GNSS Under Attack

GNSS for Timing and Safety-Critical Applications

Day 1 – Lecture – 13:00-14:00

Prof. Dr. ir. Maarten Uijt de Haag and Dr. ir. Ober

Time Standards – International Atomic Time (TAI)

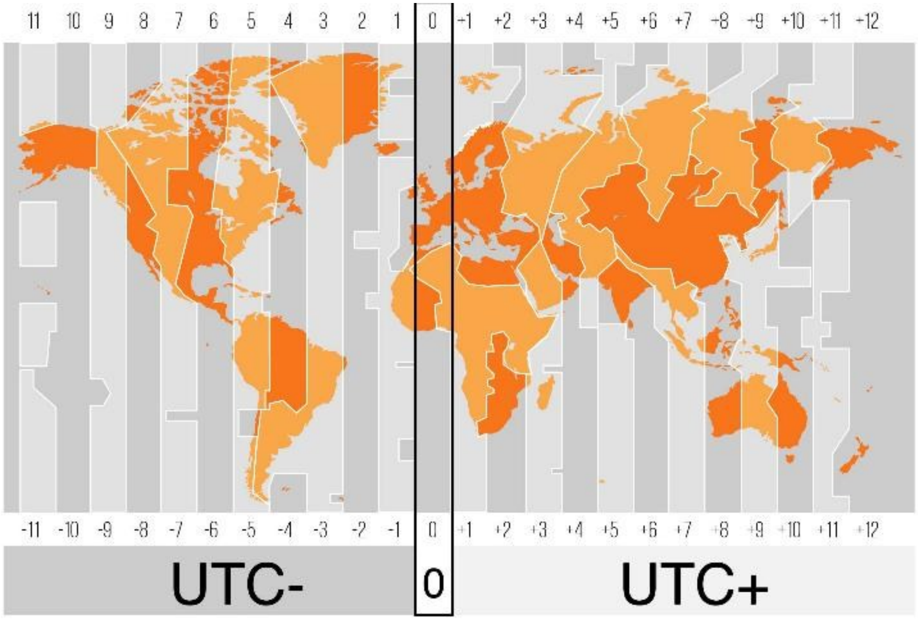
- ✈ Uniform / chronoscopic time scale
  - no discontinuities in time
- ✈ Based on the Atomic Second:

> "the duration of 9,192,631,770 periods of the radiation corresponding to the transition between two hyperfine levels of the ground state of the Cesium 133 atom"

- ✈ Computed by:
  - Bureau International des Poids et Mesures (BIMP)
- ✈ From and ensemble of:
  - atomic standards at more than 50 institutions around the world
- ✈ It is a "paper" time scale:
  - Not kept by a physical clock but computed from multiple clocks

Time Standards – Coordinated Universal Time (UTC)

- Same definition of the second as TAI
- Derived from astronomical observations of the rotation of the Earth relative to the Sun.
  - Makes it more suitable for use as a “wall-clock”
- UTC replace GMT in 1972
- Non-uniform / non-chronoscopic time scale
  - several milliseconds per day, leap seconds
- Same as TAI on January 1, 1958 @midnight
  - since then, 37 leap seconds (= TAI – UTC)



https://24timezones.com/gmt-vs-utc

Time Standards – GPS and Galileo Time

- Continuous time scale
  - Not adjusted for leap seconds
- Coincided with UTC (USNO) at 0:00H on January 6, 1980
  - Currently GPS time leads UTC (USNO) by 18 leap seconds (GPS - UTC)
- GPS Control Segment
  - Steers GPS Time to with 1µs (modulo 1) of UTC (USNO)
- **GPS Time** (GPST)
  - GPS weeks since January 6th, 1980, Seconds in week (since Sat/Sun midnight)
- **Galileo Standard Time** (GST)
  - Generally, differs between 5 and 50 ns from GPS time

Technische Universität Berlin
Flugführung und Luftverkehr

Remember the GNSS Measurement Equation

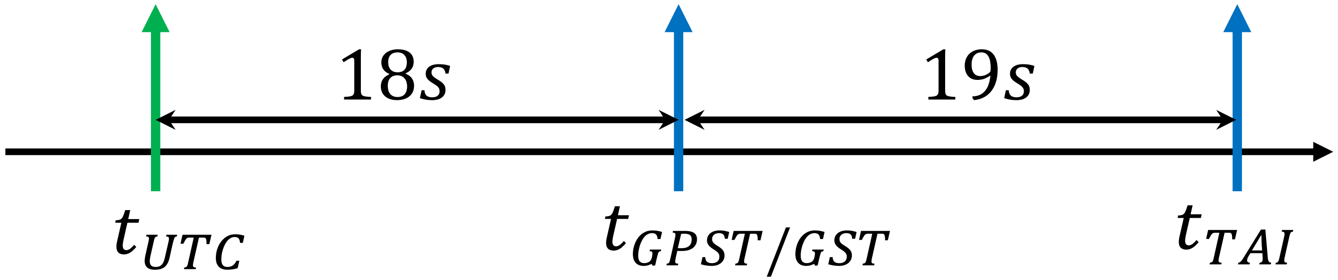
$$\mathbf{z} = \begin{bmatrix} PR_1 \\ PR_2 \\ \vdots \\ PR_N \end{bmatrix} = \mathbf{h}(\mathbf{x}) = \begin{bmatrix} \sqrt{(x_u - x_1)^2 + (y_u - y_1)^2 + (z_u - z_1)^2} + c\delta t_u \\ \sqrt{(x_u - x_2)^2 + (y_u - y_2)^2 + (z_u - z_2)^2} + c\delta t_u \\ \vdots \\ \sqrt{(x_u - x_N)^2 + (y_u - y_N)^2 + (z_u - z_N)^2} + c\delta t_u \end{bmatrix}$$

Given the measurements, $\mathbf{z}$, find the best estimate for the position coordinates (x_u, x_u, x_u) and time-offset (δt_u)

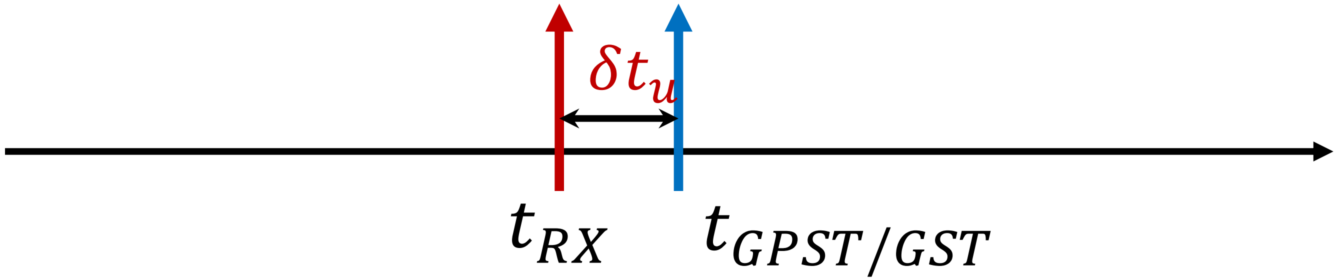
Once one knows the time-offset, this can be used to adjust/sync the user‘s local time to GNSS time

User Clock Offset

Time epoch (e.g. pulse per second):



(on 2 February 2026)



$$\sqrt{(x_u - x_1)^2 + (y_u - y_1)^2 + (z_u - z_1)^2} + c\delta t_u$$

Application of Timing

✈ Power & Energy Utilities:

- Synchronizes phasor measurement units (PMUs) to monitor grid stability, detect faults, and manage power distribution

✈ Telecommunications & IT Networks:

- Essential for synchronizing time-division multiple access (TDMA) in mobile networks (4G/5G) and ensuring accurate timestamps in data centers and IT infrastructure.

✈ Industrial Automation:

- Coordinates time-sensitive actions in manufacturing, such as robot operation and production tracking

Application of Timing

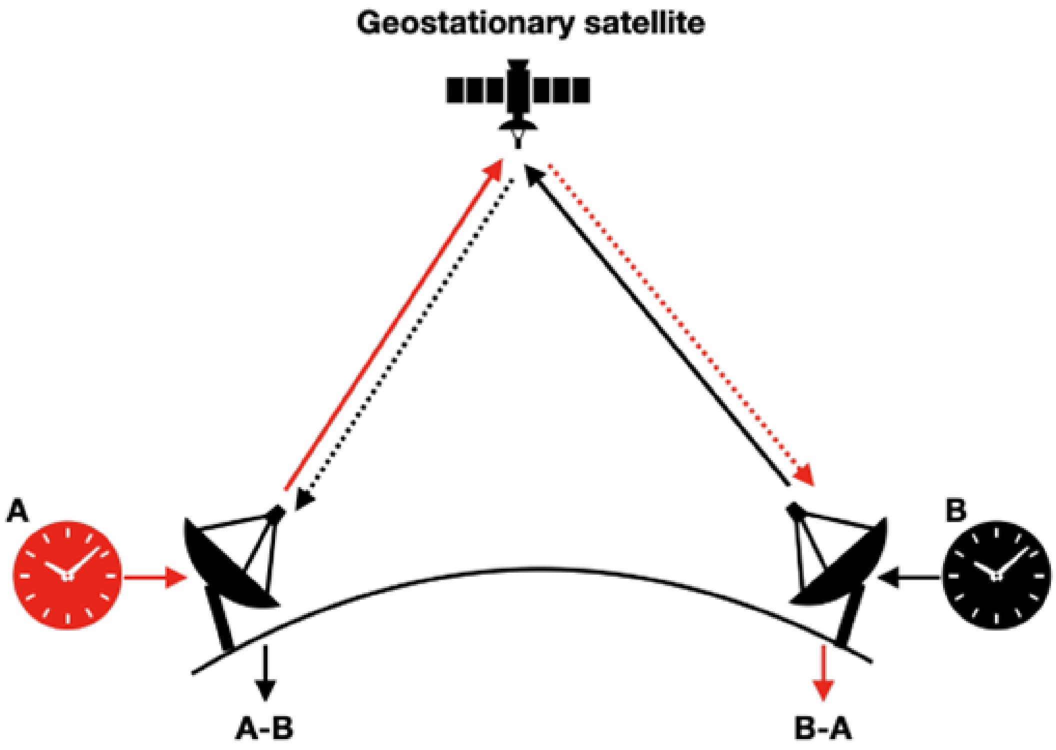
- Financial Services:
  - Enables high-frequency trading, requiring precise, traceable timestamps for transactions to ensure regulatory compliance.
- Navigation & Autonomous Systems:
  - Supports precise positioning for aviation, maritime, and autonomous vehicles (drones/AGVs) by providing accurate timing for signal processing.
- Scientific Research & Geophysics:
  - Used in geodetic surveys to monitor Earth's crust deformation, earthquake early warning systems, volcano monitoring
- Etc.

