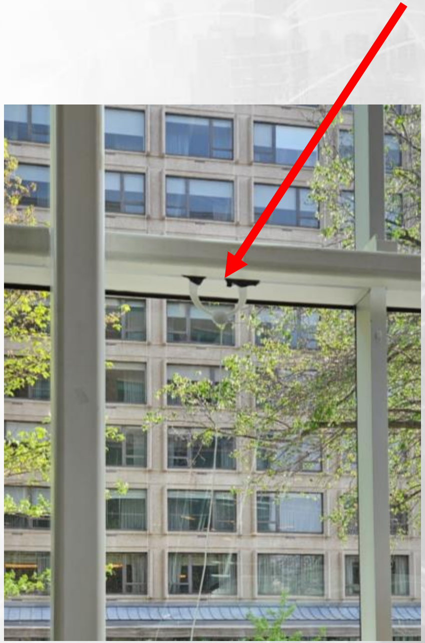
KSNV (BPS) Transmitter at Black Mountain, Nevada

Convention Center, Las Vegas, Nevada

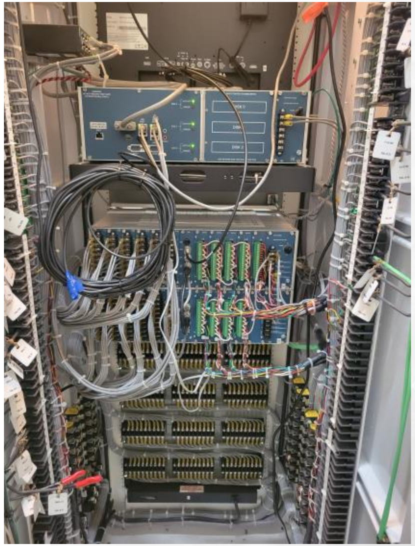
Live Demo at NAB Show

This demonstration is made possible with the support of UrsaNav® for eLoran and Sinclair Broadcast Group for ATSC 3.0 transmission of BPS.

Live Demo at Assured PNT Summit



Testing at a Power Substation



Summary

- BPS works
- BPS infrastructure already exists
- BPS is ready to be deployed
- Public-Private partnership can make it happen quickly

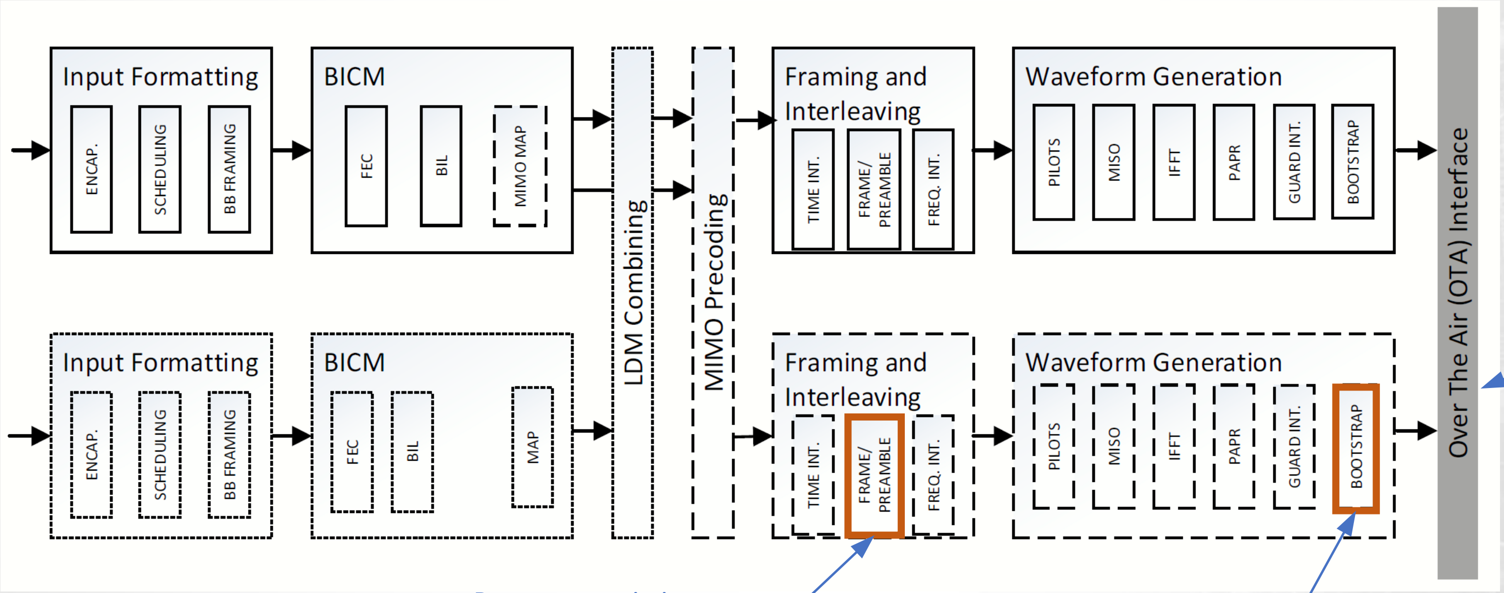
Thank You

nab.org/bps

tmondal@nab.org

Backup Slides

Timestamping



D/A converter, filter, amplifier, and transmission line add additional delay

Bootstrap emission timestamps are created here

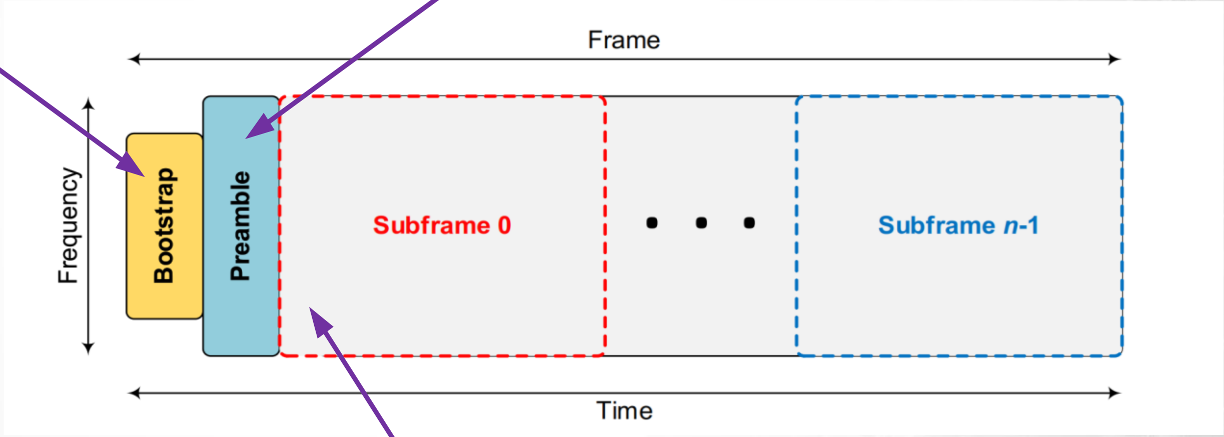
Bootstraps are created here

Source: ATSC Standard, Physical Layer Protocol, Doc. A/322:2020

ATSC 3.0 Frame

This is the most robust potion of a frame and is decodable at -12 dB SNR. The waveform is also semi-static in deployed systems.

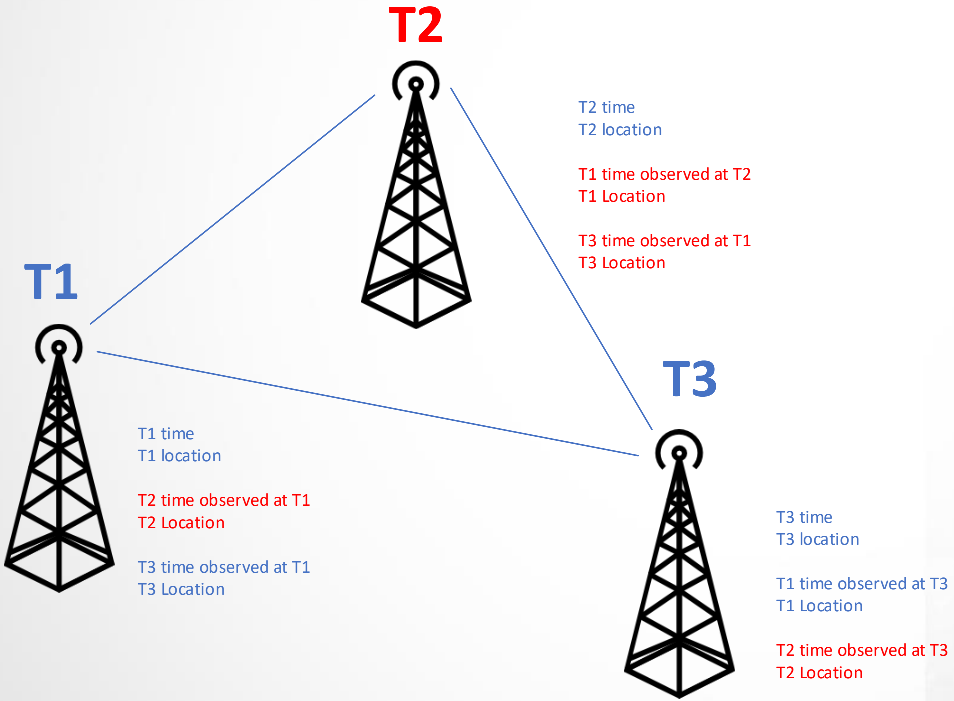
This is a very robust part of a frame and is decodable at -9 dB SNR. The preamble has dense pilot pattern that is designed for channel estimation.