Time synchronization using telecommunication link

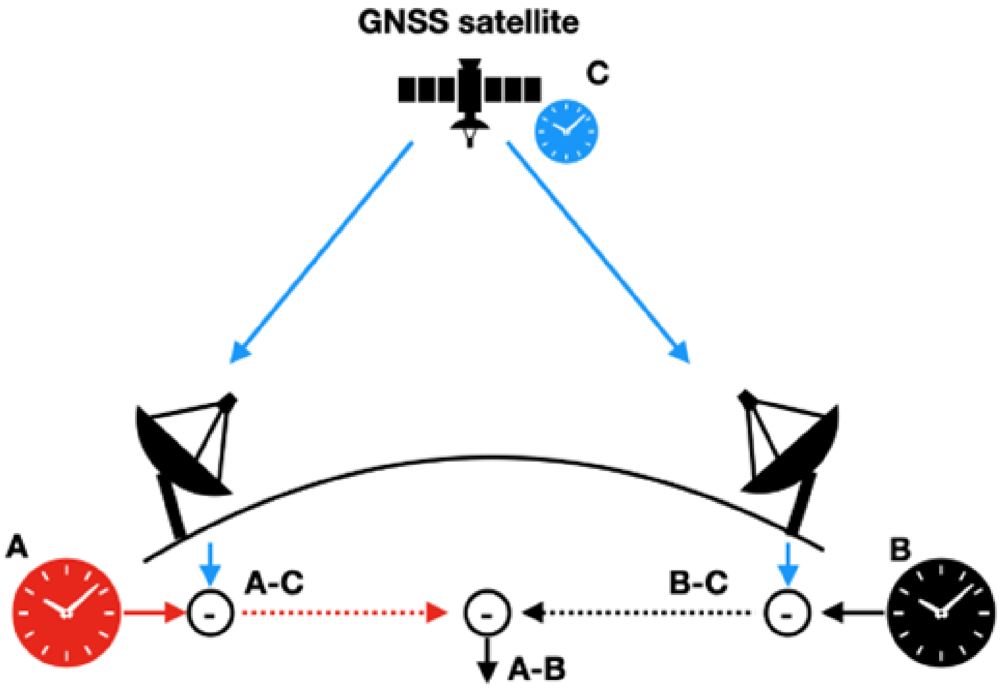
Source: NIST https://www.nist.gov/image/time-transferpng

Time synchronization using GNSS

Two-way satellite time/frequency transfer



GNSS time-transfer



Source: NIST https://www.nist.gov/image/time-transferpng

Vulnerability – Threats to Timing

Natural and Environmental Disruption

- Solar storms, atmospheric disturbances, and space weather events can disrupt satellite signals for hours or days.
- Urban environments, underground facilities, and buildings with dense construction materials can create "GNSS-denied" environments where satellite signals simply cannot penetrate effectively.

Cybersecurity Vulnerabilities

- Timing data has emerged as a critical attack vector. NTP (Network Time Protocol) hijacking allows attackers to manipulate system clocks, creating opportunities for fraud, data corruption, and regulatory violations.

Jamming and Spoofing Attacks

- GNSS jamming and spoofing incidents have increased dramatically in recent years. Unlike simple signal interference, sophisticated spoofing attacks can feed false timing data to systems, creating coordinated disruptions across multiple organizations simultaneously.

Based on: The Hidden Timing Risk: Why GNSS Vulnerabilities Threaten Critical Infrastructure

Vulnerability – Threats to Timing

The huge solar storm is keeping power grid and satellite operators on edge

The National Oceanic and Atmospheric Administration says there have been measurable effects and impacts from the biggest geomagnetic storm in decades.

Geoff Brumfiel / Willem Marx | May 10, 2024, 1:40 PM

Power Grid Warning Issued for 11 States

PUBLISHED

NOV 11, 2025 AT 02:05 PM EST

12 Nov 2025

Severe geomagnetic storm threatened power grids and communications worldwide Nov 12, 2025

Obtained from Weighted Least Squares (WLS)

$$\mathbf{z} = \begin{bmatrix} PR_1 \\ PR_2 \\ \vdots \\ PR_N \end{bmatrix} = \mathbf{h}(\mathbf{x}) = \begin{bmatrix} \sqrt{(x_u - x_1)^2 + (y_u - y_1)^2 + (z_u - z_1)^2} + c\delta t_u \\ \sqrt{(x_u - x_2)^2 + (y_u - y_2)^2 + (z_u - z_2)^2} + c\delta t_u \\ \vdots \\ \sqrt{(x_u - x_N)^2 + (y_u - y_N)^2 + (z_u - z_N)^2} + c\delta t_u \end{bmatrix}$$

$$\Delta \mathbf{PR} = \begin{bmatrix} \frac{x_u - x_1}{R_1} & \frac{y_u - y_1}{R_1} & \frac{z_u - z_1}{R_1} & 1 \\ \frac{x_u - x_2}{R_2} & \frac{y_u - y_2}{R_2} & \frac{z_u - z_2}{R_2} & 1 \\ \vdots & \vdots & \vdots & \vdots \\ \frac{x_u - x_N}{R_N} & \frac{y_u - y_N}{R_N} & \frac{z_u - z_N}{R_N} & 1 \end{bmatrix} \begin{bmatrix} \Delta x_u \\ \Delta y_u \\ \Delta z_u \\ c\delta t_u \end{bmatrix} = \mathbf{H}\Delta\mathbf{x}$$

$$\Delta\hat{\mathbf{x}}_j = \left(\mathbf{H}^T\mathbf{W}\mathbf{H}\right)^{-1} \mathbf{H}^T\mathbf{W}\Delta\mathbf{z}_j$$
$$\hat{\mathbf{x}}_{j+1} = \hat{\mathbf{x}}_j + \Delta\hat{\mathbf{x}}_j$$

(iterate)

$$\hat{\mathbf{x}} = \begin{bmatrix} x_u \\ y_u \\ z_u \\ c\delta t_u \end{bmatrix}$$

$$\mathbf{W} = \begin{bmatrix} \frac{1}{\sigma_1^2} & 0 & \cdots & 0 \\ 0 & \frac{1}{\sigma_2^2} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \frac{1}{\sigma_N^2} \end{bmatrix}$$

δt_u is the time-offset between the user clock and GNSS time (assuming all satellite clocks are synched correctly)

Obtained from Extended Kalman Filter

Measurement Update ("Update")

Measurement Equation: $\mathbf{z}_k = \mathbf{H}\mathbf{x}_k + \mathbf{v}_k$

(1) Compute the Kalman gain

$$\mathbf{K} = \frac{\mathbf{P}_k^- \mathbf{H}^T}{\mathbf{H}\mathbf{P}_k^- \mathbf{H}^T + \mathbf{R}}$$

(2) Update estimate with measurement

$$\hat{\mathbf{x}}_k = \hat{\mathbf{x}}_k^- + \mathbf{K}\left(\mathbf{z}_k - \mathbf{h}(\hat{\mathbf{x}}_k^-)\right)$$

(3) Update the error covariance

$$\mathbf{P}_k = (\mathbf{I} - \mathbf{K}\mathbf{H})\mathbf{P}_k^-$$

Time Update ("Predict")

Dynamics Equation: $\mathbf{x}_k = \mathbf{\Phi}\mathbf{x}_{k-1} + \mathbf{w}_k$

(4) Project the state ahead

$$\hat{\mathbf{x}}_{k+1}^- = \mathbf{\Phi}\hat{\mathbf{x}}_k$$

(5) Project the error covariance ahead

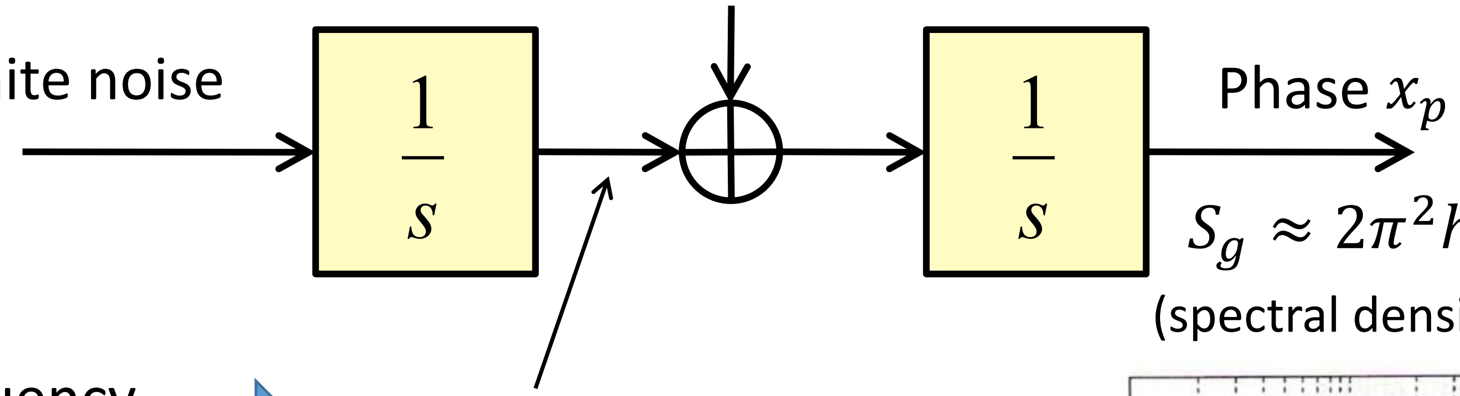
$$\mathbf{P}_{k+1}^- = \mathbf{\Phi}\mathbf{P}_k\mathbf{\Phi}^T + \mathbf{Q}$$

$\mathbf{z}_k - \mathbf{h}(\hat{\mathbf{x}}_k^-)$ are referred to as innovations or residuals

- ✈ The state vector will now also include the clock!
- ✈ For example, for a regular position-based filter: $\mathbf{x}_k = [x_k \quad \dot{x}_k \quad y_k \quad \dot{y}_k \quad z_k \quad \dot{z}_k \quad b \quad \dot{b}]^T$

What is the dynamics model for the clock error?