The rest of the frame also has scattered pilot symbols. The robustness of BPS PLP is chosen so that the data is decodable at -5 dB SNR.

Source: ATSC Standard, Physical Layer Protocol, Doc. A/322:2020

Neighbor Measurement Report for Resiliency



T2

T2 time
T2 location

T1 time observed at T2
T1 Location

T3 time observed at T1
T3 Location

T1

T1 time
T1 location

T2 time observed at T1
T2 Location

T3 time observed at T1
T3 Location

T3

T3 time
T3 location

T1 time observed at T3
T1 Location

T2 time observed at T3
T2 Location

- UE identifies compromised stations
- Helps NOC identify fault in network

JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

11100 Johns Hopkins Road
Laurel, MD 20723-6099

5G/6G NTN[1]: GNSS Resilience and Potential PNT

Presentation to the 65th Meeting of CGSIC

Vijitha Weerackody[2]
Principal Professional Staff
240-592-4516
vijitha.weerackody@jhuapl.edu

[1] NTN: Non-Terrestrial Networks. 5G NTN is also known as New Radio (NR) NTN
[2] With contributions from Kent Benson, Johns Hopkins University APL

Presentation Outline

- GNSS-enabled initial access (Release 19 NTN)
- GNSS-resilient initial access (Release 20 NTN)
  - Challenges
  - Potential solutions
    - PNT-based solutions
- Positioning in 6G Radio NTN study

Topics addressed in Release 20 NTN work:

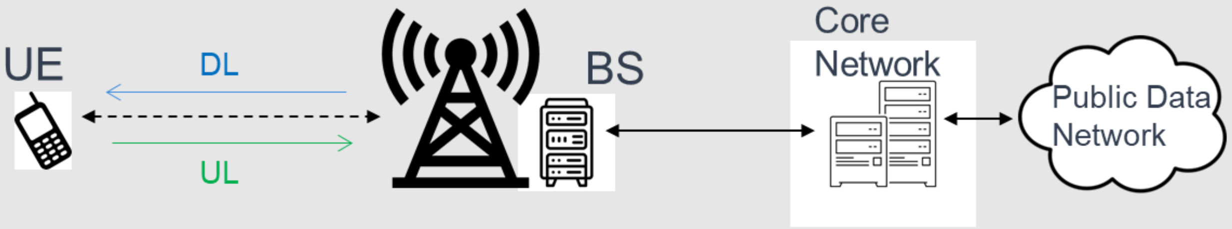
- Provide enhancements to support NTN
- Potential for PNT from commercial satellites
  - Commercial satellite-based PNT services are vital for defense and national interests[1]

---

[1] Space Force ends 'Resilient GPS' satellite program, SPACENEWS, January 19, 2026.

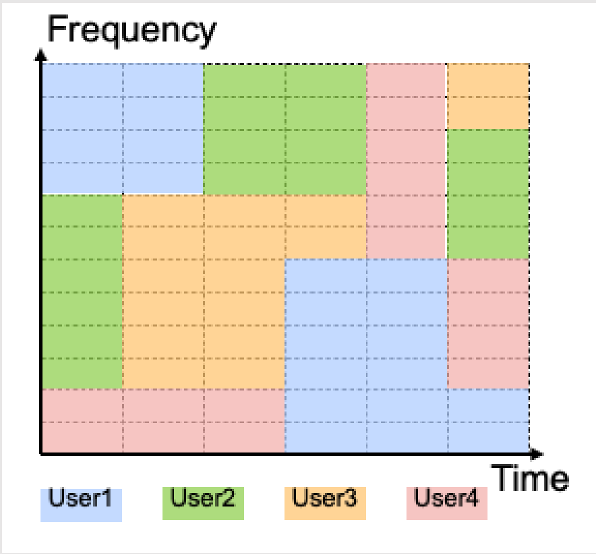
[1] "Lawmakers have repeatedly raised concerns about GPS vulnerability and have called for studies examining **commercial low Earth orbit navigation services** as potential complements or backups."

NR-NTN GNSS Resilience: Problem Statement

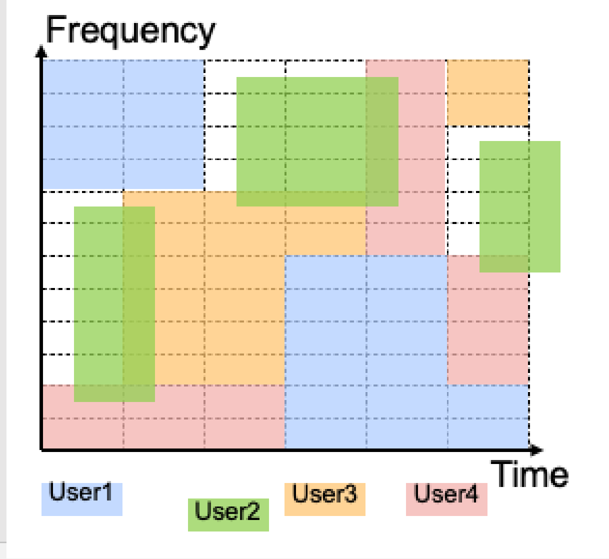


- In cellular networks, uplink time synchronization is crucial
  - UL transmissions from all UEs must be aligned in time and frequency at the Base Station (BS)
  - To be time aligned at the BS, UEs must transmit "early" due to propagation delay
    - This is the timing advance
- After initial access, in the connected mode, a closed loop is used to update the timing advance
- The Doppler frequency should also be pre-compensated in the uplink, but it is small in Terrestrial Networks (TNs)
- Adaptation to NTN networks
  - Challenge: Delays and Dopplers are significantly more than in TN
  - In Release 17 NTN (work completed in 2022), it was *assumed* that UE estimates its position using GNSS
  - In addition, satellite ephemeris sent in System Information (SIB19)
  - UE estimates its timing advance and Doppler using this information
    - UE uses these values in initial access so that at the BS, its uplink signal is aligned with the other uplink transmissions
- Problem addressed in Release 20: How to support initial access and the connected mode in the absence of GNSS?
  - Key problem: Estimating the timing advance and Doppler at the UE in the absence of GNSS

Correct time-frequency alignment at BS



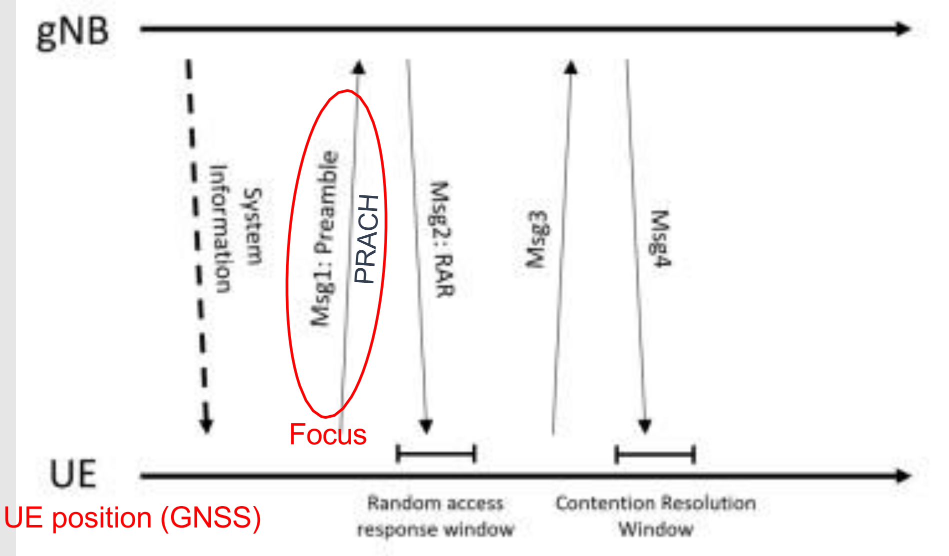
User2 not aligned at BS



GNSS-Enabled Initial Access Procedure (RACH[1] Procedure)

- Initial Timing Advance (TA)
- Uplink Doppler frequency estimation

NR RACH procedure

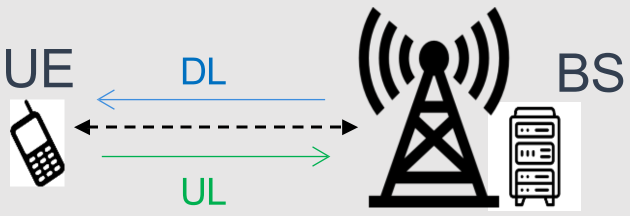


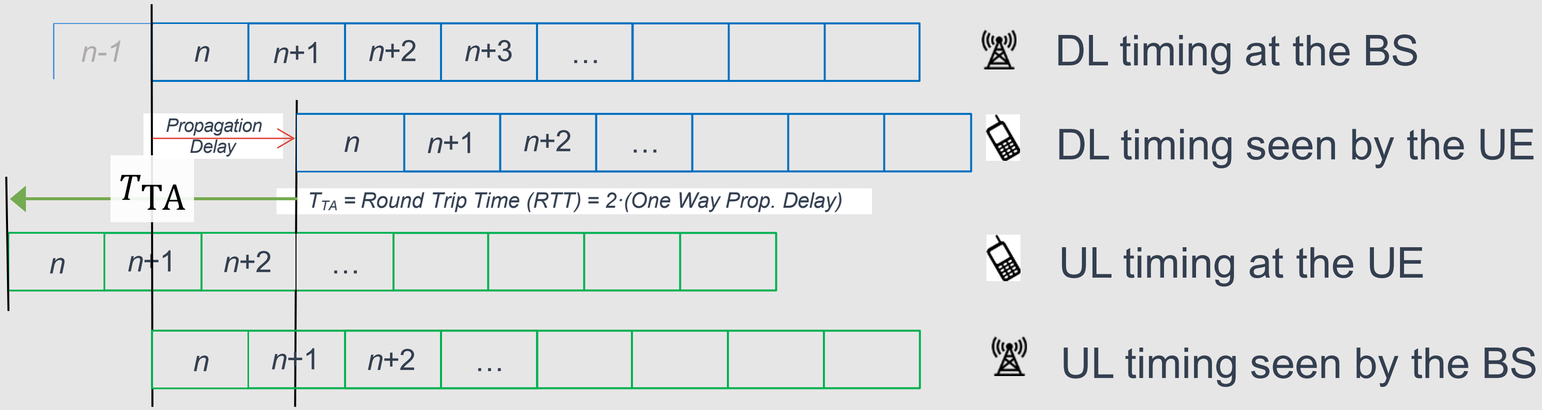
Known UE position (GNSS)

---

[1] RACH: Random Access Channel. PRACH: Physical RACH

GNSS-Enabled Uplink Time Alignment





- RACH is used to achieve Uplink (UL) time synchronization
  - UL transmissions from all UEs must be aligned in time and frequency at the BS
- Each UE transmits "early" so all of the transmissions arrive at the BS at the proper time
  - Each UE maintains a Timing Advance (TA, T_{TA}) value that determines how early it should transmit
  - If a UE wants an UL transmission to arrive at the BS at the beginning of slot n, it must transmit T_{TA} before the DL slot n transmission arrives at the UE from the BS
  - The TA is equal to twice the round-trip time from the BS to the UE back to the BS

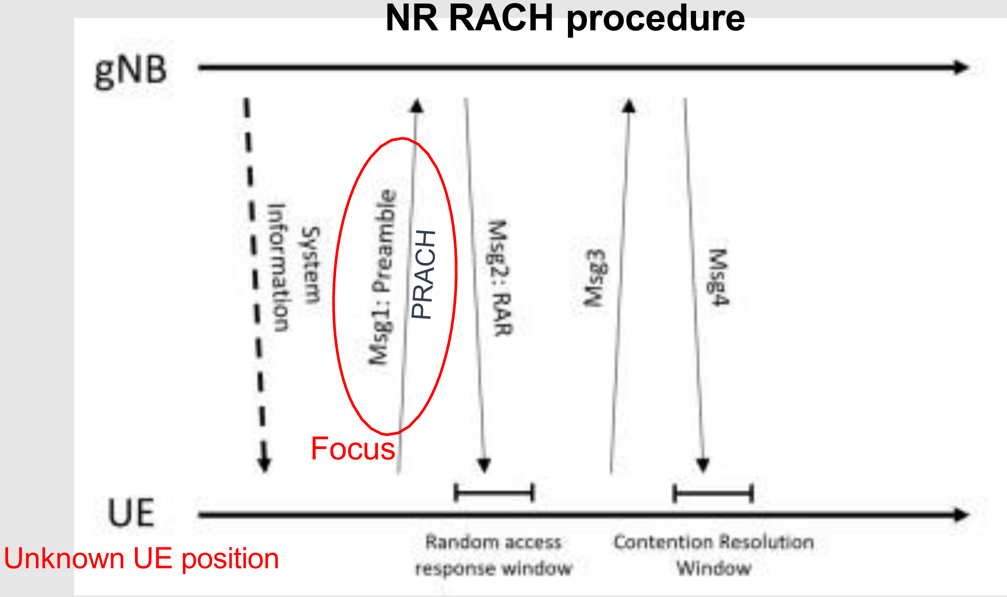
GNSS dependency:

- Initial TA: Estimated using UE's position and the satellite ephemeris (sent in SIB19)
- Doppler frequency: Estimated using UE's position and satellite ephemeris
  - GNSS used in both initial access and connected mode procedures

GNSS-Resilient Initial Access

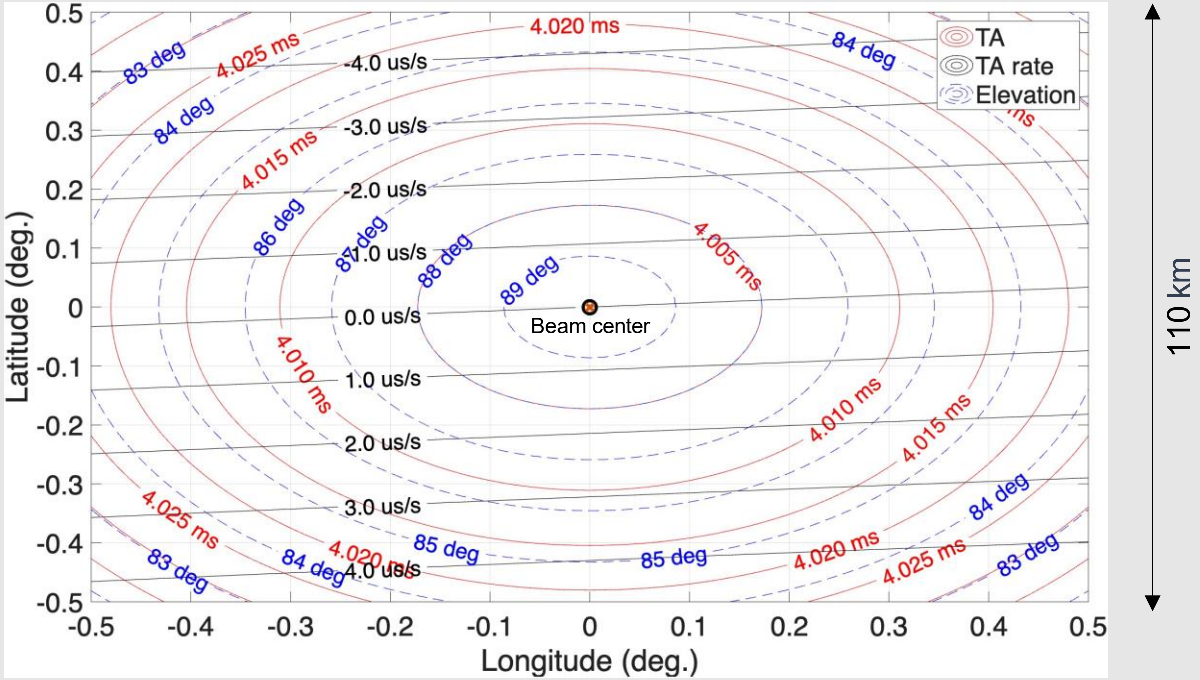
- Challenges: Large timing advance and Doppler frequency
- Potential solutions
  - PNT-based solutions