Receiver Clocks



Clock offset

$S_g \approx 2\pi^2 h_{-2}$
(spectral density)

Frequency offset

Frequency x_f

$S_f \approx \frac{h_0}{2}$ (spectral density)

Allan variance depicts the amount of rms (root mean square) drift that occurs over a specific period Δt normalized by Δt

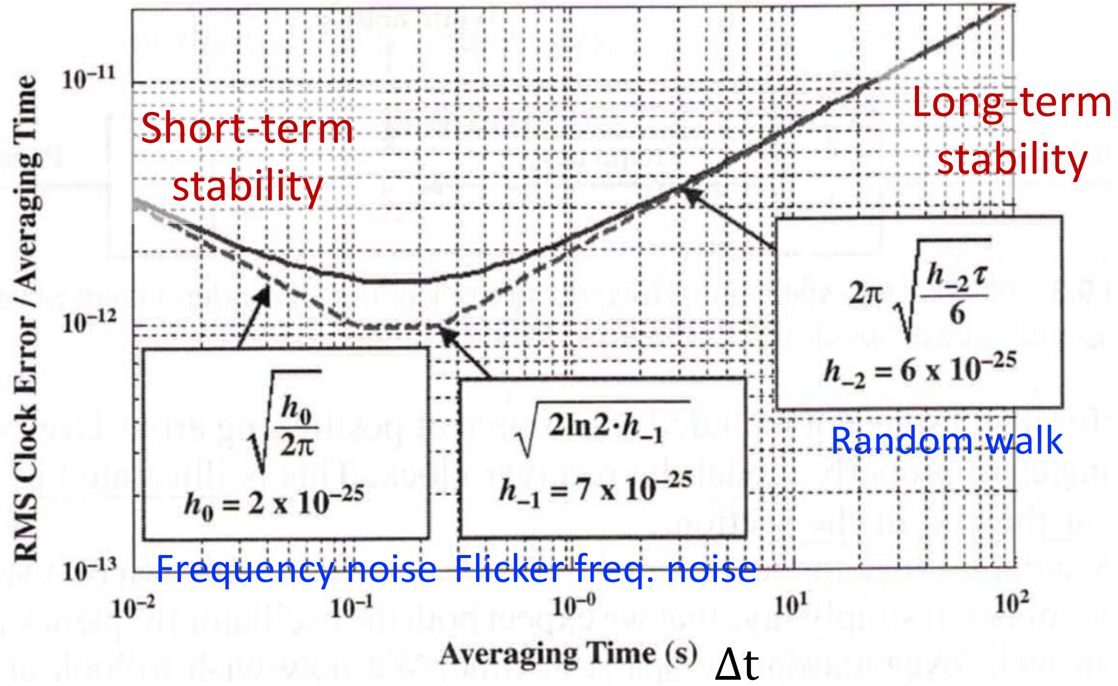
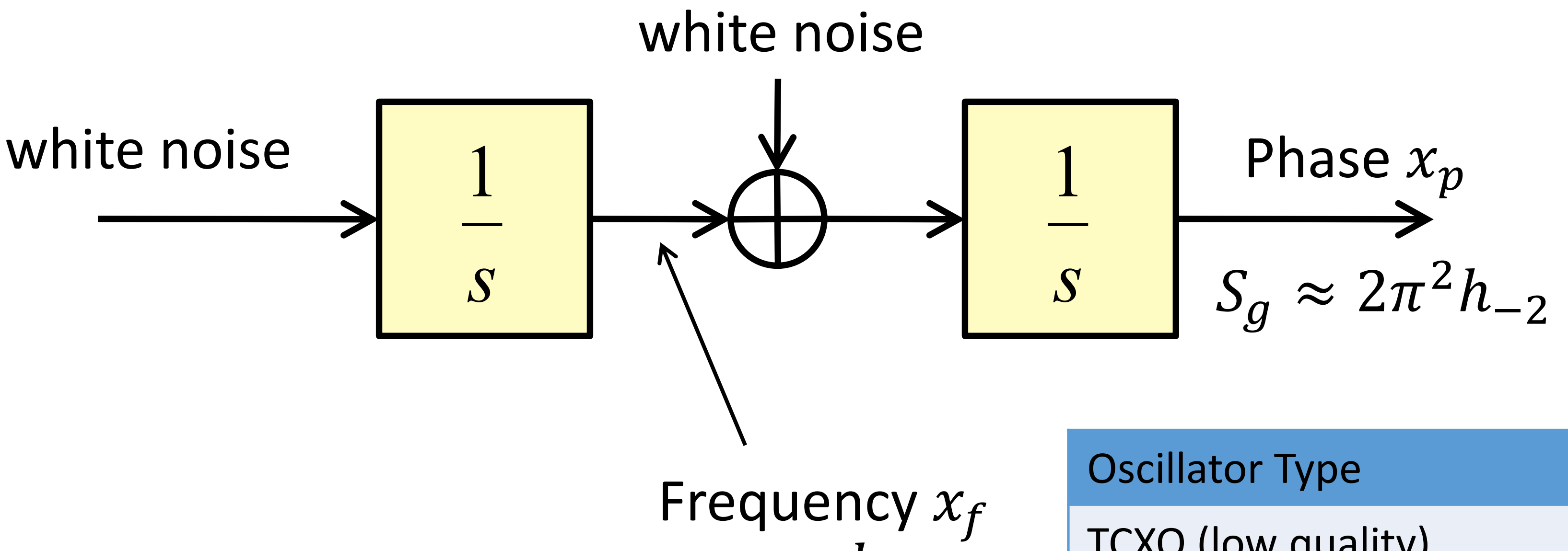


Figure 9.4 Square root of Allan variance (or Allan deviation) plot with asymptotes for a typical ovenized crystal oscillator (6).

GNSS Clock Error – Two-state random-process model



$$S_f \approx \frac{h_0}{2}$$

$$\mathbf{Q} = \begin{bmatrix} S_f \Delta t + \frac{S_g \Delta t^3}{3} & \frac{S_g \Delta t^2}{2} \\ \frac{S_g \Delta t^2}{2} & S_g \Delta t \end{bmatrix}$$

Oscillator Type	h_0	h_{-2}
TCXO (low quality)	2×10^{-19}	2×10^{-20}
TCXO (high quality)	2×10^{-21}	3×10^{-24}
OCXO	2×10^{-25}	6×10^{-25}
Rubidium	2×10^{-22}	1×10^{-30}
Cesium	2×10^{-22}	1.5×10^{-33}

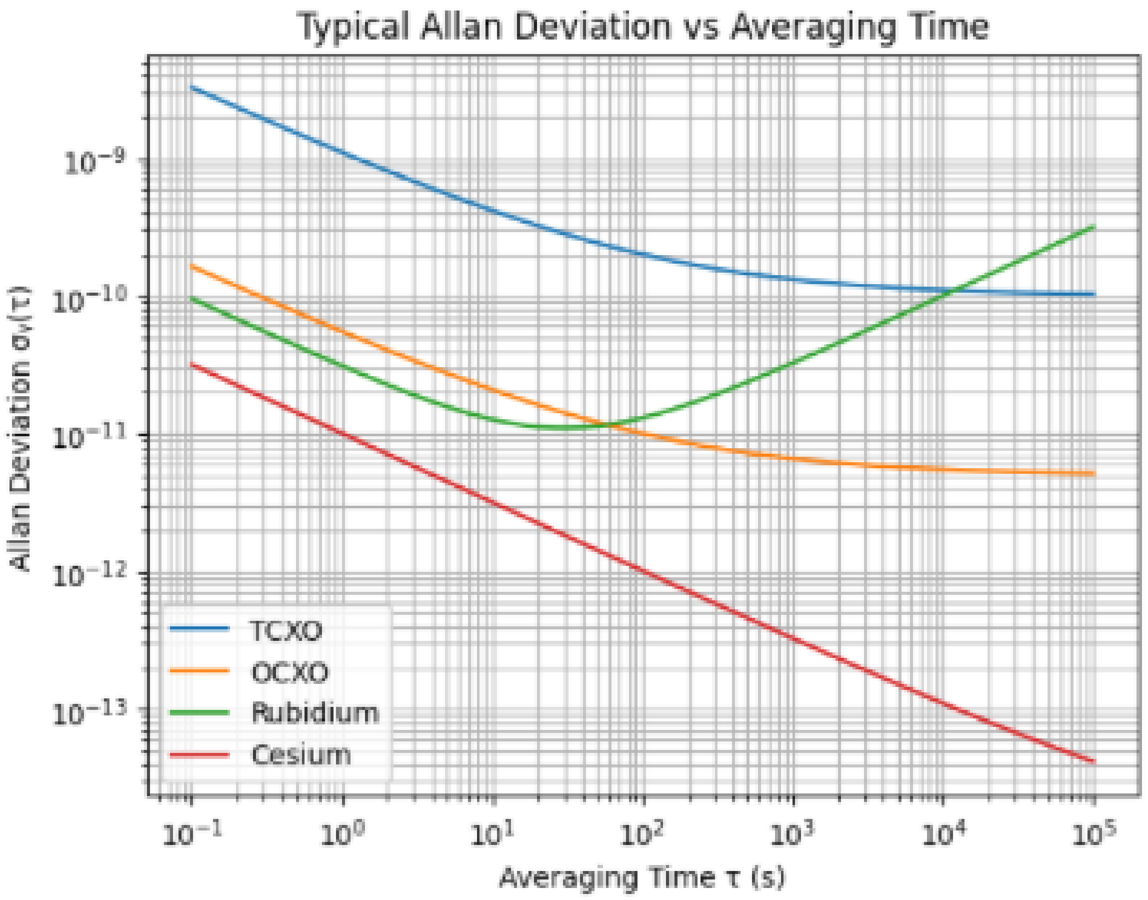
Clock units are in seconds, when treated as meters in the GPS equations, the spectral amplitude coefficients in the table must be multiplied by c^2.

Oscillators in General

Oscillator Type	Short-Term Stability (Allan Deviation)	Aging (per day)	Accuracy (Initial / Absolute)	Warm-Up Time	Power Consumption	Size / Cost	Typical Use Cases
TCXO (Temperature-Compensated Crystal Oscillator)	~1×10^{-10} @ 1 s	~1×10^{-7} to 1×10^{-8}	~±0.1 to ±2 ppm	Seconds	Very low (mW)	Very small / Low	GNSS receivers, mobile devices, consumer electronics
OCXO (Oven-Controlled Crystal Oscillator)	~1×10^{-12} @ 1 s	~1×10^{-9} to 1×10^{-10}	~±0.01 ppm	1–10 min	Moderate–High (1–5 W)	Medium / Medium	Telecom, test equipment, base stations
Rb (Rubidium Atomic Oscillator)	~3×10^{-12} @ 1 s	~5×10^{-11}	~$\pm5\times10^{-11}$	3–10 min	Moderate (5–15 W)	Medium / High	Telecom timing, GNSS holdover, network synchronization
Cs (Cesium Atomic Clock)	~1×10^{-12} @ 1 s	~1×10^{-14}	**$\pm1\times10^{-12}$ (SI second)**	10–30 min	High (30–100 W)	Large / Very high	Primary time standards, metrology labs