NR RACH procedure



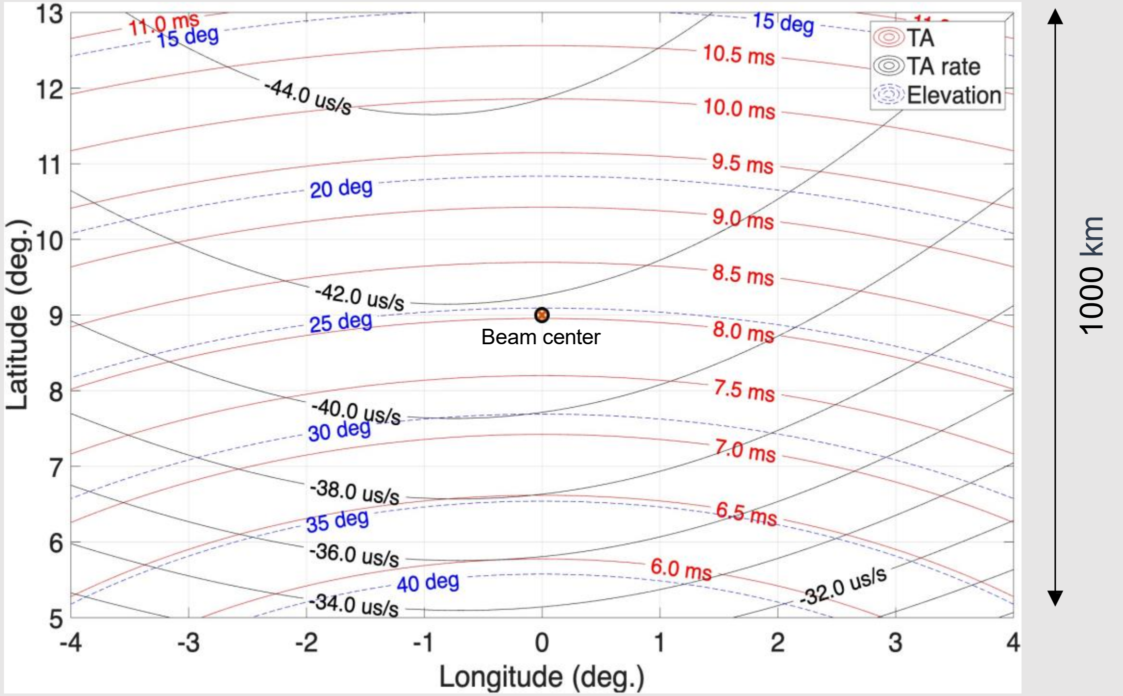
Challenge: Large Initial Timing Advance

TA, Rate of change of TA and elevation angle (nadir-beam footprint)
Satellite location: latitude 0°, longitude 0°, altitude = 600 km



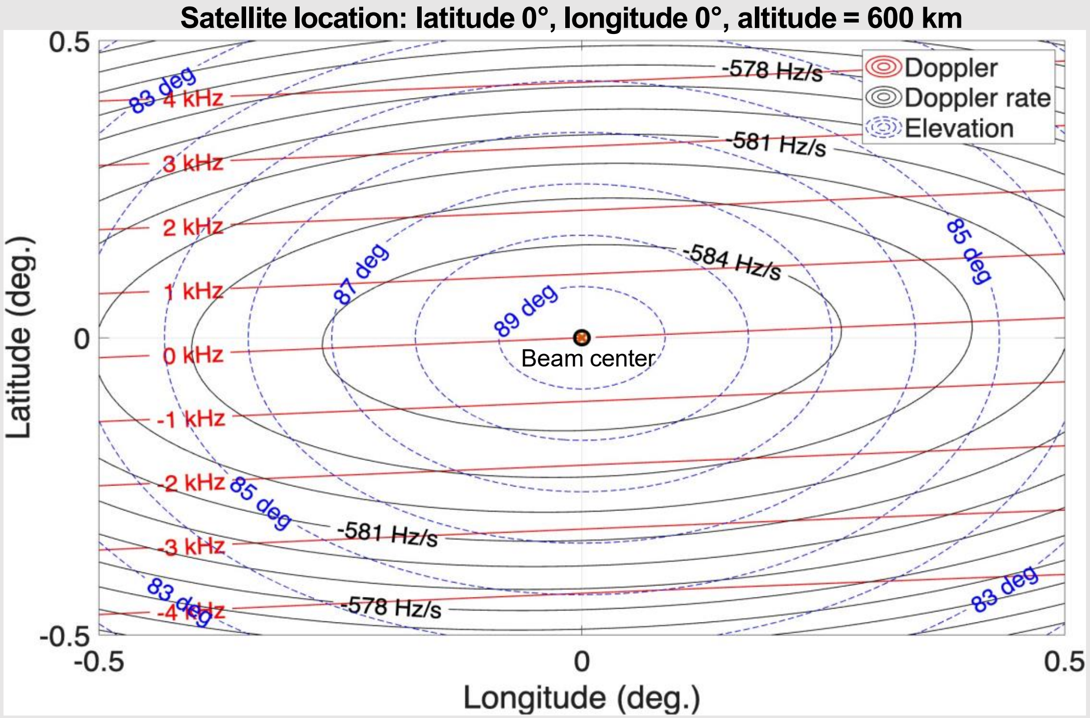
- Spatial variation of TA is low
  - Beam center TA value could be used at all points within the beam
- Time variations of TA are not insignificant
  - Approximately 5 μs per second variation at the beam edge

TA, Rate of change of TA and elevation angle (edge-beam footprint)
Satellite location: latitude 0°, longitude 0°, altitude = 600 km

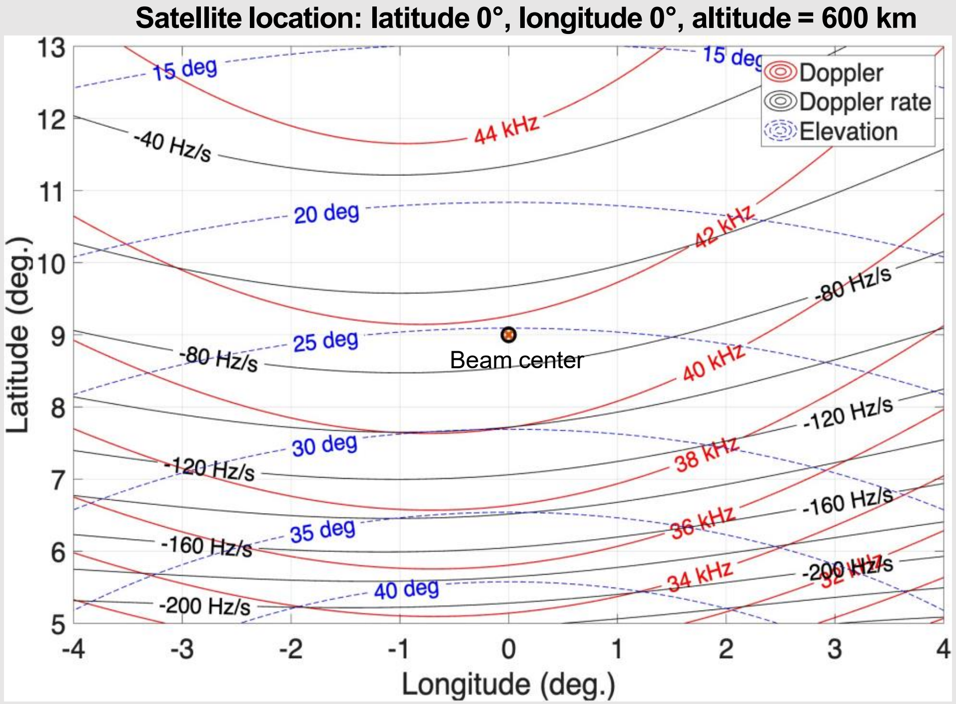


- Significant spatial variation of TA within the beam footprint
  - Significant difference in the TA between its beam center and beam edge values
  - Maximum differential change in TA is 6.36 ms when the minimum elevation angle of the coverage area is 10 degrees (TR 38.821, for 600 km altitude LEO)
- Time variations of TA are significant
  - Approximately 45 μs per second variation at the beam edge
  - Fast closed-loop TA correction from the BS is necessary

Challenge: Large Initial Doppler Frequency



Satellite location: latitude 0°, longitude 0°, altitude = 600 km



Satellite location: latitude 0°, longitude 0°, altitude = 600 km

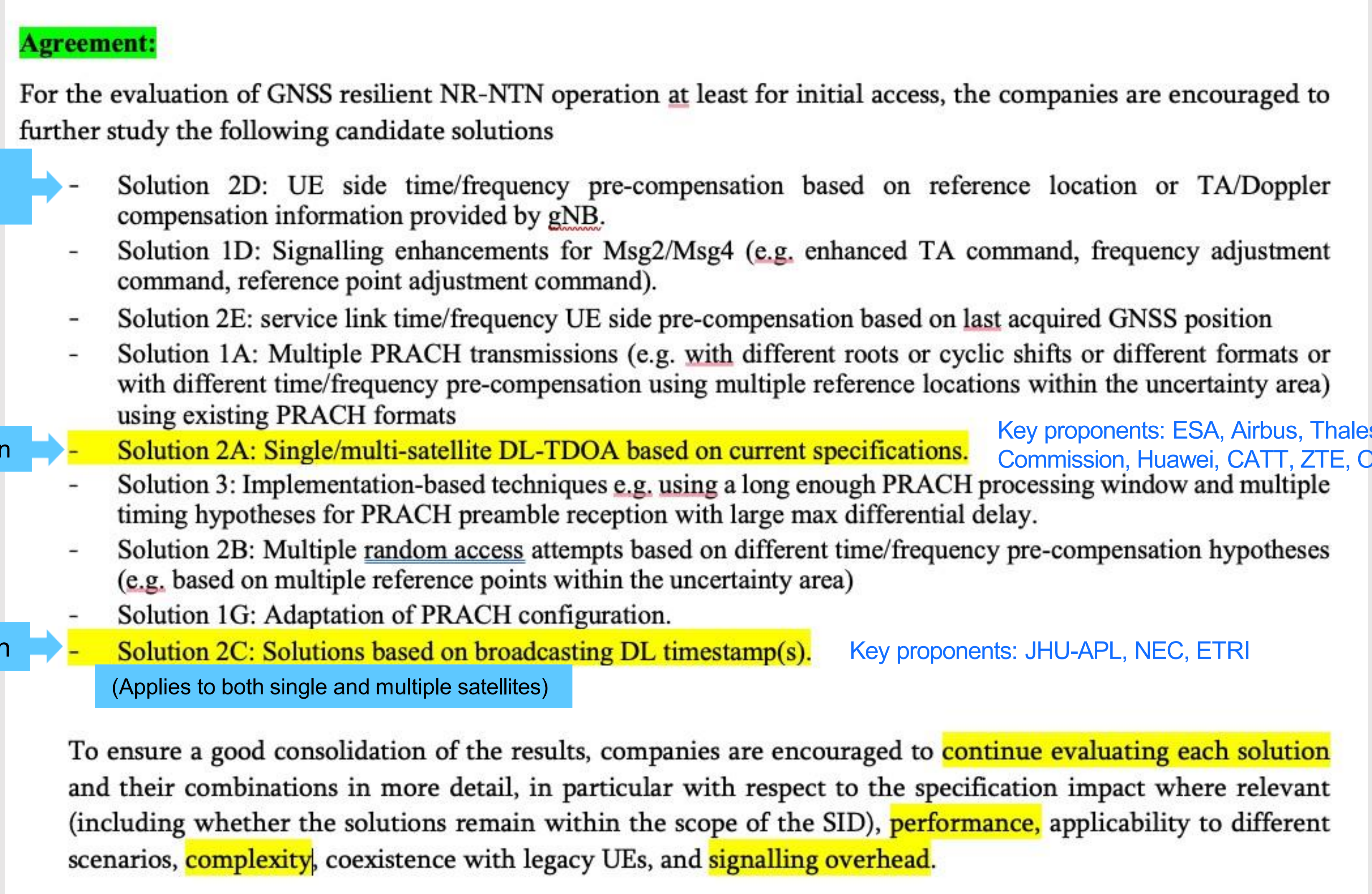
- Spatial variation of Doppler is not insignificant
  - Difference between the beam center and the beam edge Doppler frequencies is about +/- 4.5 kHz
- Doppler variations are significant
  - Approximately 584 Hz per second variation at the beam center
  - Fast closed-loop frequency corrections from BS are necessary

- Significant spatial variation of Doppler frequency within the beam footprint
  - Significant difference in the Doppler frequency between its beam center and the beam edge values
  - Maximum Doppler frequency is 24 ppm (48 kHz at 2 GHz) (TR 38.821, for 600 km altitude LEO)
- Doppler variations are low
  - Approximately 200 Hz per second variation at higher elevation angles

PRACH sequences are used for initial access

- Some are designed for large delay scenarios and some for large Doppler scenarios
- They are not designed for large delay and Doppler scenarios

RAN1#124 Key Agreement on Initial Access Solutions[1]



Agreement:

For the evaluation of GNSS resilient NR-NTN operation at least for initial access, the companies are encouraged to further study the following candidate solutions

Beam center reference

- Solution 2D: UE side time/frequency pre-compensation based on reference location or TA/Doppler compensation information provided by gNB.
- Solution 1D: Signalling enhancements for Msg2/Msg4 (e.g. enhanced TA command, frequency adjustment command, reference point adjustment command).
- Solution 2E: service link time/frequency UE side pre-compensation based on last acquired GNSS position
- Solution 1A: Multiple PRACH transmissions (e.g. with different roots or cyclic shifts or different formats or with different time/frequency pre-compensation using multiple reference locations within the uncertainty area) using existing PRACH formats

PN[T] solution

- Solution 2A: Single/multi-satellite DL-TDOA based on current specifications.

Key proponents: ESA, Airbus, Thales, Fraunhofer, European Commission, Huawei, CATT, ZTE, OPPO, Ofinno

- Solution 3: Implementation-based techniques e.g. using a long enough PRACH processing window and multiple timing hypotheses for PRACH preamble reception with large max differential delay.
- Solution 2B: Multiple random access attempts based on different time/frequency pre-compensation hypotheses (e.g. based on multiple reference points within the uncertainty area)
- Solution 1G: Adaptation of PRACH configuration.

PNT solution

- Solution 2C: Solutions based on broadcasting DL timestamp(s).

Key proponents: JHU-APL, NEC, ETRI

(Applies to both single and multiple satellites)

To ensure a good consolidation of the results, companies are encouraged to continue evaluating each solution and their combinations in more detail, in particular with respect to the specification impact where relevant (including whether the solutions remain within the scope of the SID), performance, applicability to different scenarios, complexity, coexistence with legacy UEs, and signalling overhead.

Note: Solutions were down-selected based on the number of votes for each solution

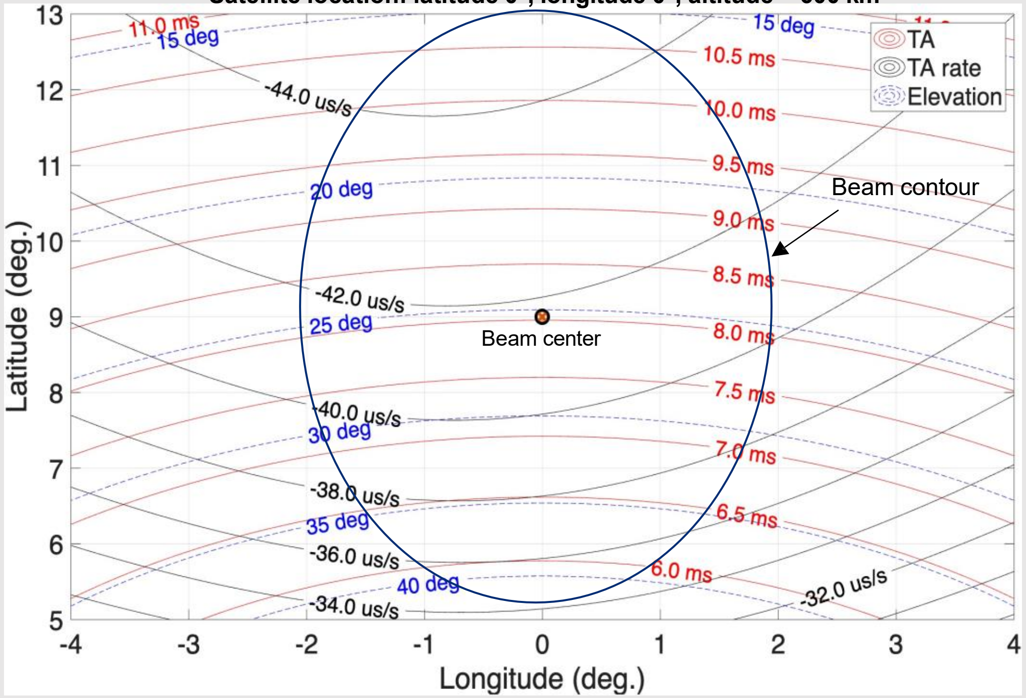
---

[1] Moderator (Thales), "FL Summary #6: Study on GNSS resilient NR-NTN operation", R1-2601705, 3GPP TSG RAN WG1 #124, Gothenburg, SE, Feb. 9th ~ 13th, 2026.