Oscillators in General

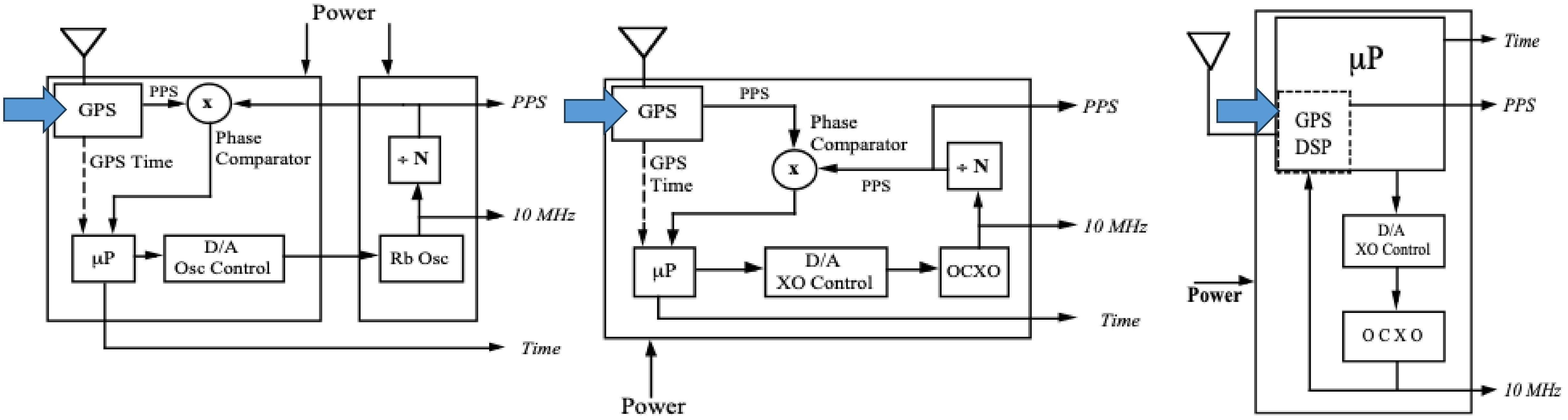
Oscillator Type	Short-Term Stability (Allan Deviation)	Aging (per day)	Accuracy (Initial / Absolute)
TCXO (Temperature-Compensated Crystal Oscillator)	~1×10^{-10} @ 1 s	~1×10^{-7} to 1×10^{-8}	~±0.1 to ±2 ppm
OCXO (Oven-Controlled Crystal Oscillator)	~1×10^{-12} @ 1 s	~1×10^{-9} to 1×10^{-10}	~±0.01 ppm
Rb (Rubidium Atomic Oscillator)	~3×10^{-12} @ 1 s	~5×10^{-11}	~$\pm5\times10^{-11}$
Cs (Cesium Atomic Clock)	~1×10^{-12} @ 1 s	~1×10^{-14}	**$\pm1\times10^{-12}$ (SI second)**



GPS-disciplined Oscillator (GPSDO)

Technische Universität Berlin
Flugführung und Luftverkehr

→ A GNSS receiver combined with a quality oscillator (e.g. OCXO, Rubidium)



Again: GNSS-dependency results in a vulnerability

From: In Sync with GPS: GPS Clocks for the Wireless Infrastructure

Safety-Critical Systems

Non-safety-related systems

Systems that perform functions that are not related to safety.

Safety-related systems

Systems that are activated to prevent or minimize the effect of a failure of a safety-critical system.

Safety-critical systems

Systems where a system failure or error results in (at least) a specified level of loss

Courtesy: DLR, Trimble, DJI

Reference: Herrmann, Debra S., "Software Safety and Reliability," ISBN: 0-7695-0299-7, IEEE Computer Society, 1999

Safety-Critical Systems

Safety is defined with respect to human life, property, or the environment.

Failure is a nonperformance or inability of the system, component, or device to perform its ***intended function*** for a specified time under specified environmental conditions.

Hazard: a potentially **unsafe condition** resulting from failures, malfunctions, external events, errors, or a combination thereof.

Risk: the frequency (**probability**) of occurrence and the associated **level** of hazard (**severity**).

Navigation Performance Requirements

We need to define the performance that is necessary (required) to perform the operation (e.g., en-route, landing, etc.); we define is performance by various parameters:

- Accuracy
  - Absolute error
  - Repeatable error
  - Relative error
  - Differential error
- Integrity
- Availability
- Continuity

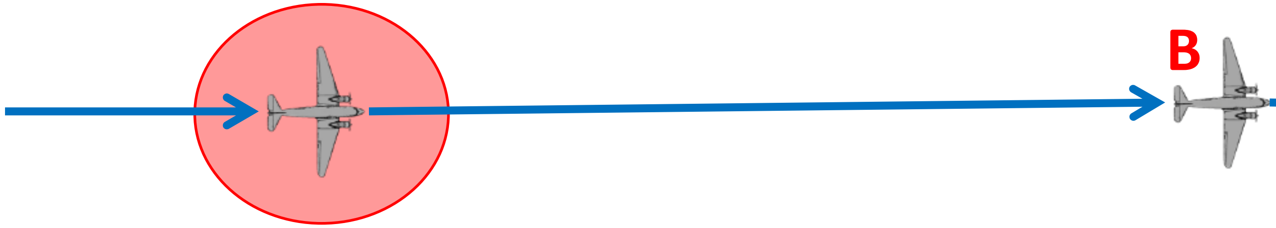
→ Coverage
→ Capacity
→ Ambiguity
→ Data
→ Security

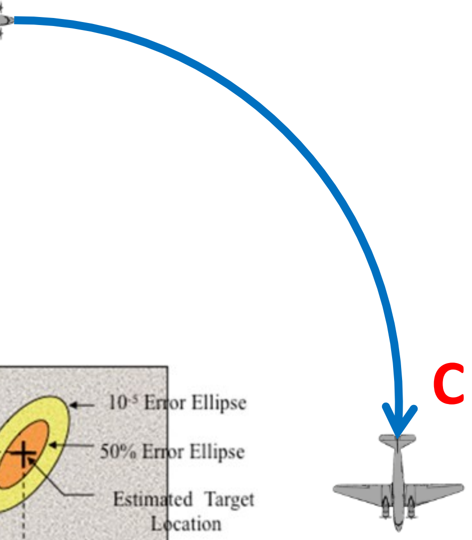
Required Navigation Performance

Accuracy

The degree of conformance between the estimated or measured position and/or the velocity of a platform at a given time and its true position or velocity.

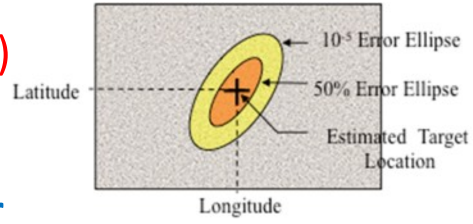
In 2D, the position error (or uncertainty) is often visualized by a so-called uncertainty ellipse (or circle)





The position estimated by the navigation aid, lies within this ellipse with a certain probability

For example: 68% (1σ), 95% (2σ), 99.7% (3σ) ellipses (we often talk about the 95% accuracy)



Position Estimation Error or **Navigation System Error**

Integrity

Technische Universität Berlin
Flugführung und Luftverkehr

The ability of a system to provide timely warnings to users when the system should not be used for navigation.

Measurements and faults:

$$\mathbf{z} = \mathbf{h}(\mathbf{x}) + \mathbf{v} + \mathbf{b}$$

Fault introduced in the measurement(s) of the navigation aid(s)

Position:

Fault in the measurements results in a position fault.

$$\delta\mathbf{x} = \begin{bmatrix} \delta x \\ \delta y \end{bmatrix} = \left(\mathbf{H}^T\mathbf{H}\right)^{-1}\mathbf{H}^T\mathbf{b} = \mathbf{A}\mathbf{b}$$

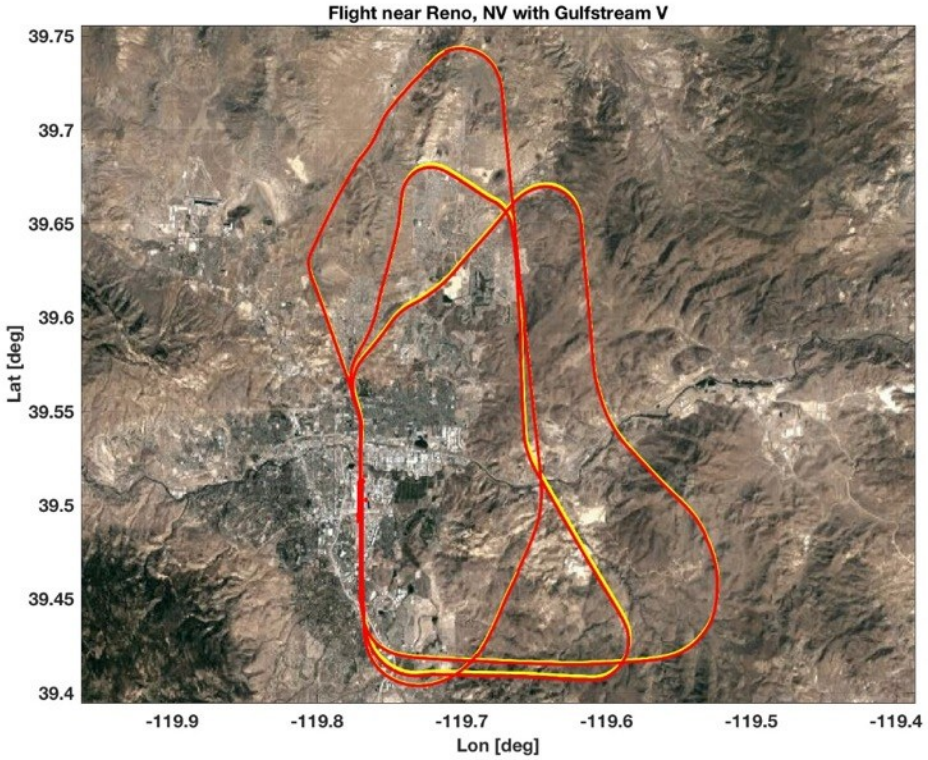
Error depends on Geometry as well

This bias, if it would stay undetected could lead to a catastrophic event; however, if the pilot is made aware of it, he/she can perform a missed approach procedure

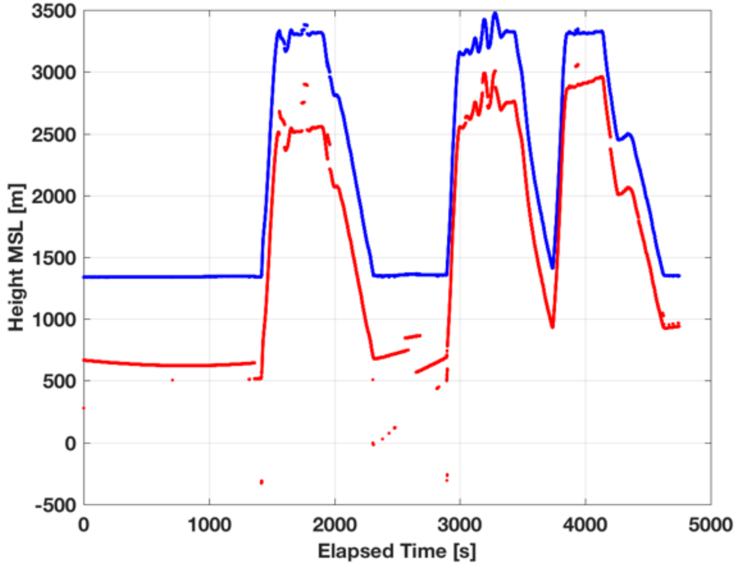
Technische Universität Berlin
Flugführung
und Luftverkehr

GPS Example (bias on one of the ranges)

Two computed trajectories:
Yellow: nominal performance of all satellites
Red: range bias of 800m on satellite 14 due to a failure



Vertical Error (blue: nominal, red: off-nominal)



Oops, not landing on the runway!