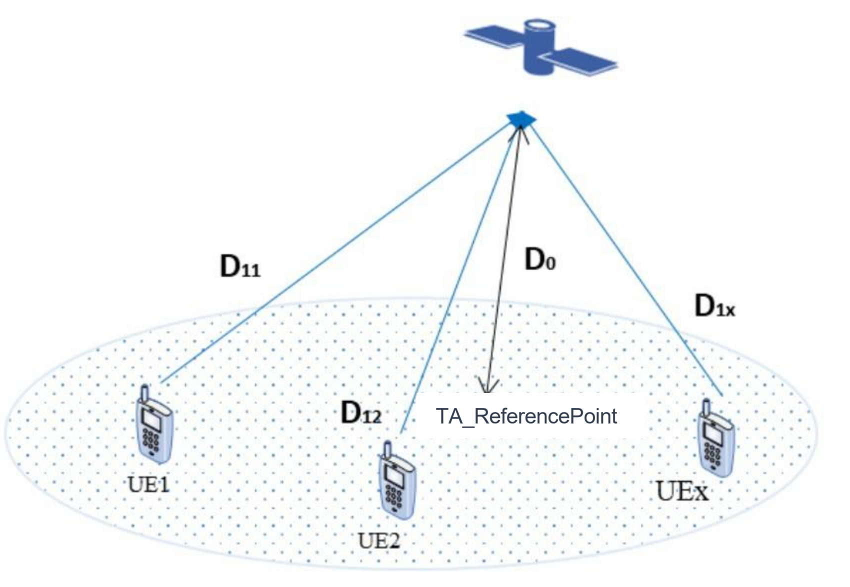
Common Reference Point for Initial Access[1,2] (Solution 2D)

- Include in the System Information the TA and Doppler at a Reference Point for initial access
    - Example: TA at the beam center or the TA values at the beam edges
- Use this TA as the TA for all points within the beam
- Problem: TA variations could be too large
- Example: TA_ReferencePoint (beam center) = 8 ms
- Approximate range of TA: 5.5 ms to 11 ms
    - Cannot use a single TA for initial access at all locations within the beam footprint

Satellite location: latitude 0°, longitude 0°, altitude = 600 km



Reference Point for TA on the ground[1]



---

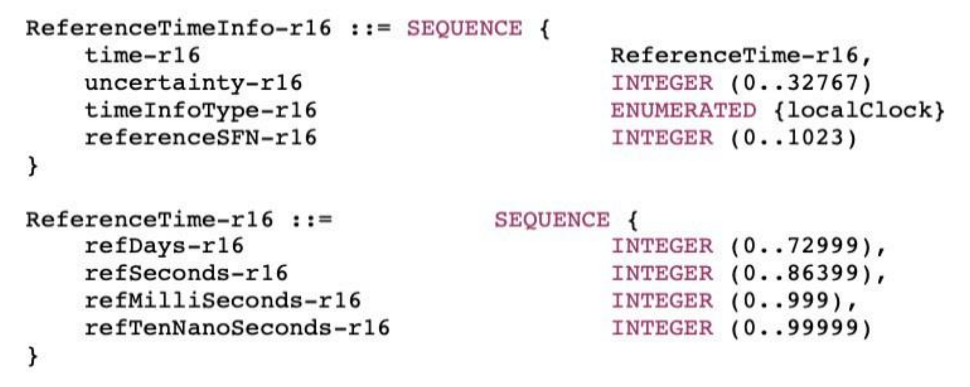
[1] 3GPP: TR 38.821, § 6.3.4.

[2] H. Li, C. Sun, X. Wang, Y. Bai, T. Cui and S. Wang, "Performance Analysis of a Non-terrestrial Network with Timing Advance Compensation in 3GPP," *2023 International Conference on Wireless Communications and Signal Processing (WCSP)*, Hangzhou, China, 2023.

Downlink Timestamps Broadcast by gNB (SIB9) (Solution 2C)

- Use gNB signals to estimate UE position
- The gNB broadcasts the transmit time of System Frame Number (SFN) in SIB9[1]
  - *ReferenceTimeInfo* IE (TS 38.331) contains this information
- The location of UE can be estimated using multiple observations of this time
  - Use the satellite ephemeris in the computations
- Transmissions from multiple satellites will enhance the position accuracy
- SIB9 is contained in system information (SI), the SI is sent with periodicity *si-Periodicity* (3GPP TS 38.331)

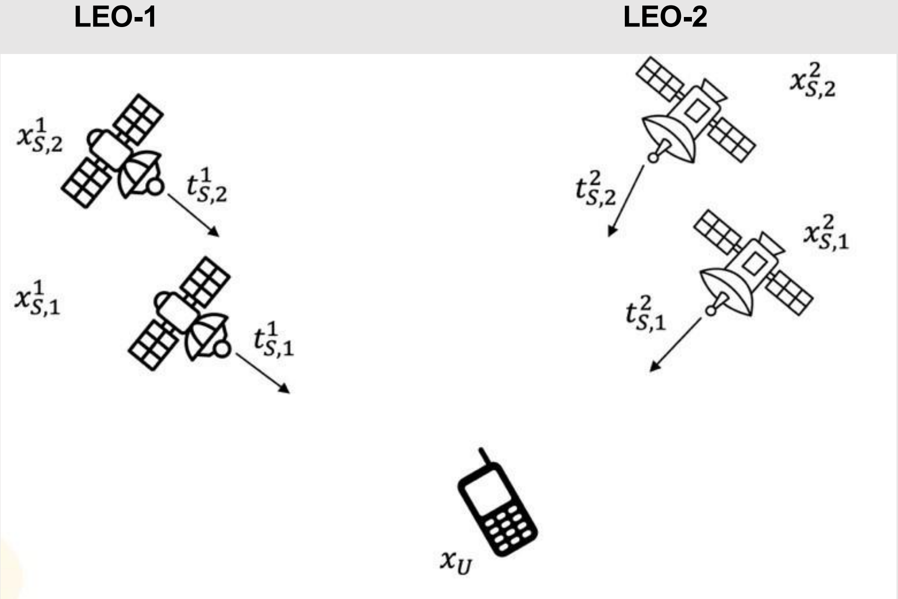
***ReferenceTimeInfo* (TS 38.331)**



```
ReferenceTimeInfo-r16 ::= SEQUENCE {
    time-r16                            ReferenceTime-r16,
    uncertainty-r16                     INTEGER (0..32767)
    timeInfoType-r16                    ENUMERATED {localClock}
    referenceSFN-r16                    INTEGER (0..1023)
}

ReferenceTime-r16  ::=          SEQUENCE {
    refDays-r16                         INTEGER (0..72999),
    refSeconds-r16                      INTEGER (0..86399),
    refMilliSeconds-r16                 INTEGER (0..999),
    refTenNanoSeconds-r16               INTEGER (0..99999)
}
```

Two LEO satellites broadcasting timestamps



$x_!^"$, $x_!^\#$: satellite positions sent in SIB19
$t_!^"$, $t_!^\#$: timestamps sent in SIB9

Specification Impact: Broadcast the SIB9 contents (currently it is an on-demand SIB)

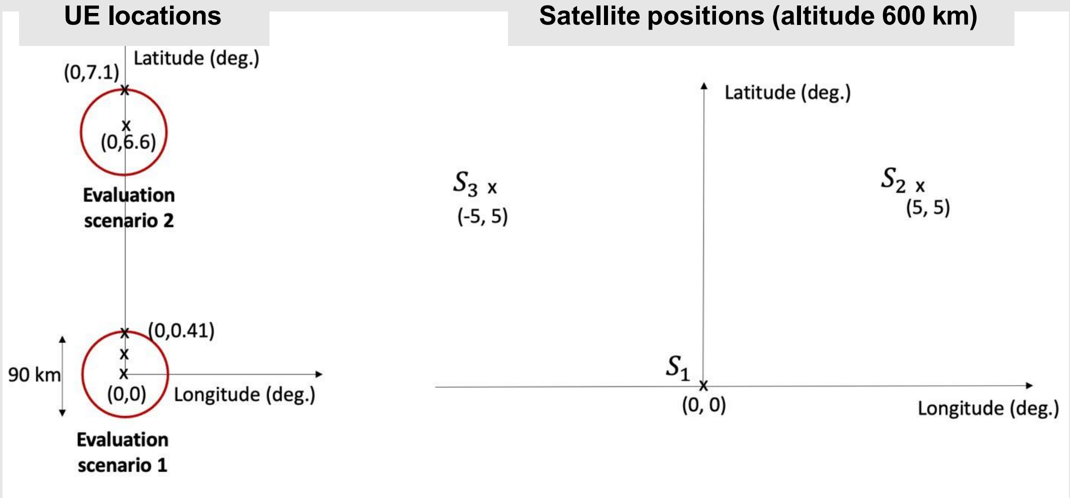
---

[1] Nokia, Nokia Shanghai Bell, "Discussion on UL time and frequency synchronization for NTN," R1-2006422. 3GPP TSG RAN WG1 #102, e-Meeting, August 17th – 29th, 2020.