Conclusion: we need an INTEGRITY monitor that finds out when a large error like this occurs and either gets rid of it or notify the user.

Technische Universität Berlin
Flugführung und Luftverkehr

Hazardous Misleading Information

- Defined as the probability that the position uncertainty exceeds the alert limit defined for the application without an alert

$$P_{HMI} = Pr\left(|\delta \hat{\mathbf{x}}| > AL \cap d^2 < T\right)$$

Position error exceeds alert limit — No alert

- Alert Limit:
  - It defines the maximum allowable position error for safe operation in a given application. If the system's calculated Protection Level (a statistical bound on the possible position error) exceeds the alert limit, an alert is triggered to indicate that the positioning information should not be trusted for safety-critical functions.

Based on: Swift

Hazardous Misleading Information

- Defined as the probability that the position uncertainty exceeds the alert limit defined for the application without an alert

$$P_{HMI} = Pr\left(|\delta\hat{\mathbf{x}}| > AL \cap d^2 < T\right)$$

Position error exceeds alert limit

No alert

Procedure		Hor Acc (95%)	Vert Acc (95%)	HAL	VAL	TTA	Integrity (P_{HMI})	Continuity
*	LPV200	16 m	4 m	40 m	35 m	6.2 s	$2{\cdot}10^{-7}$/app[3]	$1 - 8{\cdot}10^{-5}$/15s