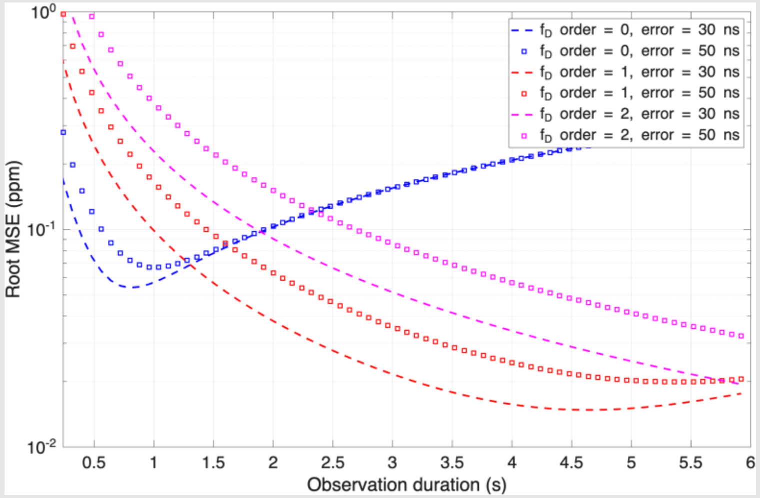
Downlink Timestamps: Performance[1]

- Doppler estimated using a Taylor series model (on a single satellite basis)
  - $f_D(t) = -f_c(a_0 + a_1 t + a_2 t^2)$
  - Coefficients estimated using the observed arrival times of timestamped messages
  - Required accuracy is 0.1 ppm, which can be achieved in an observation duration with a single satellite
- Delay estimated from the position

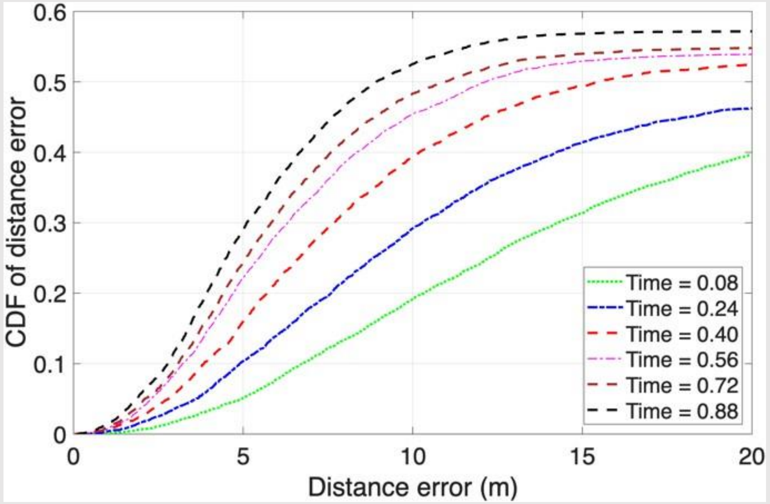
Simulation scenario for position estimation



Doppler frequency estimation results (Single satellite scenario)



Position estimation for different observation durations (Three satellite scenario)



Initial access requires estimation of delay and Doppler frequency, not the position

- Doppler frequency and delay can be estimated to the required accuracy level in about 1.5 s (with a single satellite)
- Position estimation accuracy increases with the observation duration (and the number of satellites)

---

[1] The Johns Hopkins University Applied Physics Laboratory, “Discussion on NR-NTN GNSS resilience”, R1-2603080, 3GPP TSG RAN WG1 #124bis, Malta, MT, April 13th -17th, 2026.

Positioning Reference Signaling (PRS) Sent by gNB (Solution 2A)

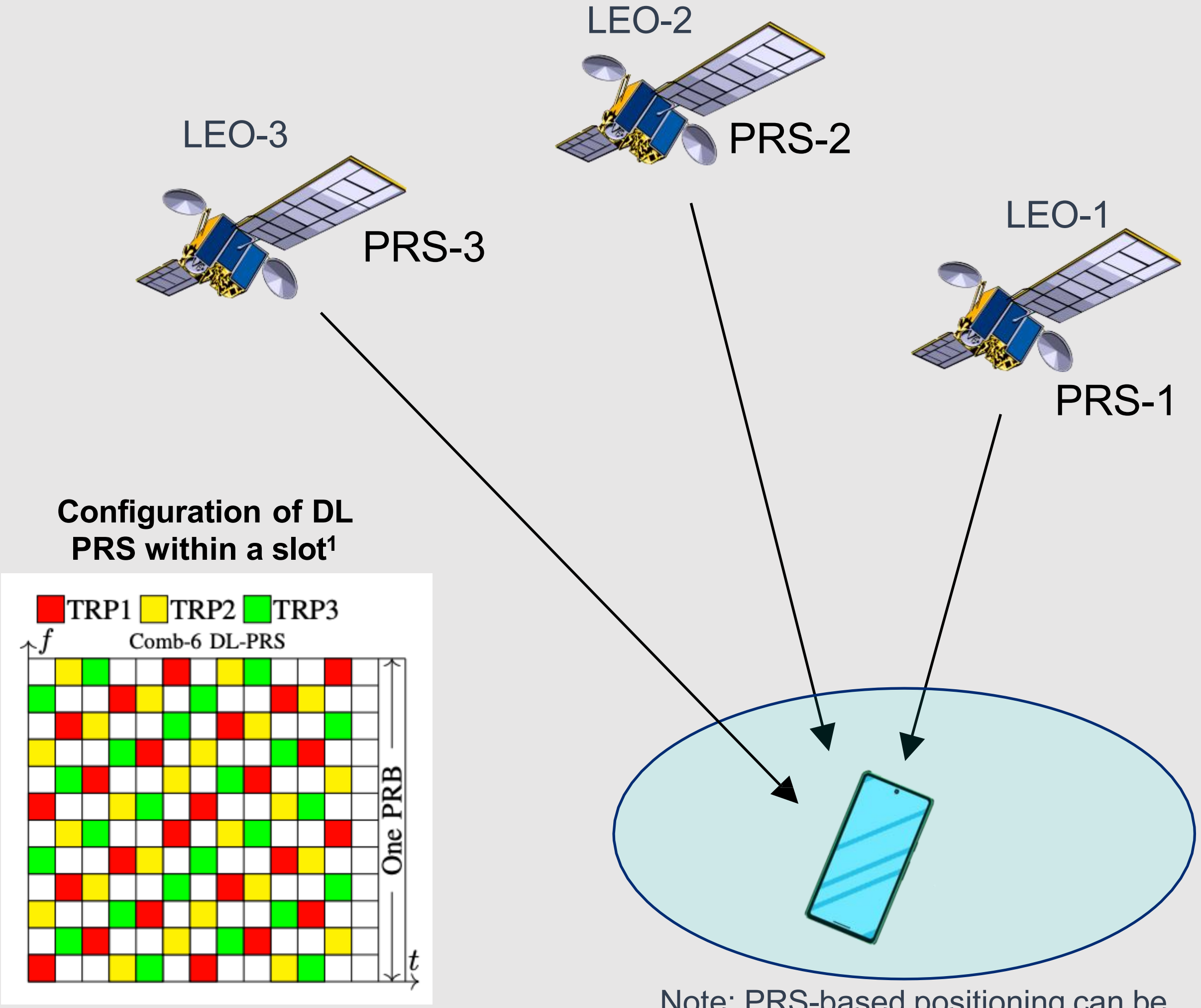
- Positioning Reference Signals (PRS) are supported by the 3GPP NR waveform
  - PRS consists of multiple single-tone signals that are sent in short bursts
- Realizing positioning from PRS sent from LEO satellites is significantly more challenging
  - Key challenge: Doppler and time-varying delays of PRS from LEO satellites
- <u>Important: PRS does not provide timing</u>
  - Higher-layer network protocols provide timing (using SIB contents), after connecting to the network

Relative merits of timestamps- and PRS-based approaches

- PRS:
  - Does not provide timing, network provides timing (increasing latency)
  - Proposed work is based on TDOA: receiver clock drift errors are manageable
  - Significant receiver complexity and bandwith resources
  - Not suitable for applications that <u>do not connect</u> to the network, or require very low-latency timing
- Timestamps:
  - Provides both positioning and timing
  - Based on TOA, receiver clock drift is a concern
    - Possible to use TDOA techniques

- **Multi-satellite timestamped signals will result in a <u>de facto GNSS</u> system**
  - **PNT is available from a large number of commercial satellites in diverse frequency bands**
- **Need significant support from companies for the timestamps approach to**

PRS signals from multiple satellites

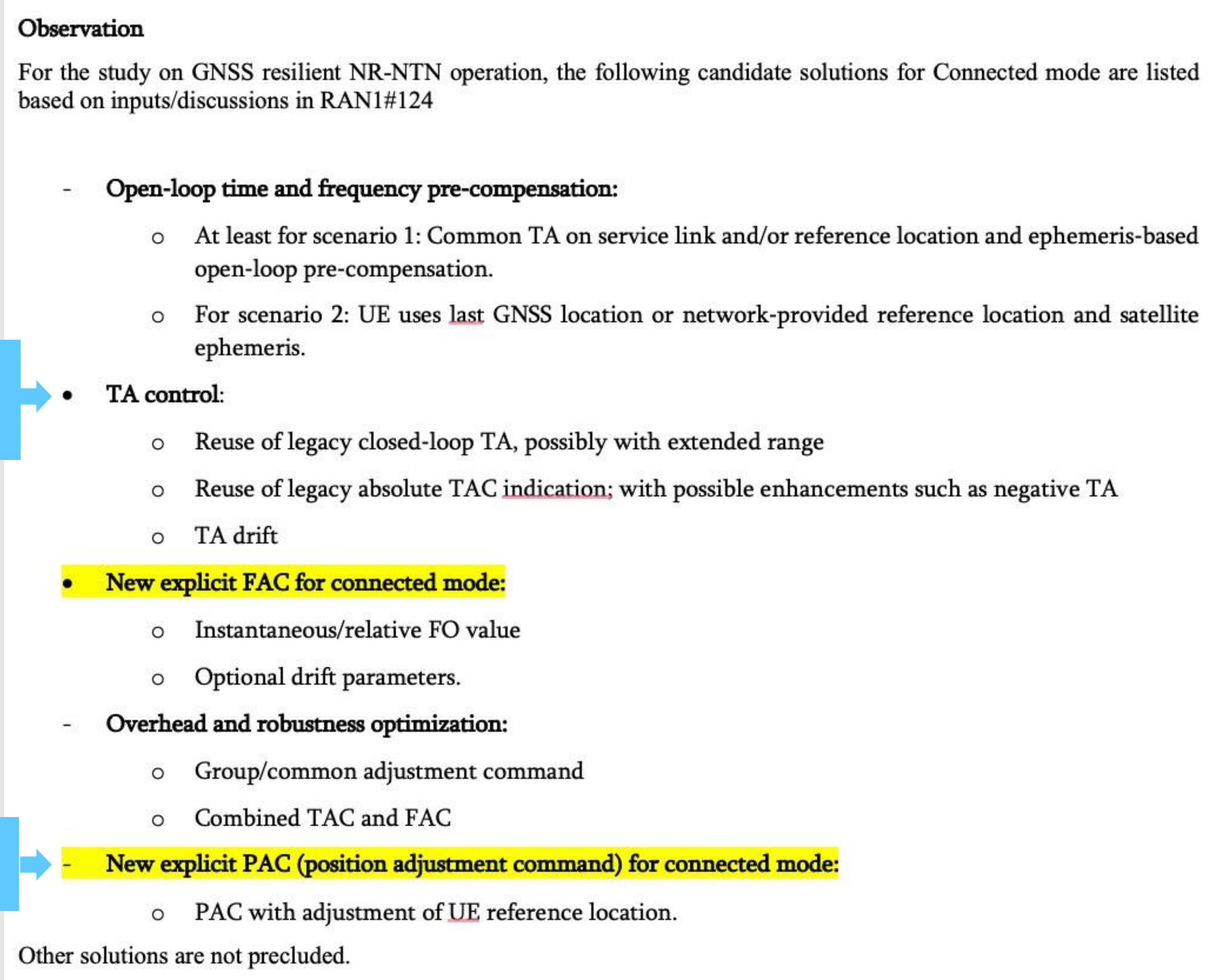


Note: PRS-based positioning can be realized even with a single satellite

Configuration of DL PRS within a slot[1]

[1] S. Dwivedi et al., "Positioning in 5G Networks," in IEEE Communications Magazine, vol. 59, no. 11, pp. 38-44, November 2021

RAN1#124 Observation on Connected Mode Operation[1]



Observation

For the study on GNSS resilient NR-NTN operation, the following candidate solutions for Connected mode are listed based on inputs/discussions in RAN1#124

- **Open-loop time and frequency pre-compensation:**
    - At least for scenario 1: Common TA on service link and/or reference location and ephemeris-based open-loop pre-compensation.
    - For scenario 2: UE uses last GNSS location or network-provided reference location and satellite ephemeris.
- **TA control**:
    - Reuse of legacy closed-loop TA, possibly with extended range
    - Reuse of legacy absolute TAC indication; with possible enhancements such as negative TA
    - TA drift
- **New explicit FAC for connected mode:**
    - Instantaneous/relative FO value
    - Optional drift parameters.
- **Overhead and robustness optimization:**
    - Group/common adjustment command
    - Combined TAC and FAC
- **New explicit PAC (position adjustment command) for connected mode:**
    - PAC with adjustment of UE reference location.

Other solutions are not precluded.

Currently supported, but in the absence of GNSS the update rate could be high

New command supports closed-loop positioning

---

[1] Moderator (Thales), "FL Summary #6: Study on GNSS resilient NR-NTN operation", R1-2601705, 3GPP TSG RAN WG1 #124, Gothenburg, SE, Feb. 9th ~ 13th, 2026.

Positioning in 6G Radio (6GR) NTN Study

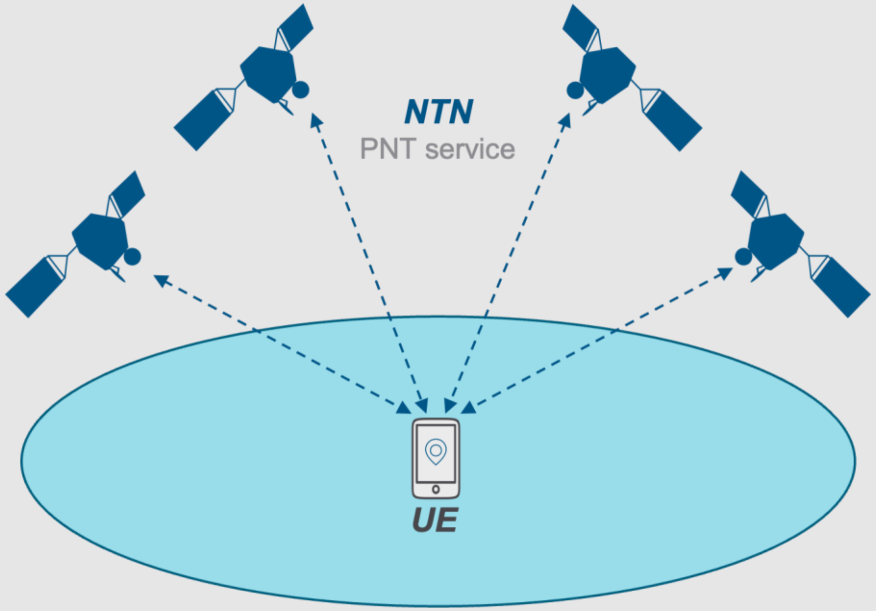
A large group of satellite companies[1] proposed including PNT in the 6GR NTN study at the recently concluded RAN1 meeting, but agreement was not reached on this topic

- Proposal 1: RAN1 to study the support of Positioning, Navigation and Timing (PNT) services over NTN
- Proposal 2: The 6G radio interface/access shall be defined to enable accurate and resilient Positioning, Navigation and Timing (PNT) services over NTN (without dependencies to GNSS service)

Another group of satellite companies also proposed including (but agreement was not reached on this topic)

- Proposal 7: The 6G radio interface/access shall be defined to provide high-accuracy and resilient positioning without GNSS service.

PNT service over NTN deployment, e.g., for resilient satellite positioning.[1]



Significant interest in including PNT in the 6GR study

---

[1] Airbus, ESA, European Commission, Thales, Fraunhofer IIS, Fraunhofer HHI, DLR, TNO, Novamint, SES, AST Space Mobile, Iridium, Sateliot, Toyota ITC, ETRI, JSAT, “Positioning, Navigation and Timing (PNT) with 6GR NTN”, R1-2602881, 3GPP TSG RAN WG1 #124bis, St Julian, Malta, 13th – 17th April 2026.

[2] Thales, ESA, SES, Iridium, Eutelsat, TNO, Novamint, “Considerations on 6G Radio for NTN”, R1-2601908, 3GPP TSG RAN WG1 #124bis, St Julian, Malta, 13th – 17th April 2026.

JOHNS HOPKINS
APPLIED PHYSICS LABORATORY