Accuracy

Alert Limit

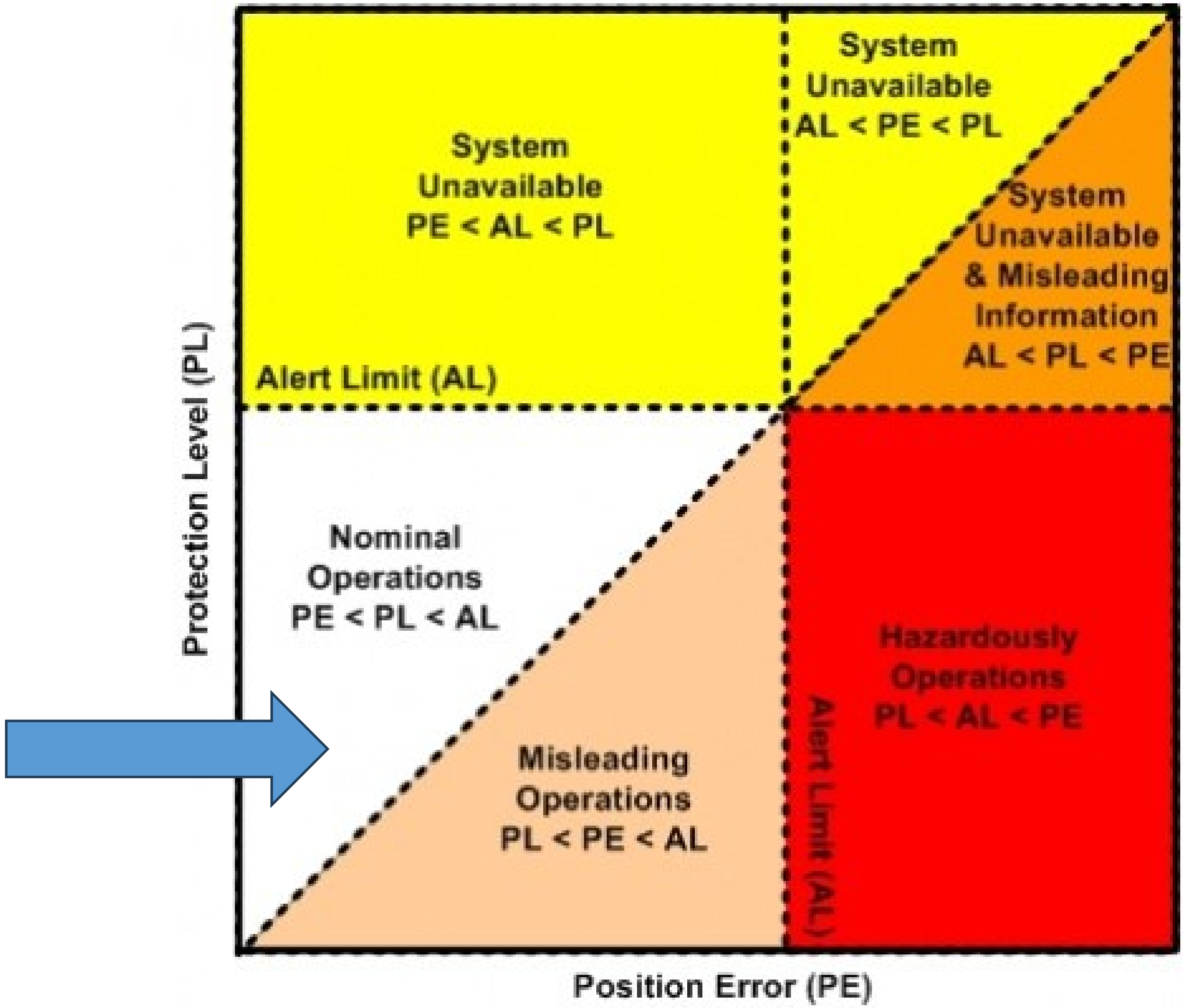
Integrity Risk

Continuity

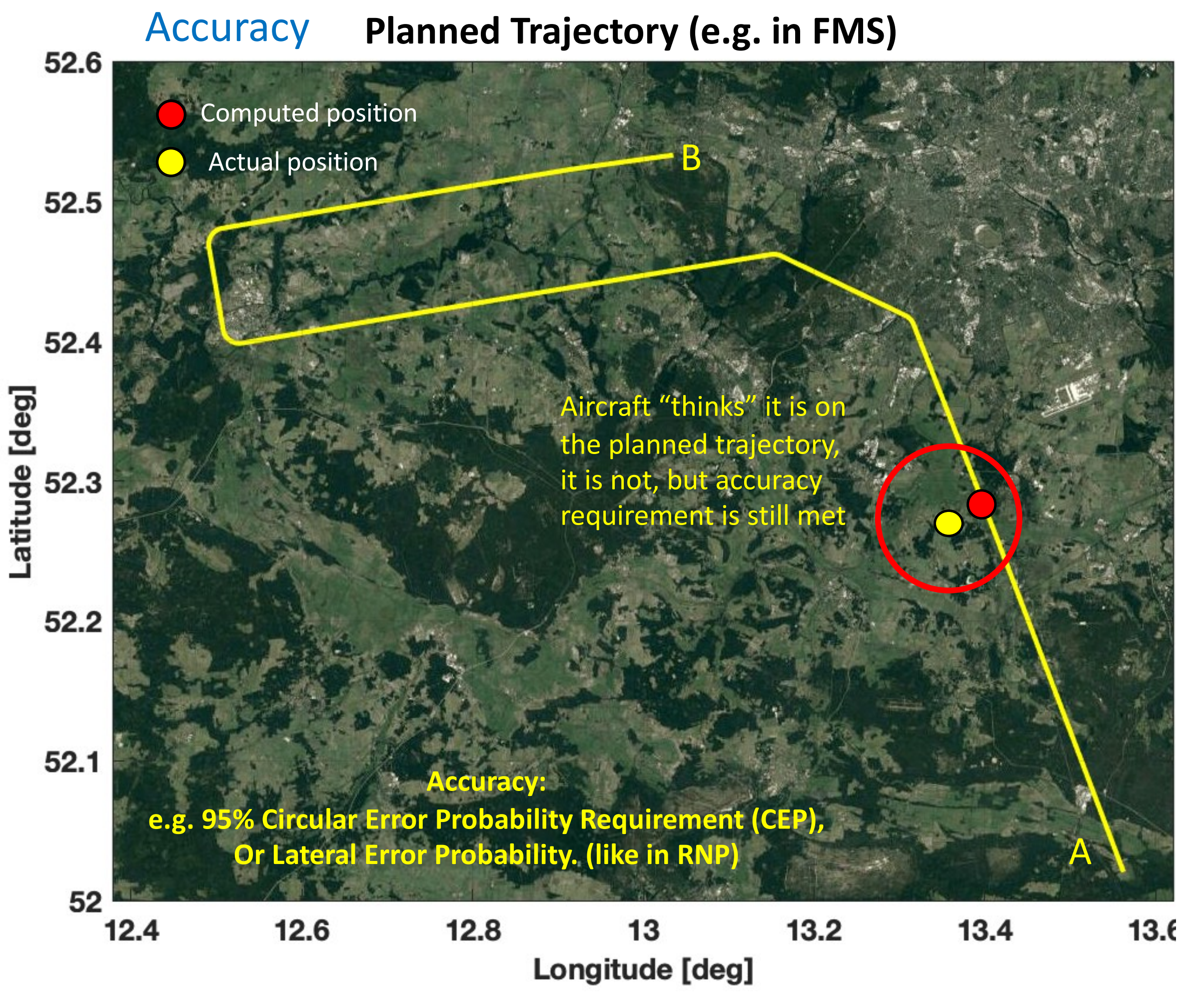
Tiem To Alert

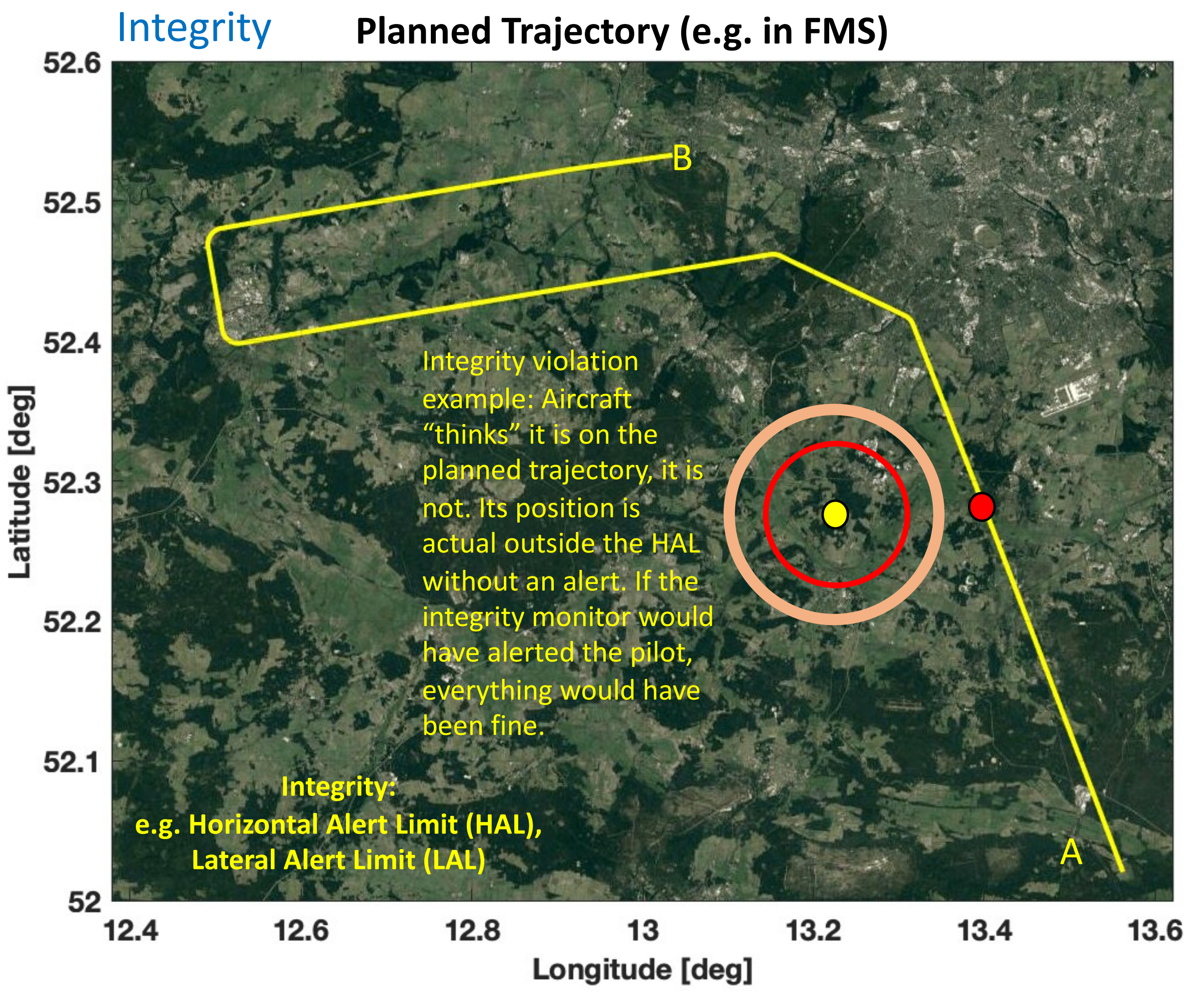
Hazardous Misleading Information

For safety-critical operations, we would like to operate here; when GNSS by itself can not achieve this, PNT (Position, Navigation and Timing) resilience must be included



Accuracy and Integrity





Technische Universität Berlin
Flugführung und Luftverkehr

Continuity of Service

The ability of a system to perform its intended function without interruption during the intended operation, if it did so at the beginning of the operation.

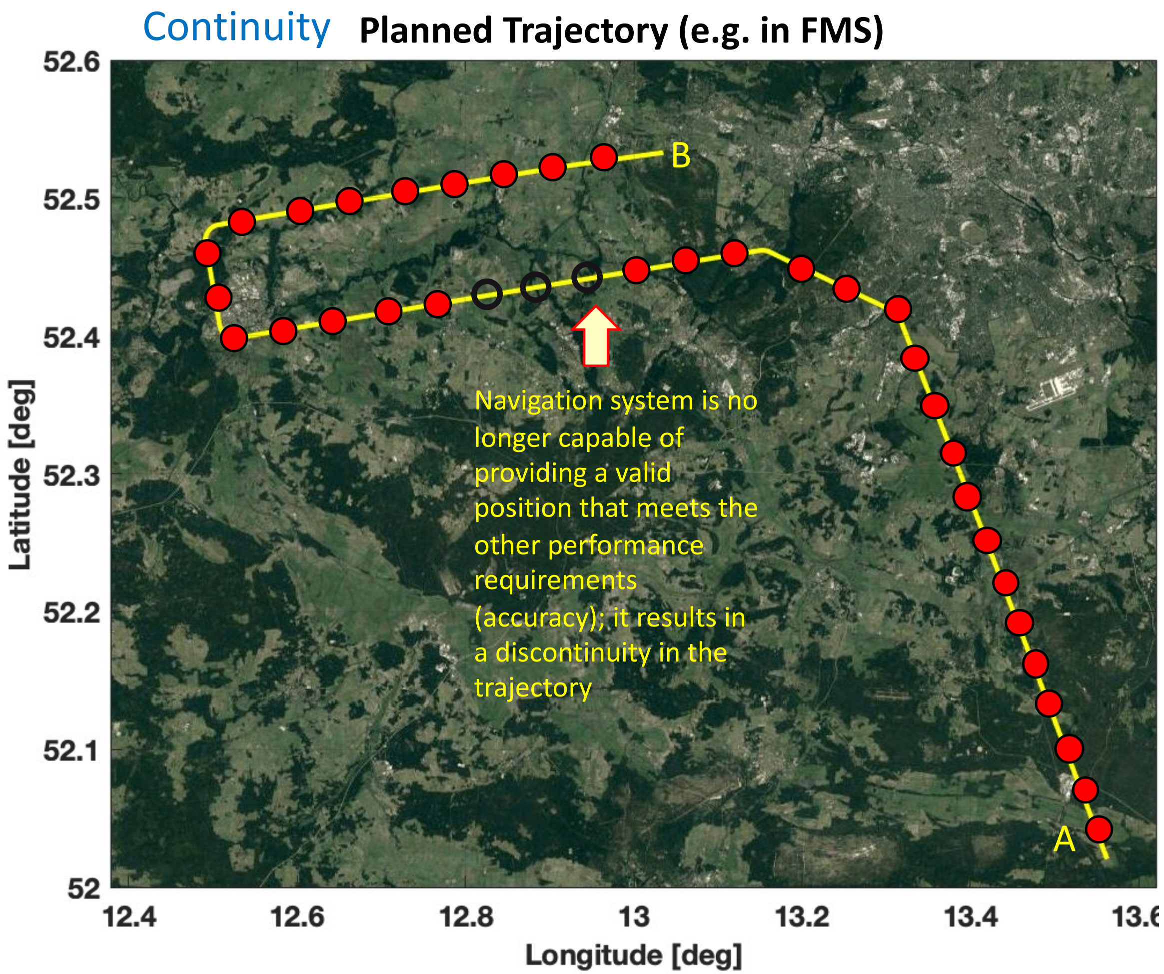
- Probability of system performing what it is supposed to (intended function) over time period (t_{start},t_{end}) **assuming that it started the operation**
- Drives the number of alarms that indicate that the system is not functioning
- Expressed by the **probability/ hour**

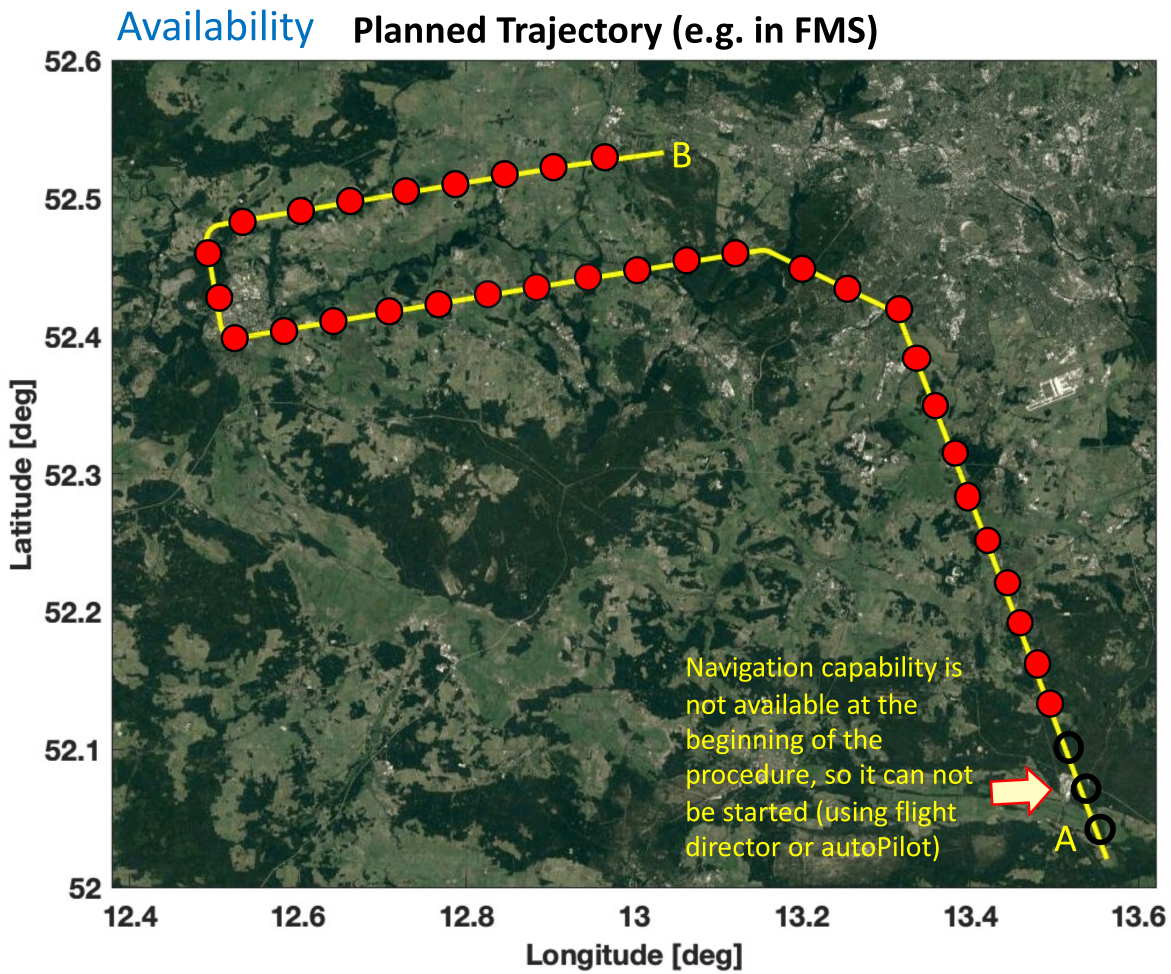
Availability

Is an indication of the ability of the system to provide usable service within the specified coverage area and is defined as the portion of the time during which the system is to be used for navigation during which reliable navigation information is presented.

- OR: Ability of the navigation system to provide the required guidance at the initiation of the intended operation
- Availability of the other RNP functions
  - Accuracy, Integrity, and Continuity
- Usually presented in one of two ways:
  - Probability, e.g. A = 0.999
  - Percentage of time, e.g. A = 23.976 hrs/day

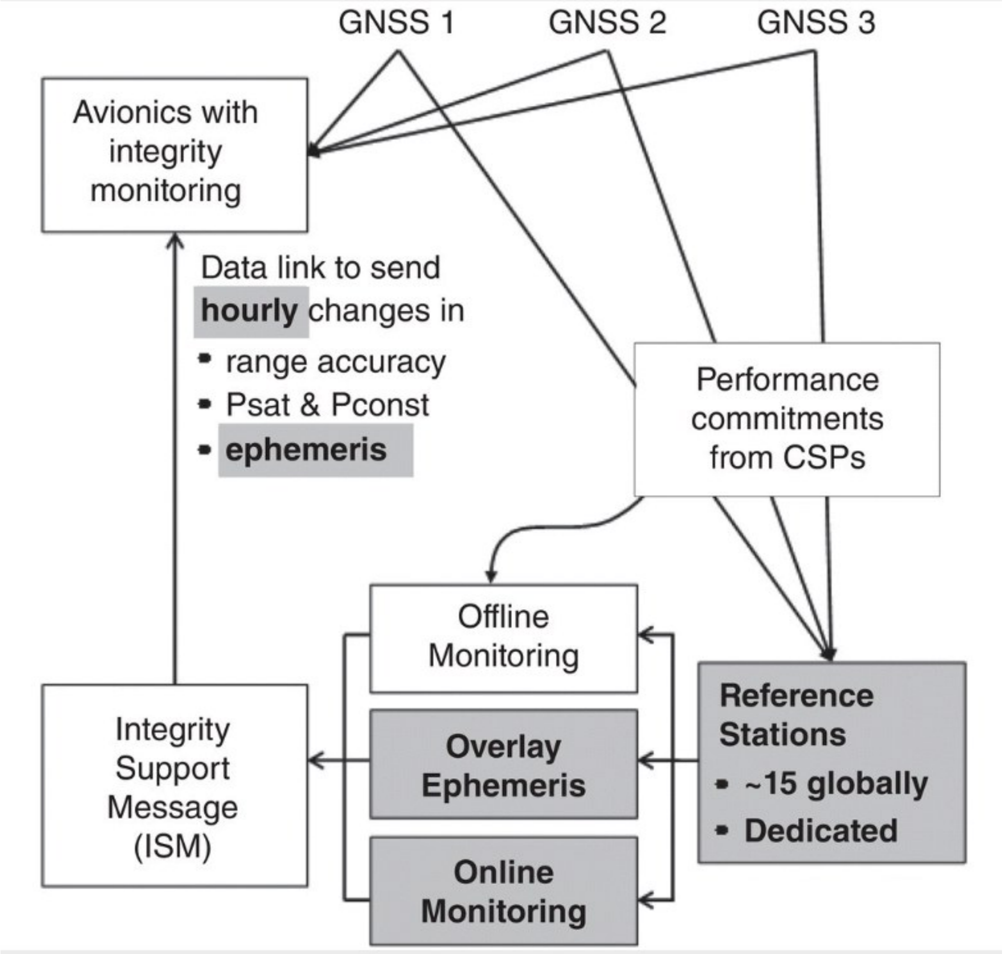
Continuity and Availability





Resilience Strategies (1)

- Built-in Fault Detection and Exclusion:
  - Receiver Autonomous Integrity Monitoring (RAIM)
  - Advance RAIM – Multi Constellation, Multi-Frequency
  - Residuals:
    - actual measurement – predicted measurement
  - Principle:
    - use the estimator residuals to assess if a fault occurs on one or more satellites (detection), and, if possible, identify the satellite(s) that have a fault (exclusion)



Weighted Least Squares Estimator (LSE) – Revisited

$$\mathbf{z} = \begin{bmatrix} \rho_1 \\ \rho_2 \\ \vdots \\ \rho_N \end{bmatrix} = \mathbf{h}(\mathbf{x}) + \boldsymbol{v}$$

Measurements

Measurement Covariance matrix

$\mathbf{C}_{acc}$

Linearization → $\mathbf{z} = \mathbf{H}\mathbf{x}$

Weighting → $\mathbf{W} = (\mathbf{C}_{acc})^{-1}$

Weighted LSE (WLSE) → $\hat{\mathbf{x}} = \left(\mathbf{H}^T\mathbf{W}\mathbf{H}\right)^{-1}\mathbf{H}^T\mathbf{W}\mathbf{z} = \mathbf{A}\mathbf{z}$

Covariance Matrix → $\mathbf{P} = \left(\mathbf{H}^T\mathbf{W}\mathbf{H}\right)^{-1}$

Dimension variance → $\sigma_q^2 = \left(\mathbf{H}^T\mathbf{W}\mathbf{H}\right)^{-1}_{q,q}$

Residual vector → $\mathbf{r} = (\mathbf{I} - \mathbf{H} \cdot \mathbf{A})\mathbf{z} = (\mathbf{I} - \mathbf{P})\mathbf{z}$

Integrity – Test Statistics

Residual-based Test Statistic

$$q_{RB}^2 = \mathbf{r}^T\mathbf{W}\mathbf{r} = \mathbf{z}^T\mathbf{W}(\mathbf{I} - \mathbf{G}\mathbf{S})\mathbf{z}$$

$$q_{RB}^2 \sim \chi^2(N_{sat} - M, \lambda_{RB}^2)$$

$$\lambda_{RB}^2 = \mathbf{f}^{\mathrm{T}}\mathbf{W}\left(\mathbf{I} - \mathbf{G}\mathbf{S}^{(0)}\right)\mathbf{f}$$

- Single test statistic for detection
- Need to find the worst-case fault vector, $\mathbf{f}^w$
- Computationally intensive to find this vector

Solution-Separation (SS) Test Statistic

$$\Delta\mathbf{x}^{(k)} = \hat{\mathbf{x}}^{(k)} - \hat{\mathbf{x}}^{(0)} = \left(\mathbf{S}^{(0)} - \mathbf{S}^{(k)}\right)\mathbf{r}$$

$$\Delta_{SS,q}^{(k)} = \mathbf{e}_q^T \Delta\mathbf{x}^{(k)}$$

$$\Delta_{SS,q}^{(k)} \sim N(0, \sigma_{ss,q}^{(k)})$$

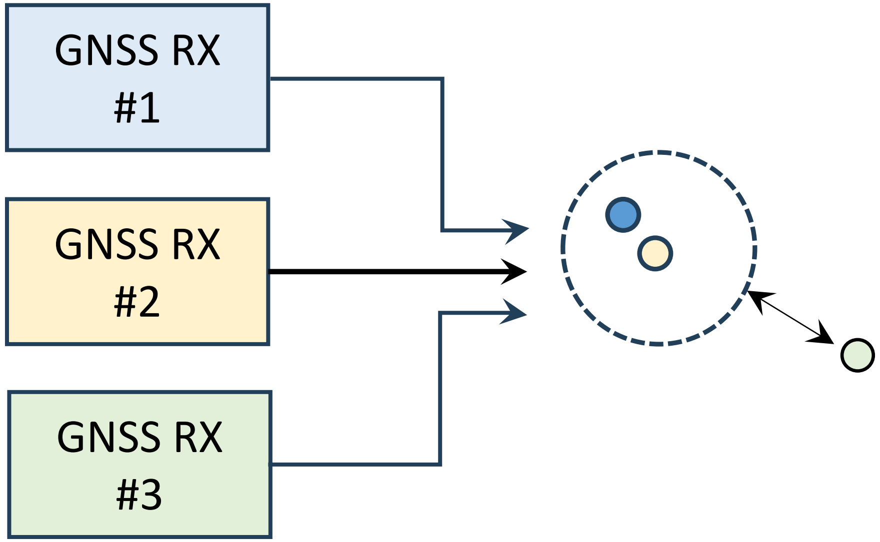
$$\sigma_{ss,q}^{(k)} = \sqrt{\mathbf{e}_q^T\left(\mathbf{S}^{(0)} - \mathbf{S}^{(k)}\right)\mathbf{C}_{acc}\left(\mathbf{S}^{(0)} - \mathbf{S}^{(k)}\right)\mathbf{e}_q}$$

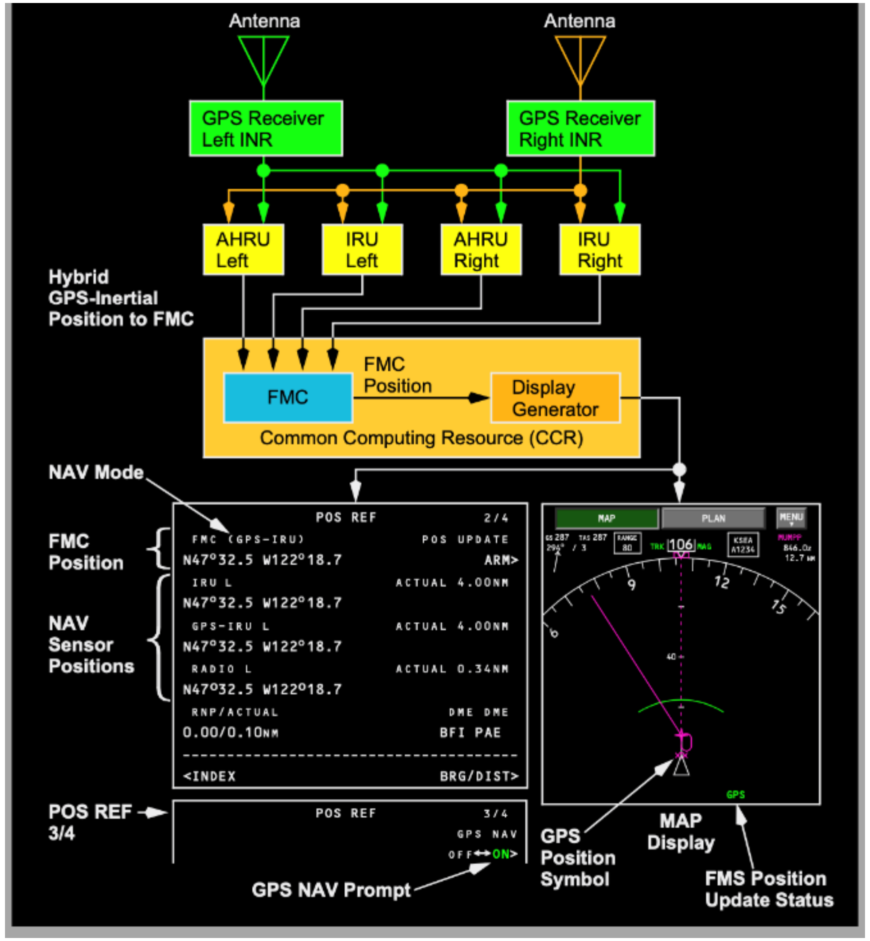
- Difference between all in view and fault-tolerant position solution (exclude the faulted satellites/constellation)

$\mathbf{e}_q^T$: vector with same size as state vector with a ‘1’ in the qth dimension. For example, q = 3 for z-dimension (Up)

Resilience Strategies (2)

- Redundancy
  - Use of multiple (dissimilar) GNSS receivers; check the **consistency** of their output or perform **voting** among its outputs
  - Does not help when there is a common cause faults

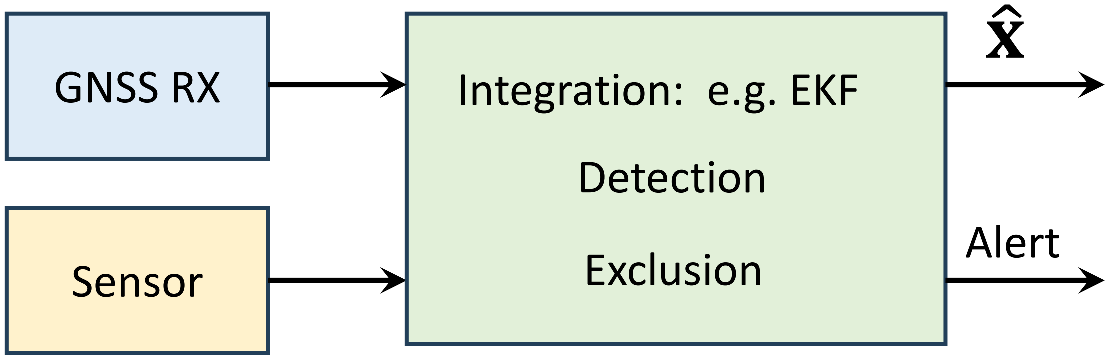




Technische Universität Berlin
Flugführung und Luftverkehr

Resilience Strategies (3)

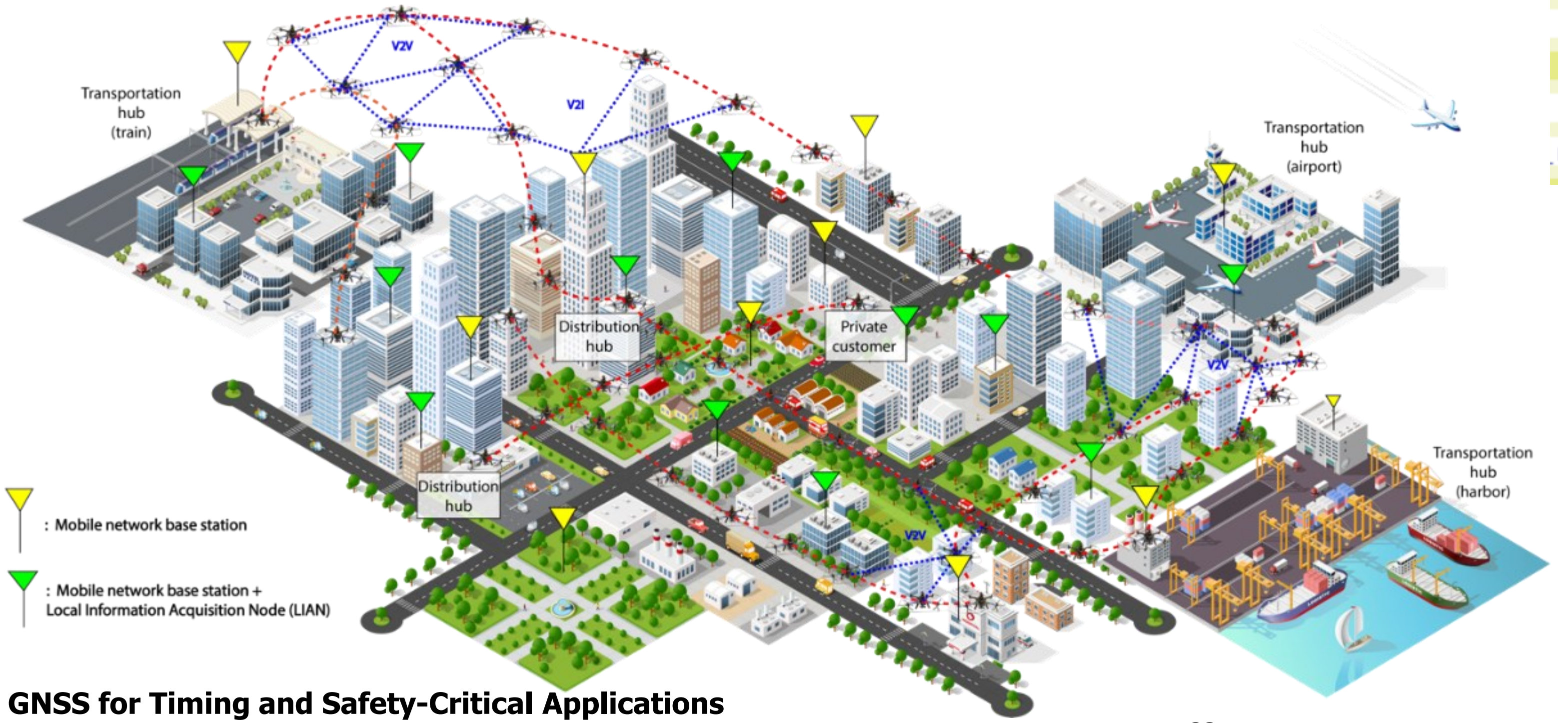
- Sensor fusion
  - Combine GNSS with other sensors (e.g. inertial navigation systems, baro, cameras, LIDAR, signals-of-opportunity, beacons, etc.)
  - Use estimators such as Kalman filters, particle filters, factor graph optimization, etc. to fuse the measurements or position outputs of the individual sensors
  - **Detection**: Perform a consistency check among the outputs or perform residual/innovation monitoring
  - **Identification**: multiple sub-filters, each designed to detect a particular failure mode

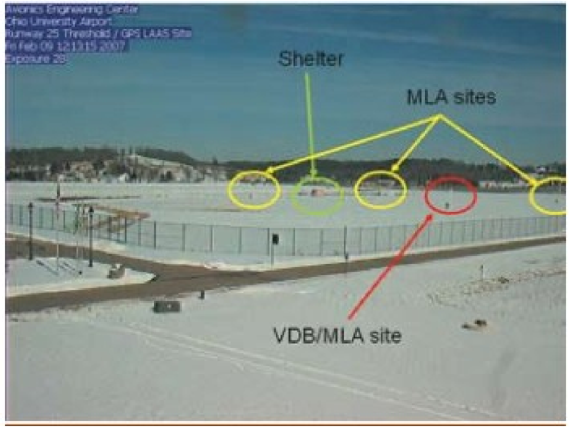


Can improve *accuracy* (noise reduction), *integrity* (FDE), *continuity* (coasting where necessary), *availability* (sensor may be available where GNSS isn't)

Resilience Strategies (4)

- Differential corrections and Local Monitors
  - Use local stations to monitor GNSS (using receivers and or software-defined radios) and perform detection and exclusion of faulty satellites as well as detection of interference presence in a local area



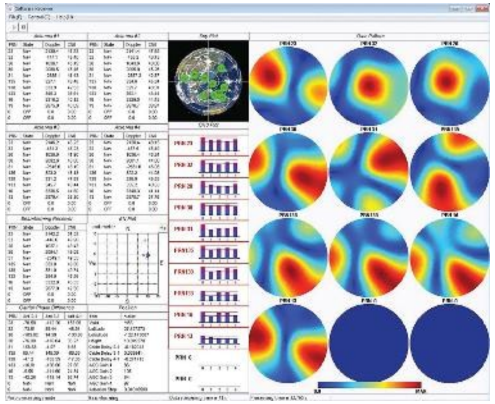


Technische Universität Berlin
Flugführung
und Luftverkehr

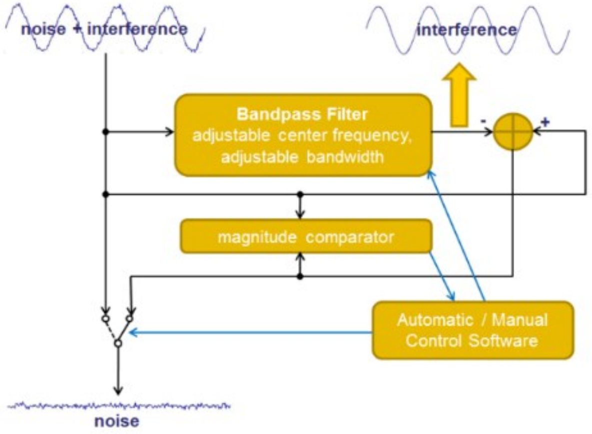
Resilience Strategies (5)

- Improved receiver design and antennas
  - Add antennas that are capable of nulling out interference sources through beam(s) steering; e.g. using a Controlled Reception Pattern Antenna (CRPA)
    - Antenna array + signal processing
  - Include receiver processing techniques to detect interference of spoofing
    - Various manufacturers include some detection capabilities inside their receiver
    - For example AIM+

Courtesy of Hexagon, QinetiQ



From: Chen et all., Off-the-Shelf Antennas for Controlled-Reception-Pattern Antenna Arrays



Courtesy of Septentrio

Train Example – Application of Resilience

- Consider the train localization example; used by ERTMS ((European Rail Traffic Management System) to reduce reliance on Balises, autonomous train control, virtual block signaling, etc.
  - Use of track signatures (GNSS alternative): use magnetic, curvature, and vibration sensors to estimate the train positions using a digital map.

Heinrich and Siebler, Onboard Train Localization with Track Signatures: Towards GNSS Redundancy, DLR

  - Use the fusion of GNSS with inertial navigation system, odometers, or 5G to obtain an accurate position able to continue operation in GNSS-denied areas such as tunnels

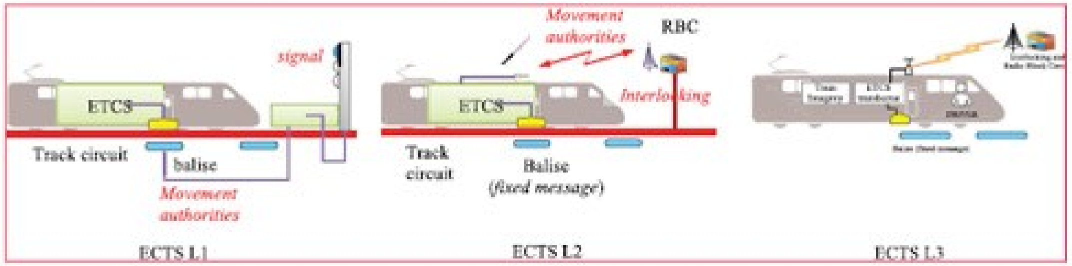


Figure 1: ERTMS paradigms

Neri, et al., "On the Integrity of GNSS-IMU Train Positioning Exploiting the Track Constraint," and "A resilient high integrity train positioning based on GNSS and FRMCS/5G"


Questions?